Extended Use of Acoustic Positioning Systems

By Jan-Erik Faugstadmo & Are B. Willumsen

*Kongsberg Maritime AS*
Abstract

Acoustic positioning systems were originally used primary as a position reference system to the DP. For several years, these systems have also been used for riser monitoring and emergency BOP control. Today’s operations also require control of other sub-sea systems and uploading of both real time and logged data. This can be status information, raw and processed data used for fatigue monitoring of wellheads. Survey operations also have a need for using the acoustic positioning system to perform long baseline calibration and uploading of sensor data.

The underwater acoustic communication channel has a relatively limited bandwidth. Care must be taken to enable the positioning system to perform several tasks, while not affecting its main purpose as position reference. It is critical that the DP class is not affected. This paper will discuss how this can be addressed by use of integrated positioning and communication, dedicated operator stations, and flexible use of inertial navigation. Integration of acoustic position measurements into inertial navigation work well with simple standard models for the behaviour of the acoustic positions. However, use of improved models based on the nature of the acoustic measurements allow for better performance, integrity, and ease of use.

Introduction

Acoustic positioning systems permanently installed on DP vessels can be extended for use in new applications and better utilized as DP reference. The improvement in acoustic communication enables the system to be used for control and retrieval of subsea data while being used for DP reference. New positioning technique and use of aided inertial navigation improves the overall positioning performance and ease of use at the same time reduces the number of transponders on the seabed.

Positioning and Acoustic Modem function

In DP applications, the acoustic positioning system is traditionally used as one of two primary position reference systems. Positioning of ROV’s and control of BOP emergency shut down system on drilling units are often included. However, the installed acoustic positioning systems are capable of executing more tasks like acoustic communication for control and retrieval of subsea sensor data.

The challenge is that the system must provide a reliable and stable position with good position update rate to the DP system while executing other tasks. Simultaneous acoustic activity can cause interference and loss of position.

The underwater communication channel

The design of acoustic positioning and communication system faces the following limiting factors:

- Bandwidth
- Propagation delay
- Overlapping signals
- Multipath
- Noise

The above factors are subjects for a paper on it’s own. In this paper they are briefly discussed.

Bandwidth

The data speed is proportional to the bandwidth. In order to transmit data at high data rate, high bandwidth is a necessity. The bandwidth in acoustic positioning system that operates at 10-35kHz are approximately 30% of the center frequency.
Example: a system with 8kHz bandwidth may have the capability of transmitting 16kBit/s. This is the gross data rate without overhead for error correction, brake between messages etc. Due to the relative low carrier frequencies, the data rate is very limited compared to radio and wired systems.

Higher frequency systems can be designed to provide relatively high bandwidth, but the operational distance will be very limited, typical less than 200m, and not very useful for most DP applications.

**Propagation delay**
The velocity in water is approximately 1500 m/s, this is very low compared to electromagnetic waves, which is 299792458 m/s, or 200000 times faster. In water, acoustic messages will take long time from the transmitter to the receiver. Two-way transmission on 3000m distance will take 4 seconds. This is a very limiting factor for both position update rate and data communication speed.

**Overlapping signals**
Overlapping signals will occur when signals from two or more transmitters appears in the receiver at the same time. A data message sent by acoustic communication can be relative long and the probability of overlapping signals will increase.
The dynamic range of the signal is very large. The transmission loss in water is defined by:

\[ T_l = 20\log(R) + R\alpha \]

Where:
- \( R \) = range in meters
- \( \alpha \) = frequency dependent absorption factor in water
  (@10kHz = 1dB/km, @25kHz=5 db/km)

Example: We have two transmitters with same carrier frequency @ 25kHz, one located at 250m and one at 2500m distance.
Transmission loss:
- \( T_l(250m) \): 49.2 dB.
- \( T_l(2500m) \): 80.5 dB.

As we see, the difference is equal to 31.3dB or 1000 times signal strength in power.
If the signal from these two transmitters where received at the same time, the signal from the unit at 2500m will be xx times lower and impossible to detect, it will be totally suppressed by the stronger signal.

If two or more transmitters are at approximately same distance, the probability of getting detection of the signals are higher. However it will limit the robustness and the opportunity to operate with higher data rate. Higher data rate are more sensitive to interference.

The carrier frequency of these signals will be different, if the separation of the carrier is sufficient, the signals may be separated and detected. But, the limited bandwidth does not allow for great separation.

Two signals at a bandwidth of 4kHz separated by 2kHz will be separated with 3 dB only. As a rule of thumb, overlapping signals must be 9dB apart to achieve safe detection.

In acoustic communication, various methods can be used to improve the separations of the signals, but this will have an effect on the achievable data speed. The issue with overlapping signals will still be present, though.
Multipath

Multipath occurs when there is more than one signal path from the transmitter to the receiver. Typical are reflections from surface, seabed and structures causing both the direct signal and the reflected signal to appear in the receiver. If the reflected signal arrives later than the direct signal it is easy to reject it. But if the reflected signal appears in the receiver in the same time slot as the direct signal it will interfere and possibly cause loss of signal. Modern algorithms are capable of suppressing multipath to some degree, but again, this is done at the expense of the data rate. Acoustic positioning systems with directional transducers and/or electronic beam formers are able of suppressing multipath when the reflected signal is from another direction than the direct signal.

Multipath is seldom a huge problem when operating vertical, and is often the biggest challenge when operating over long horizontal distances.

Noise

The most dominating noise in DP applications is from thrusters. Other noise sources can be generated by ROV’s, drilling and noise from various sea states. Acoustic positioning systems with directional transducers and/or electronic beam formers are able of suppressing noise when the noise is from another direction than the signal.

The maximum data speed is in general a function of the signal to noise ratio (SNR). Higher signal to noise ratio means higher data speed. If the SNR drops 3dB, the bit error rate will increase 100 times.

![Bit Error Rate as a function of $E_b/N_0$ for a BPSK modulated signal](image)

Bit error rate as function of SNR
Communication Profiles
A acoustic communication system must handle the above limiting factors in the optimal way. The problem is that there exists no optimal solution for all conditions. It is necessary to have different communication profiles that can be selected for various scenarios. The various communication profiles uses different signal processing algorithms.

The below table shows an overview of the present available profiles used in HiPAP and cNODE systems.

<table>
<thead>
<tr>
<th>Speed [bit/sec]</th>
<th>Cymbal (PHY)</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bandwidth [Hz]</td>
<td>Telegram Duration [sec]</td>
</tr>
<tr>
<td>170</td>
<td>4000</td>
<td>2.0</td>
</tr>
<tr>
<td>450</td>
<td>4000</td>
<td>2.0</td>
</tr>
<tr>
<td>1100</td>
<td>2000</td>
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<td>1.9</td>
</tr>
<tr>
<td>12000</td>
<td>8000</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Overview of communication profiles

Interleaved Positioning and modem function
The HiPAP Transparent Modem is a software function in HiPAP that enables the user to make use of the HiPAP system for two-way acoustic communication between the user’s top-side computer and the user’s subsea system. A cNODE Modem is connected to the user’s subsea system. The central part of this function is to interleave acoustic data communication between the positioning signals to avoid overlapping signals in the receivers.
General Functions

- Interleaving positioning and communication
- Single topside system for positioning and data transfer
- Continuously transmission
- Applies a beam forming antenna for data communication

If the HiPAP has no positioning tasks ongoing, it will use all available time to perform the modem function. If positioning is ongoing, (SSBL or LBL) the time will be shared between positioning and communication. The user can configure the time period the HiPAP shall use for positioning.

Ex:
If the time period is set to 10 seconds, the HiPAP will then perform positioning for 10 seconds and then allow one data message to be sent and received; this may last for up to 2 seconds in addition to the two way travel time in water.

HiPAP is often used for position reference in DP application, and will maintain the position update rate to the DP while performing acoustic communication. HiPAP will act as a master and it will always send a request for data to the cNODE and wait for the reply. The cNODE cannot transmit data without receiving a request first; the HiPAP will not listen for messages without sending the request first.

The user can control the modem for various communication profiles, power, serial number and channel for the subsea cNODE Modem. This can be done via menu in APOS or via Ethernet.

Multi Sub Band

<table>
<thead>
<tr>
<th>Channel number and carrier frequency (Fc):</th>
</tr>
</thead>
<tbody>
<tr>
<td>M8xx – Fc 24.0kHz</td>
</tr>
<tr>
<td>M6xx – Fc 24.4kHz</td>
</tr>
<tr>
<td>M4xx – Fc 24.8kHz</td>
</tr>
<tr>
<td>M2xx – Fc 25.2kHz</td>
</tr>
<tr>
<td>Mxx – Fc 25.6kHz</td>
</tr>
<tr>
<td>M1xx – Fc 26.0kHz</td>
</tr>
<tr>
<td>M3xx – Fc 26.4kHz</td>
</tr>
<tr>
<td>M5xx – Fc 26.8kHz</td>
</tr>
<tr>
<td>M7xx – Fc 27.2kHz</td>
</tr>
<tr>
<td>M9xx – Fc 27.6kHz</td>
</tr>
</tbody>
</table>

| Bandwidth of each band is 4kHz          |
| Total number of unique channels is 560 |
| 29.6kHz                                 |

The Cymbal acoustic protocol includes operation in several frequency sub-bands. Telemetry executes in the same sub-band as the selected transponder interrogation and reply occurs. This simplifies the frequency management of the system and eases multi vessel operations. Each sub-band consist of 56 positioning channels and 6 LBL interrogation channels. A total of 560 unique channels for positioning along with 60 unique LBL interrogation channels are available. In a modem application, the interrogation channel is used to wake up the mode from sleep mode.
Application - Fatigue measurements

Monitoring of the wellhead fatigue during drilling operation may require an acoustic modem functionality to retrieve wellhead fatigue data from the sensors at the BOP. Utilizing existing acoustic positioning system to perform this task reduces the need for installation on new equipment onboard. The acoustic system can operate as a modem transferring data between an external sensor system subsea and to an external system at top side or onshore.

An alternative solution is to use a cNODE transponder with integrated sensors for fatigue measurement; the sensors are MEMS gyros and accelerometers. The sensors are sampled and the data is processed subsea to provide a compact data set to be transferred via the modem function. The data are presented topside on the Sensor Logger Client, a computer connected to the HiPAP system. The HiPAP system will at a preset interval request data from the cNODE, typically every 15 minute. Both raw and processed data are also stored in the cNODE.

The Sensor logger is also used to configure the fatigue measurements, processing and data retrieval.

![Sensor Logger Client](image-url)
Application Survey

The APOS Survey OS is an operator station designed for use by surveyors for operation of the HiPAP system. The APOS Survey OS can be located in the surveyor’s room remotely from the bridge of the vessel. The station is based on APOS software.

The purpose of the Survey APOS OS is to allow the surveyor to operate the APOS in a survey application without need to change configuration and settings in the onboard system. The APOS survey OS can be configured with options that is not included in the onboard system, e.g. LBL. On startup, the survey system can select to transfer settings from the onboard system to the survey station. These settings, like level arms and alignment can be freely modified locally on the APOS survey.

Interfacing to the onboard system is done by use of high speed serial line that inhibits possible virus spreading to the existing onboard system.
Multi-LBL

The HiPAP Multi-LBL solution enables the systems onboard a vessel to utilize only one LBL transponder array to provide several separate independent position inputs to the DP system. The vessel may be equipped with two, three or four HiPAP systems. Each system will provide position input to the DP based on independent measurements.

**Principle of operation**

One of the systems onboard provide the acoustic interrogation of the seabed LBL transponder array and send an electric trigger signal to the other systems. All systems receive the same signal from the transponder array and can thereby compute an independent position. The electrical trigger enables independent range measurements to the transponders.

In case the interrogating system fails, one of the other systems automatically takes over and interrogates the seabed LBL array and provides the electrical trigger signal. The seabed transponder array can consist of 3 to 8 transponders. Typically 4-5 transponders will be used in one array providing good redundancy. Three transponders are required to provide a full LBL solution. By this, redundancy is achieved both onboard the vessel and on the seabed array.

A hardware trigger line must be installed between the transceivers.

Common mode failure on the HiPAP system onboard is handled by automatic takeover if the interrogating system is failing or a fail on the trigger line occurs. On the LBL transponder array common mode failure is handled by use of redundant transponders in the array.

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**Multi LBL system diagram**

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Comparison HiPAP 1 vs HiPAP 2, local positions

The Figure above shows the position in north and easting for HiPAP 1 and 2. HiPAP 3 is used as the triggering system.

Position difference combined North and East

The Figure above shows the difference in position between HiPAP 1 and 2. HiPAP 3 is used as the triggering system. There is a position difference between the two systems that is related to an inaccuracy from the dimension measurements of the level arms onboard the vessel. This shows that accurate dimension control is necessary to have good integrity between the systems.
Acoustic positioning, Inertial and Integration

The benefits of coupling inertial navigation with the acoustics have been well accepted over the last decade leading to widespread adoption. To sum up the benefits are
- Increased battery lifetime
- 1 Hz update always.
- Improved accuracy
- Improved integrity
- Improved weighting
- Less transponder deployment

Tightness of coupling

The tightness of coupling in an inertial navigation system refers the degree the measurements are transformed before used; more transformations is described as looser coupling (or integration). In acoustic position measurements for instance, calculating the longitude and latitude from multiple acoustic observations before feeding longitude and latitude to the navigation system constitutes a loose integration. Whereas a very tight coupling could be each acoustic element on the transducer individually providing measurements for the inertial navigation system.

Tighter coupling can also be achieved going the other way, with INS estimates data (position, velocity, orientation, errors, or other) utilized in the acoustic system to get better. An example of such is using the INS estimated position as input into the acoustic system for better tracking of incoming signal.

The tightness of coupling is something that must be carefully addressed in system design. Tighter coupling generally provides increased performance, but the drawbacks are increased system complexity and risk of reduced robustness. If well designed, the robustness should improve.

Representation

The two most intuitive representations of the acoustic position measurement is the range & bearing or the Cartesian XYZ. One immediate thought might be that the range & bearing is the untransformed representation. However, no acoustic system measures range and bearing. It measures transmission time and differences in time of arrival, which in turn are transformed into range & bearing or XYZ by using some estimate or measurement of the speed of sound profile. To get correct transformation, you normally would use all three measurements in the transformation together.

The transformation between range/bearing and xyz is one-to-one. For every value of range & bearing there exists one and only one XYZ-value. This means that each representation holds the exact same amount of information.

One may argue the uncertainty (white noise) is normally better described in a range and bearing frame, and that is almost always true. However, there is still a one-to-one conversion between them, so they hold the same amount of information, and will give the same end-result in the navigation system if treated correctly. Systematic errors such as box-in error and sound profile errors are better described in the XYZ frame.

The seemingly big benefit in using a range & bearing representation is that you can use one even if you do not have a valid measurement of the other. In Kongsberg Maritime acoustic systems, this is though rarely the case. If the system was unable to determine range, its bearing was not trustworthy either and vice versa.

The one situation where a bearings-only approach would be beneficial is when somebody else is pinging the transponder(s). Kongsberg Maritime has never arranged for such a system, and have instead created the MULBL feature in its systems allowing multiple vessels to use the same array simultaneously.
Secondly, getting a rough estimate of the range, and thus the full XYZ is never a problem, as the vessels depth and transponder depth are fairly well known. Therefore, unlike popular misconceptions, representing the acoustic measurement in terms of range and bearing is not the one true way of representing the acoustic measurement, nor is it important for navigation system performance.

**Dimension**

HAIN Reference has successfully been using loosely integrated 2D positions from HiPAP and HPR as inputs for the last 10+ years [1]. The geographical 3D position is calculated by the acoustic system based on either an SSBL or an LBL solution and the orientation of the vehicle received from a third sensor. Only latitude, longitude and the covariance decomposed into latitude and longitude are sent to HAIN for updates. This means that the depth information and covariance are disregarded. However, this is a robust solution, primarily because DP has no interest in the depth information. Normally the errors in time of flight and the difference in time of arrival are uncorrelated. When the transponder is straight below the transducer, the uncertainty ellipse is aligned with horizontal plane. This is shown in the figure below. When the ellipse is aligned with horizontal plane there, the horizontal and depth are decoupled and depth information will give no input to the horizontal direction. The 2D and 3D approaches will then give the same result in terms of horizontal position and accuracy.

![Uncertainty ellipses XZ](image)

When the transponder isn’t straight down the results from 2D and 3D will differ. A comparison of updated horizontal position with 2D approach and 3D approach with the transponder 3/10 of water depth horizontally offset are shown in the figure below. It shows 2D error ellipses after a 2D and a 3D position update. One can see that the difference between the methods are irrelevant as compared to total accuracy, even with a rather large horizontal offset of the transponder (3/10 of water depth as opposed to the normal 1/10). Obviously, the difference in estimated depth is significant, but that is irrelevant to its purpose as a DP position reference.

![Uncertainty ellipses 2D and 3D updates TP](image)
Multiple Transponders

When using multiple transponders there is a bigger difference in the tightness than in the single transponder case. In a loosely coupled system, the traditional LBL solution (latitude, longitude, and covariance) is computed by the acoustics and fed to the navigation system. A more tightly coupled solution would have each transponder’s measurement being treated as individual measurements in the navigation system. See below:

It is possible to implement a semi-tight coupling by calculating longitude and latitude from each transponder and feeding that into the INS. However, this has the clear drawback that the depth information is disregarded, which in normal LBL operations holds most of the information. This is especially so in deeper waters. The LBL algorithm will utilize the depth information, hence in the loosely coupled solution; the depth information will be utilized. To use multiple transponder tightly in an INS well, one has to use all three dimensions of the measurement as shown in the “Dimensions” chapter. The big benefit of using the measurements tightly instead of as an LBL array is the ease of use. New transponders can be taken in and out as sources for the INS, and one does not have to go through the process of setting up or altering the array. This is especially important with the newest acoustic systems that can easily afford to have a separate channel for each individual transponder, and still have an abundance of channels available. There will though still be many situations where LBL mode of interrogation is required. For older acoustic systems, the number of channels are much more limited. Requiring the user to operate the transponders in LBL mode. Using a tight integration scheme will though result in almost the same performance whether you run the transponders as single SSBL or as an LBL array. The only thing separating the performance are acoustical differences (turnaround time, number of lost replies, etc.)

Unlike many other acoustic inertial systems [2], LBL and HAIN in loose integration works perfectly well with only a single reply from the LBL array. In short, as long as the acoustic system receives any valid reply from a transponder in the array, it will produce an acoustic position for HAIN. The position will
obviously have a larger error ellipse than full array response, but compared to no position it will do wonders.

<table>
<thead>
<tr>
<th>Location of transponders with valid reply, and resulting HAIN uncertainty ellipse</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 TP</td>
</tr>
</tbody>
</table>
| ![Diagram of transponders and uncertainty ellipse](image)

HAIN position standard deviation development with time and different transponder scenarios.

Orientation

If one wants to use the directional measurements from the acoustic system for vessel positioning, the orientation of the vessel itself is necessary information. One can very well utilize the range information without orientation knowledge, but not the bearing.

In a loosely coupled solution, the orientation is fed to the acoustic system from some source. Feeding the navigation system’s orientation for this is not recommended as this may lead to positive feedback and unstable navigation.

By using a tightly coupled solution, one is able to allow for acoustics-inertial positioning without the need for the extra input of orientation to the acoustic system. The navigation system receives the measurement represented in a way independent of the vessel’s orientation. This autonomy requires that the navigation system is accurate enough to be able to maintain estimate of its own heading.

Error Estimates

The systematic errors of an acoustic position measurement is normally dominated by the speed of sound estimates, the transponder boxed-in position and the transducer alignment. Kongsberg Maritime created the run-time calibration of LBLs to let the LBL-algorithm estimate and compensate for these errors, while doing positioning. When the navigation can use the transponders’ individual measurements instead of the computed LBL solution, it can keep track of correlation between estimated errors and other states of the system. This may prove to give some improvements in robustness and accuracy in the future. Kongsberg Maritime have not noticed any such effects yet.

Multiple SSBL
HAIN has been extended with the Multiple SSBL feature, which holds a tighter integration of the acoustic measurements. All three dimensions of the measurement is used. Additionally multiple SSBL transponders can now be used as aiding sources for HAIN at the same time. The operator can select and de-select transponders to be used to aid HAIN during operation. This is performed with just a few clicks of the mouse and requires no further actions. Imagine also the situation when an operator notices that the HAIN performance is insufficient running on a single transponder, one can simply deploy another transponder and get almost immediate performance improvements. One should be aware though that there will be no baseline measurements (ranges between transponders) when using the transponders in SSBL mode instead of setting up the full array. This will lead to less accurate boxed-in positions of the transponders, and subsequently additional systematic errors in the HAIN output. HAIN will mitigate some of this.

The feature also holds tighter integration for LBL. HAIN will not use the calculated LBL position, but rather each replying transponder as independent transponders. As described in the preceding chapter, for Kongsberg Maritime acoustics and HAIN the tight integration (Multiple SSBL) does not lead to much improvement in performance nor robustness, but it gives significant benefits operationally. This is summarized in table below.

<table>
<thead>
<tr>
<th>Improvements by tight integration (Multiple SSBL)</th>
<th>Robustness</th>
<th>Accuracy</th>
<th>Ease of use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marginal</td>
<td>None</td>
<td>Yes</td>
<td></td>
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</tbody>
</table>
Conclusion
Modern acoustic positioning systems are capable of providing functions for extended use. Utilizing the built-in capabilities for acoustic communication, the system can be used to control and monitor subsea equipment. By combining the acoustic positioning system with aided inertial navigation, an accurate and reliable position can be maintained during periods with acoustic data communication.

Acknowledgements
We would like to thank our customers for approaching us with challenging applications that make us design new and effective solutions for use of acoustic positioning systems.

References
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Jon Parker, New interfaces for aided inertial sensors, MTS DP Conference Houston, October 2015

References
[1] Are B. Willumsen & Torbjørn Hals, 10 Years of Experience From Acoustic Aided Inertial, MTS DP conference Houston, October 2013