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Technology Advances Providing Extreme Acoustic Positioning Repeatability for Deepwater Drilling and Minerals Exploration

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Abstract

The frontiers for deep sea minerals exploration in water depths ranging between 4000m and 6000m pushes the maximum range demands for the acoustic positioning systems, that operate in the traditional Medium Frequency band. Reliable operations in 6000m of water required the development of a new wider acoustic transducer array. The operational performance envelopes and physical design difference between the workhorse HiPAP 502 and the new HiPAP 602 acoustic positioning transducer is explained. The extreme positioning performance achieved with a larger transducer coupled with closely integrated inertial navigation system, further improves position availability and robustness of the reference for the Dynamic Positioning System.

Abbreviation / Definition

dB	Decibels
DI	Directivity Index
EHF	Extra High Frequency Band (Acoustics)
GNSS	Global Navigation Satellite Systems
HAIN	Hydroacoustic Aided Inertial Navigation
HiPAP	High Precision Acoustic Positioning
Hz	Hertz
IMU	Inertial Measurement Unit
INS	Inertial Navigation
LBL	Long Baseline
LF	Low Frequency Acoustics Band (Acoustics)
MF	Medium Frequency Band (Acoustics)
NL	Noise Level
TL	Transmission Loss (acoustics through water)
SIMOPS	Simultaneous Marine Operations
SL	Source Level (acoustic transducer/transponder)
SNR	Signal To Noise Ratio
SSBL	Super Short Baseline

Introduction

Acoustic positioning reference systems for Deepwater drilling and construction vessels have provided robust and reliable position inputs for DP reference in water depths up to 4000m. However, minerals deposits of polymetallic nodules and rare earth muds can lie in water depths between 4200m and 6000m. With the Drillship Vitoria 10000 being converted for deep sea minerals recovery tests, she needed an upgrade to allow the acoustic positioning reference system to operate in water depths to 6000m. This upgrade required the design of a new transducer to extend the range capability of the HIPAP in the medium frequency band out to 7000m.

Section 1 – Why Utilize a Medium Frequency Transducer Design.

The Medium frequency band (MF) nominally between 20KHz to 34KHz has been used since the 1960's for offshore positioning. The band was chosen as the optimal compromise between range and measurement accuracy.

Acoustic signals in the Low Frequency band at the 10Khz band travel further in water and systems exist with range capabilities of more than 13km, however this system was not considered ideal for this operation, for several reasons. Firstly, the measurement accuracy of super short baseline (SSBL) positioning systems is mainly a function of the frequency wavelength versus the transducer array diameter and signal to noise ratio of the received transponder signal. Therefore, the LF systems have a reduced measurement precision for the same size diameter of transducer array diameter versus MF. Secondly propulsion and thruster generated acoustic noise is higher in the LF band and thirdly there is a desire to maintain the acoustics in the MF band to allow other vessels to pre-lay and calibrate the transponder arrays for operations without minimal refit costs.

Conversely higher frequency acoustic systems 50KHz and above offer much improved angular accuracy, however these systems are range limited to 1000m due to the increased in water signal absorption at higher frequencies.

Historically MF systems with analogue receivers were limited to around 3000m of range but with the advancement of lower power digital signal processing platforms and implementation of new broadband signal protocols, like Kongsberg's Cymbal, the acoustic range and performance improved.

The digital signal processing of longer codes on broadband carrier frequencies improved both the received acoustic signal to noise ratio and precision in measurement timing of the acoustic range observations. These developments led to a 3-fold improvement in SSBL angular measurement accuracy from approximately 0.2 to 0.06 degrees and a 10 times improvement in range measurement precision, from approximately 20cm to better than 2cm. This greatly increased the position repeatability and reliability of acoustic positioning reference systems.

In addition to improved acoustic positioning performance the introduction and adoption of the digital Cymbal acoustic protocol from 2010 onwards dramatically increased the range capability of HiPAP SSBL systems from 3000m to 5000m and extended the available unique navigation channels from 16 to over 560. The additional channels allow multiple vessels to operate in SIMOPS, even within acoustic interference range simultaneously. Each SSBL system processed it owns unique signals through correlation filters in the DSP receivers, which filter out and ignoring signals transmitted by other systems.

Section 2: Sonar Equation for Acoustic Positioning

The HIPAP systems use a technique called super short baseline acoustic positioning (SSBL). SSBL systems measure the phase difference of the acoustic signal replies from seabed reference transponders across the transducer array. The SSBL system also measures the two-way acoustic travel between the vessels transducer and seabed reference transponder. The phase observations and measurement timing are used to calculate a range and bearing to the reference transponder from which a relative vessel position is calculated.

The performance of SSBL systems in terms of range, angular accuracy and ultimately position repeatability is dependent upon the signal to noise ratio, of the received signal at the vessels acoustic transducer.

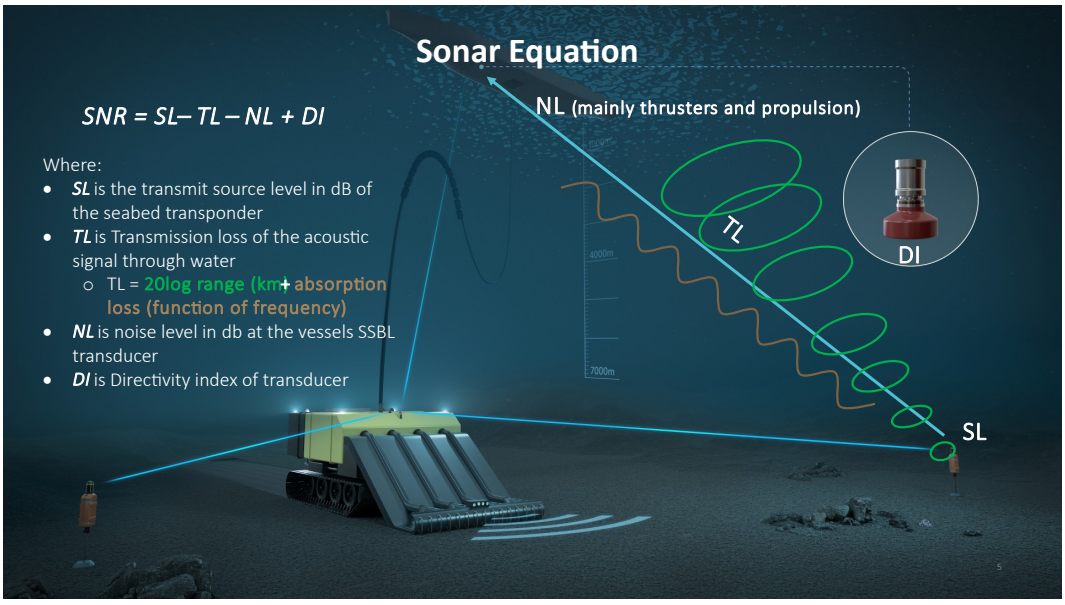

Fig 1. Sonar Equation

The signal to noise ratio (SNR) is described by the sonar equation:

$$SNR = SL - TL - NL + DI$$

Where:

- ***SL*** is the transmit source level in dB of the seabed transponder
- ***TL*** is Transmission loss of the acoustic signal through water
    - TL = 20log range (km) + absorption loss (function of frequency)
- ***NL*** is noise level in db at the vessels SSBL transducer
- ***DI*** is Directivity index of transducer

Cymbal improved the signal to noise ratio by spreading the acoustic energy over a wide frequency using a broadband carrier which increased the signal power or energy in transmission. Combined with running correlation filters to match the signal in the digital receiver, the background noise level and interference was effectively reduced.

Noise level (NL) is the background noise at the receiver. The key source of noise at the SSBL system include wave noise, thruster and stern propulsion noise as well as mud pumps resonating through the riser. Over the last 15 years more careful vessel design with consideration to keep SSBL transducers as far away from mechanical noise sources and adoption of variable speed thruster over older variable pitch thrusters has contributed to a much quieter environment for SSBL system installation and positioning performance.

Another important factor that impacts the performance of SSBL system is the Directivity Index (DI) which is related to two key areas of transducer design. These factors are transducer array dimensions or diameter and whether the transducer is actively using beamforming for transmission and reception of the acoustic signals.

Electronic beamforming or steering and focusing the listening beam is achieved by carefully adjusting the phase and amplitude of the signals fed to each transducer in the array. Beamforming in the HiPAP system utilizes the signal from a massive number of receiver elements covering the entire spherical transducer head.

The directivity gain achieved by focusing narrow listening beams towards the seabed reference transponder reply signals, results in a significant overall increase to the received signal strength. By focusing listening beams, the noise from sources such as propulsion is greatly reduced. The beam forming also provides the benefit of reducing multipath impact. The higher the DI the greater the range and angular accuracy that can be measured.

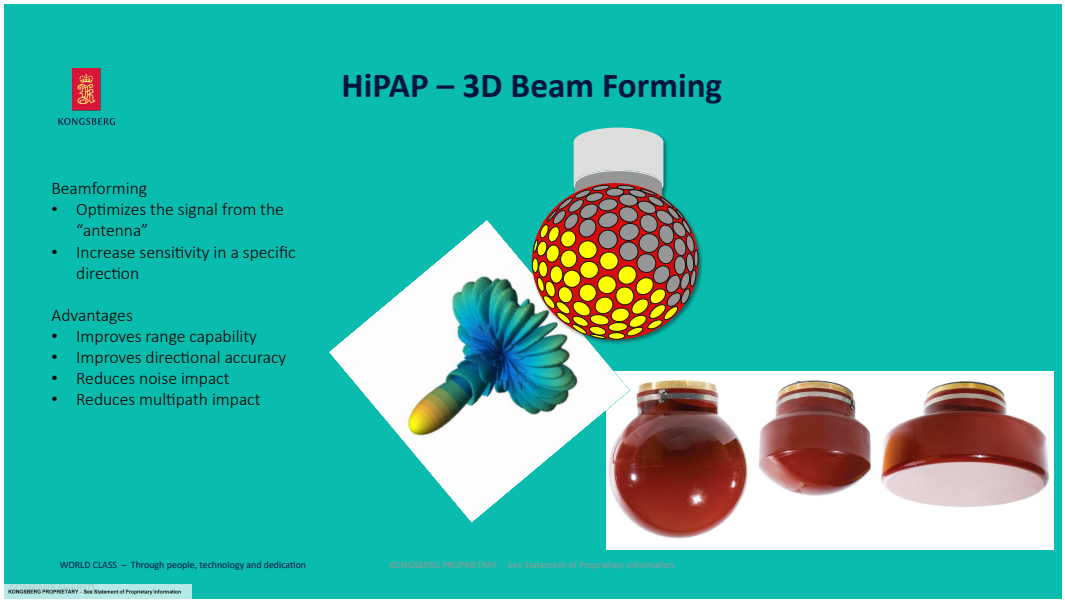

Fig 2. HiPAP 3D Beamforming

DI is also a function of beam width (Figure 3) which is inversely proportional to the transducer size. The larger the overall diameter of the transducer when compared to the acoustic wavelength, at a given frequency, the narrower the beam that can be focussed towards, any given direction. With narrower focussed beams the DI is increased providing enhanced signal to noise, resulting in an increase to both maximum acoustic range and angular measurement accuracy.

The transmission of acoustic interrogation signals from HIPAP also benefits from beamforming. By focusing energy and minimising the spread to unwanted directions, the acoustic propagation path of the interrogation signal is maximized.

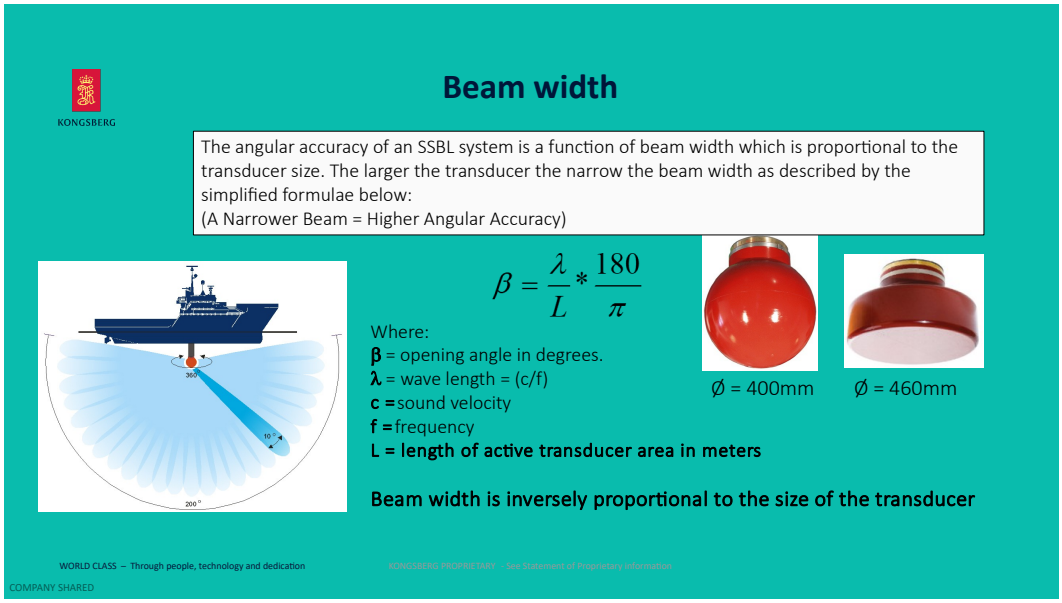

Fig 3. Beamwidth Calculation

Section 3: HiPAP 602 Transducer

To take advantage of DI and increase the HIPAP system range to 7000m, within the MF band, it would prove necessary to develop a new transducer with an increased diameter. Ideally the transducer should be as large as possible to maximise the directivity gain and performance.

Consideration was given to an almost 1000mm diameter transducer which would provide for incredibly narrow listening beams. However, since most vessels in operation are fitted with a DN500mm or 20'' gate valves, a 1000mm transducer size would not practical, nor acceptable for most installations. Instead, the design criteria adopted was to develop the largest possible transducer whilst still fit through existing installed gate valves.

The HiPAP 602 Transducer was therefore designed with a 460mm diameter, that is still significantly wider than the 400mm diameter HiPAP 502 transducer array.

Increasing the transducer diameter to 460mm reduced the narrow listening beams from 10 degrees to approximately 6 degrees versus the HiPAP 502. Significant directivity gains achieved with the narrow beams has increased the range capability of the HiPAP system to 7000m and resulted in an approximately 50% improvement in the acoustic angular measurement accuracy, versus the HiPAP 502.

The HiPAP 602 transducer was developed in a planar form factor to be able to utilize the full diameter of the gate valve, thus maximising number of active transducer elements and to keep total weight to an acceptable number. The planar design does create some operational compromises or limitations. Planar transducers are only useful in a cone of operation under the vessel, i.e. they do not perform with the same range and angular accuracy specifications in all directions.

In the case of the HiPAP 602 transducer the planar array presents a large diameter for the seabed transponder reply signals, that arrive from a direction within a +/- 30° cone below the vessel. Outside

the 30° cone, at higher elevation angles, less transducer face is visible, which reduces system angular measurement accuracy and range (Figure 4).

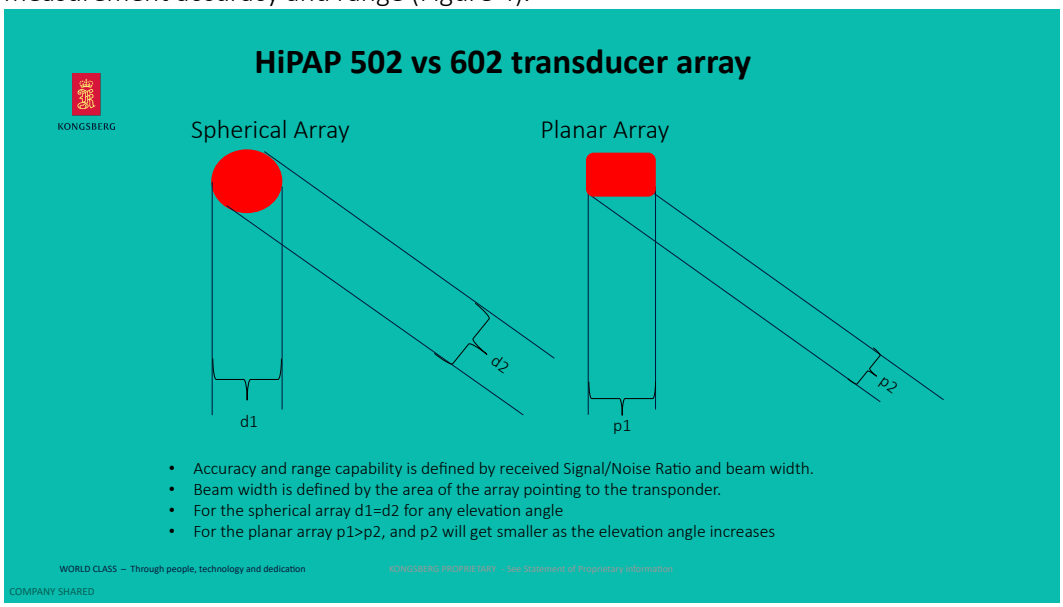

Fig 4. Spherical vs Planar Array

The HiPAP 602 range and angular accuracy are specified as 7000m and 0.04° within the main operational cone of +/-30 degrees below the vessel. Thereafter from 30° to 60°, the angle accuracy is reduced to 0.06° and range reduces to 5000m. At higher elevations the system is not recommended for use as too little of the transducer face will be visible for reliable operation.

The HiPAP 602 is therefore not a replacement for the HiPAP 502 but rather a transducer to optimise positioning repeatability and accuracy in a cone of operation +/-30° below the vessel. This makes the transducer particularly suited for deeper water operations.

A major operational advantage of enhancing the range capability through changing the transducer only and retaining the existing transceiver electronics is that the existing installed base can be quickly and efficiently refitted with minimally changes on board the vessel (Figure 5).

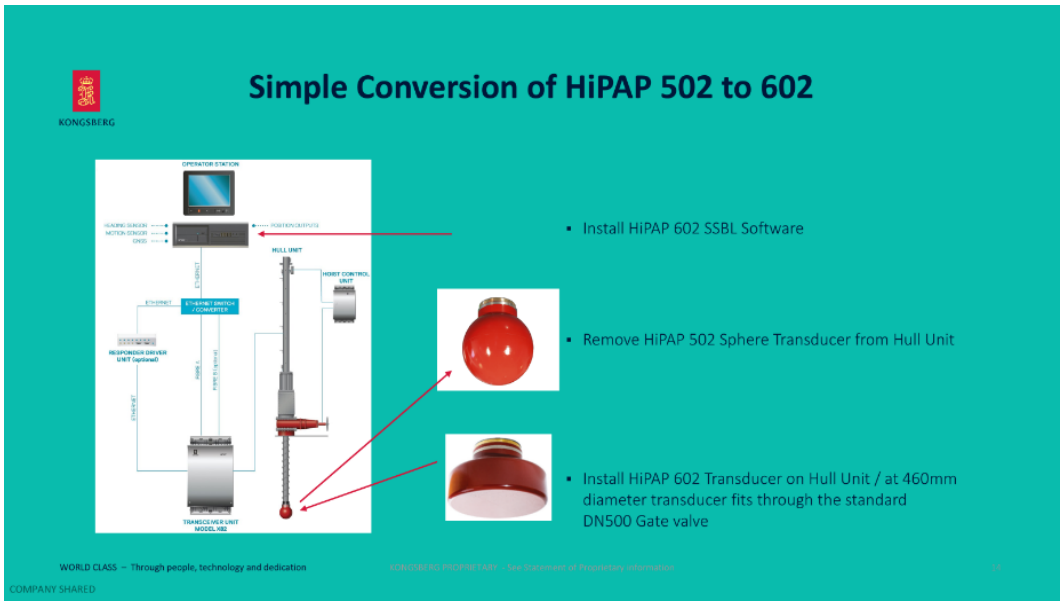

Fig 5. Transducer Refit

The HiPAP 602 transducer is calibrated for alignment of pitch, roll and heading after installation in the same way as the HiPAP 502, by using the cardinal point method. This requires the vessel to sit at four points typically North, South, East and West of a seabed transponder, logging, acoustic transponder positions, GNSS vessel position and attitude sensor data. A least squares adjustment then calculates new alignment and positions for the transponder.

The calibration results for the HiPAP 602 in 750m of water show that the position standard deviation post calibration including all errors in GNSS, IMU, sound velocity and acoustics is less than 0.05° (Figure 6). Therefore, the results met the design expectation that the acoustic angular error alone is within 0.04° prior to those additional errors above. The resulting position standard deviation off a single SSBL transponder in 750m water in easting and northing was +/- 0.65m

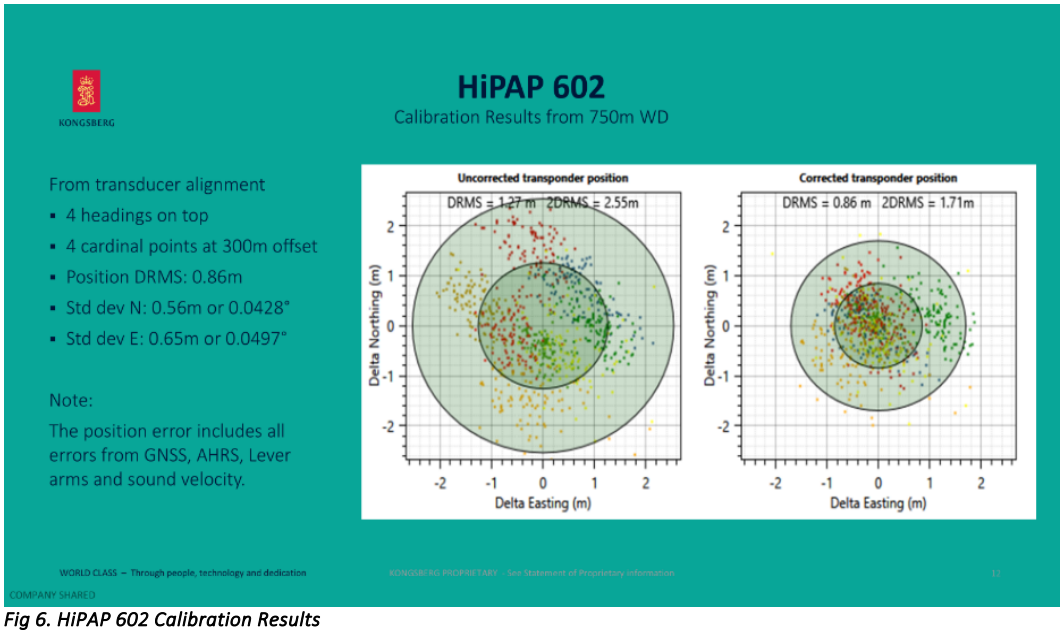

Fig 6. HiPAP 602 Calibration Results

Section 4: Multi-SSBL aided Inertial Navigation

Given that acoustic transmission time in water is nominally 1500 m/s, the positioning updates in 4500m of water take at least 6 seconds considering two-way transmission time and a bit of processing.

In order, for the acoustic positioning system output to have the equivalent weighting to GNSS in the Dynamic Positioning System it is required to have a standard deviation of less than 1m and update rate of at 1 Hz. Therefore, the HiPAP position is used as an aid to the Hydroacoustic Acoustic Inertial Navigation Systems (HAIN)

The hydro acoustic aided inertial navigation system further improves the extreme position repeatability of HiPAP 602 and increases the output position update rate to the dynamic position system from approximately 0.12 Hz to 1 Hz.

For deeper waters, arrays of at least four to five seabed transponders are used to provide a long baseline position to the DP system and as an input to HAIN. A minimum of three LBL ranges are required to calculate a position and at least four to calculate with position quality. The LBL positions are typically repeatable to approximately +/-0.5m irrespective of water depth. However, if not enough transponders are available, due to loss of some transponder replies, then LBL position aid to the HAIN would be lost, resulting in the HAIN going into free inertial drift mode. An output of a calculated LBL position from HiPAP to the HAIN system would be considered a ***loosely coupled*** solution.

To enhance robustness the later HAIN reference systems, utilise a ***tightly integrated*** solution (Figure 7). By HAIN receiving multiple raw SSBL observations as a pose to LBL positions from HIPAP, a solution called Multi-SSBL, the availability of the position solution is maintained even in the event some acoustic transponder ranges are dropped.

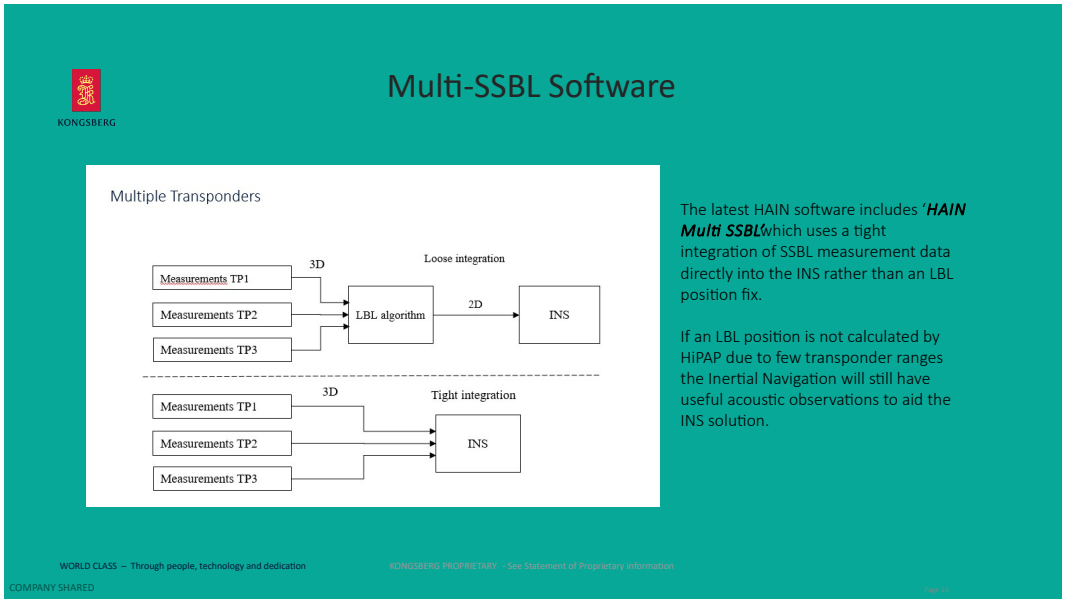

Fig 7. Multi-SSBL Positioning Aiding to HAIN

With the Multi-SSBL solution the HAIN system continues to compute a position by using all available raw acoustic SSBL observations and measurement quality from HiPAP. Even with only two seabed transponder replies in a navigation cycle the position accuracy can be almost as good as a four transponder LBL array, provided the transponder geometry allows for a 90° range angle of cut. Effectively there is a graceful degradation of output position standard deviation from the INS solution

if the number of acoustic SSBL ranges is reduced (Figure 8). This solution is therefor more robust than a complete loss of an LBL aided position, in the loosely integrated method.

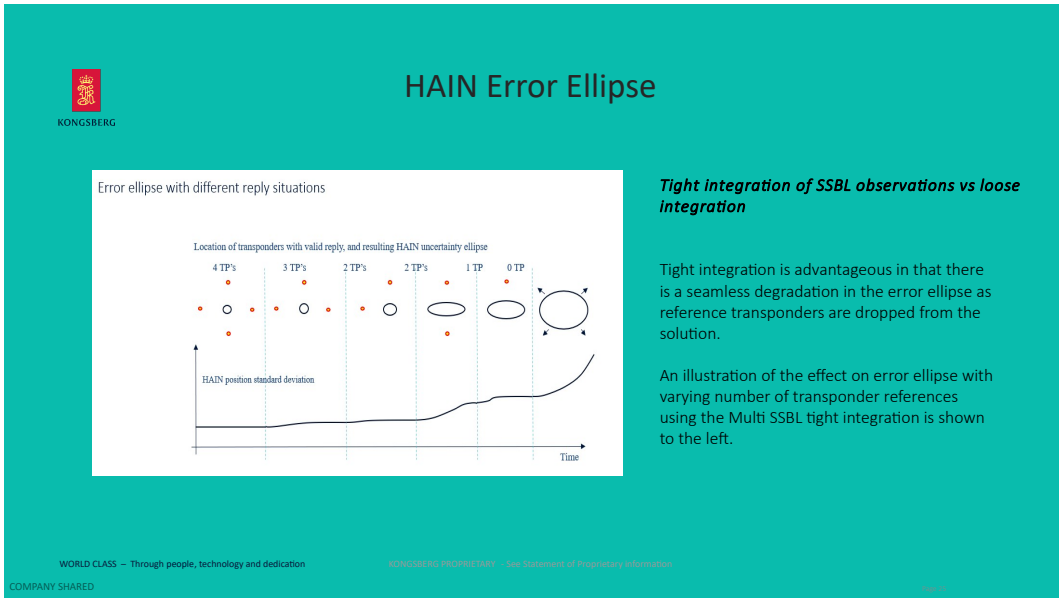

Fig 8. HAIN Error Ellipse with Multi-SSBL Transponder Aids

Given the HiPAP 602 has a 50% improvement in angular accuracy over the HIPAP 502 the positioning standard deviation with HAIN is also enhanced providing improved resilience and robustness. Combining the increased angular accuracy and position repeatability of HiPAP 602 and tightly coupled multi-SSBL HAIN is also a benefit for operational cost savings. In some operations fewer transponders could be deployed, water depth dependent.

The HAIN position output is also dependent upon the quality of the inertial measurement unit. As shown in figure 9 below, in 700m of water it is possible to position off a single SSBL transponder to a 1m standard deviation with HiPAP 502, but operational depth can be increased to 1000m with HiPAP 602 with the same 1m standard deviation.

With the SSBL aiding HAIN MGC R3 the operational window for position reference off a single transponder can be increased to approximately 2500m and 2900m respectively, vessel noise dependent. Of course, this does not provide redundancy but serves to demonstrate that in the event multiple transponder replies are lost, that in increasing water depths, with a single SSBL transponder aid, HAIN can still provide a useful position, with weight in the DP system.

That operational window can further be extended with HiPAP 602 up to 3500m with the higher grade IMU MGC R4. This therefore presents an increase in robustness for DP operations in these water depths where an LBL array is deployed and, in the event some SSBL ranges replies are lost.

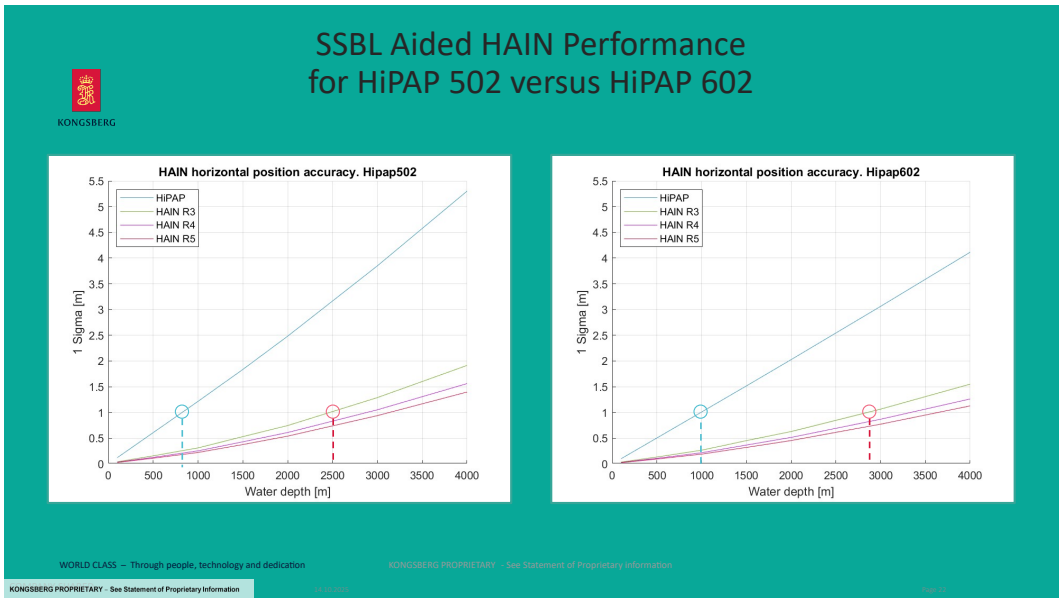

Fig 9. Improvement in HiPAP SSBL position with different grade IMUs

Should acoustic aiding be lost to the HAIN system, it will start fee inertial mode. Due to double integration of raw accelerations into velocities and position, the free inertial position, will drift over time. The growth in inertial error depends upon the quality of the acoustic aid prior to loss and the quality of the IMU sensors. The MGC R4 and MGC R5 use higher grade accelerometers and gyros compared to MGC R3.

In the example below (Figure 10) should an SSBL aided INS position solution have an error of +/-2m in 4000m of water, prior to an acoustic dropout, the INS errors will grow to an estimated 8m in 2 minutes with an MGC R3 IMU versus approximately 4.2m with an MGC R4. After 4 minutes the error with an MGC R3 IMU is estimated at 20m versus 10m for an MGC R4. A higher grade IMU for HAIN therefore results in an increase in time before the DP system rejects the position.

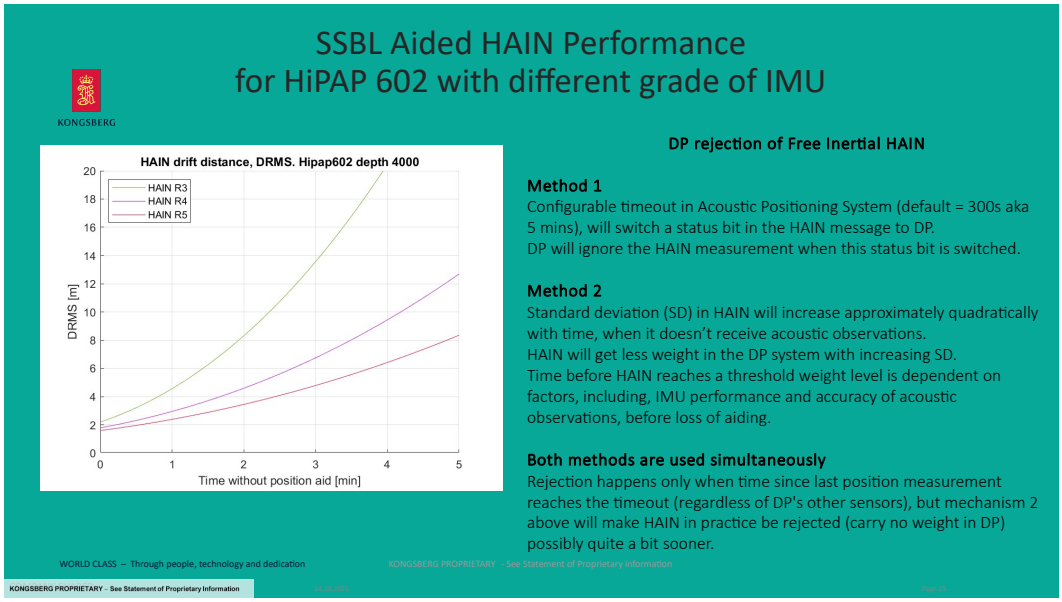

Fig 10. Estimated Error of HAIN Free Inertial Drift after loss of single SSBL aid in 4000m

The DP will reject the HAIN position either by timeout, where the HAIN output message from the acoustic system will flag a status bit as no longer valid, typically after 300 seconds or much sooner through DP rejection or no allocation of weight to the HAIN sensor, due to the large, estimated error.

Conclusion

The HiPAP 602 with a 50% improvement in SSBL angular accuracy versus HiPAP 502 and range capability to 7000m, provides extreme acoustic positioning accuracy for an SSBL system.

The HiPAP 602 transducer starts to provide notable performance advantages for all deepwater vessels in operations from 750m depth and beyond when compared to HiPAP 502. However, the wide planar transducer is recommended only for those operations where the seabed transponders are deployed within a +/-30° cone under the vessel.

The extremely accurate SSBL observations fed to Multi-SSBL HAIN, as a tightly coupled solution, provides for a more robust and repeatable DP reference. Both the SSBL aided HAIN position repeatability and free inertial drift performance can be significantly improved by using higher grade IMU like MGC R4 versus the MGC R3.