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10 Years of Experience From Acoustic Aided Inertial

By Are B. Willumsen & Torbjørn Hals

Kongsberg Maritime AS

Abstract

This paper focuses on the experiences gained from Kongsberg Maritime's 10 years of using acoustic aided inertial navigation (INS) for DP reference on different types of vessels. Acoustic and inertial systems are in general a perfect match, in that we manage to get the best of both worlds; the no drift of the acoustics and the low noise of the inertial.
Issues regarding the integration into DP will be discussed: the importance of acoustic/INS being independent of GNSS, the different failure modes of the INS compared to the acoustic positioning, and how to avoid common failure modes between INS and its aiding source in the DP interface.
The paper will cover the advantages and problems discovered over the years. INS has provided higher DP weighting, more robust positioning, a stable reference at greater depths, and requirement for fewer transponders. The paper will also discuss how to operate the INS. The last ten years have also given a few problems in for instance export regulations and acoustic issues. The INS has on some installations revealed problems in the acoustic positioning normally hidden by acoustic measurement noise.

Introduction

DP reference systems based on underwater acoustics have been around for many years. They rely on receiving acoustic signals from one or more transponders on the seabed and measuring the distance and/or direction to them. By measuring this, one calculates the vessels position with reference to the seabed transponder(s), which again is used as a position reference for DP.
An Inertial navigation system (INS) is based upon measuring the rotation rates and accelerations of the vehicle by means of gyroscopes and accelerometers respectively. These are in turn integrated to yield position, velocity and orientation of the vehicle. The rotation rates and accelerations will normally measure at 50-500 Hz, and practically without delay. So since the INS integrations are done on every measurement, the INS will output positions without delay and up to the rates of the measurements.
The INS will diverge from the truth, due to natural errors in the gyroscopes and accelerometers (see Figure 2). It must therefore be aided by externally referenced positions. That being said, INS can operate without any external reference for some time, making it suitable for many special applications such as underwater, space and military. This also means that from an operational standpoint, the inertial position is always a combination of the aiding position and the inertial sensors.
A bare INS does not use any model information or similar of the vessel it is on. The same INS will therefore work about equally as well on a drilling rig as on a missile.

HAIN

Kongsberg Maritime offers an inertial navigation system that use hydroacoustic position measurements as the external reference aid – namely the HAIN Reference (Hydroacoustic Aided Inertial Navigation). The first sea-trials of the system were in 2003, and the product has since then developed into an established system for DP position reference, used on various vessels.
The HAIN system is also applicable for underwater acoustically positioned vehicles such as AUVs and ROVs (HAIN Subsea). In fact HAIN use is based on the navigation system originally developed for the HUGIN AUV. Since the inertial navigation is basically the same for all vehicles (see Introduction) the navigation SW is the same for all applications.
The setup of HAIN is shown in Figure 1. The acoustic positioning operator stations – APOS – sends the acoustic positions to HAIN and in return receives the inertial positions. APOS is responsible for sending both the bare acoustic and inertial positions to DP. All positions are transmitted with their corresponding accuracy figures (standard deviations) and status information (this is omitted in Figure 1)

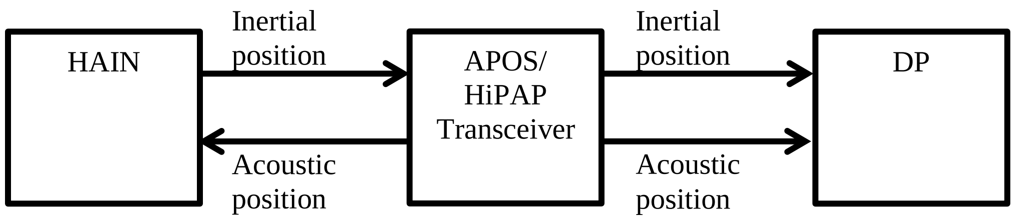

Figure 1: HAIN system setup

Data integrity

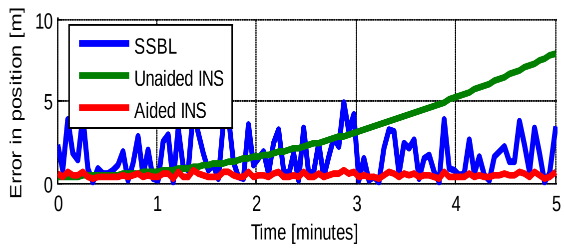

Figure 2: Typical position errors with time

One of the main focuses when the initial system was developed was the data and system integrity.
The behaviour of an INS is radically different from that of an acoustic. If you compare INS position to an SSBL (Super Short Base Line) position they are quite opposite in behaviour. The SSBL has a high degree of white noise, and will almost always change quite a bit from one measurement to the next. On the upside it will almost never move slowly away from truth, which is hard to detect. The INS on the other hand, will normally change little from measurement to measurement, but may on the other hand drift slowly off. This is shown in Figure 2.
Validating INS is a bit different from SSBL. INS is stable by nature; making it difficult to set the limits for variation in the measurement itself. LBL (Long Base Line) and GNSS measurements resemble more the behaviour of the INS; hence the methods used for these types of measurements should also be applied for INS. The slowly drifting off errors can normally only be detected by comparing the INS with the other reference systems (GNSS, DP's own vehicle model etc.).
An INS will also calculate both the orientation and velocity of the vehicle. An integrity test for the INS could therefore be to compare these values with the estimates in the DP. However it is our subjective experience that these tests will not fail before the position measurements are too far off.
The INS will normally try to estimate errors in the sensors (acoustic and inertial). If those errors are too high, it's an indication of problems with one or more sensors. This will normally prompt a restart of the INS to try to resolve the problem. Repeated restarts must be dealt with by the operator.

System integrity

Initially a lot of work was done in maintaining system integrity of the DP using acoustic aided INS. This process took considerable time and work and included all class authorities, users, academia and Kongsberg Maritime. These key points where identified:

- The INS position is never independent of its aiding position. Hence the two should never be used as references simultaneously.
- If INS is unaided for longer periods of time, it will become less and less accurate. This will also show in the corresponding standard deviation. Anyhow a valid safety measure is to exclude the inertial position if it has been unaided for a certain period of time, typically 3-5 minutes.
- DP should still receive acoustic positions if the INS fails.
- INS must be independent of GNSS, hence no information from there should enter INS.

The setup shown in Figure 1 was deemed sufficient of handling both of these, but some extra measures were taken:

- The inertial position sent to DP will be flagged as invalid if INS is running unaided for more than a user specified amount of time.
- Both acoustic and inertial positions are transmitted with information on which transponder and which transceiver is used, so that DP can avoid using both inertial and aiding positions as references simultaneously. This feature is an absolute requirement for DNV class approval.

The reader should note that APOS consist of several redundant computers. Should one fail, another will automatically take over and operate both acoustic and inertial positioning. The acoustic transducer and the INS also offer redundancy, albeit not leaving the system fully operational. Should the acoustic transducer fail, the inertial position will be valid for only a certain amount time. Should the INS fail, you will have to survive on acoustic positioning only. Full redundancy here is therefore resolved by having two or more transducers and INSs on-board. In general our customers have set one separate INS for each transducer. One could argue that it is better to let the acoustic system decide which measurements to send and only send one type of measurement. Letting the choice between INS and acoustics be transparent to DP. However it is our experience that we benefit more from the setup of Figure 1, since:

- The DP operator will be able to see both inertial and aiding positions on the screen, and can select between them if necessary.
- If the INS should fail, the DP operator can change to acoustic reference.
- The transducer might have a dual use in tracking an ROV or transponders used for the Riser Management System

Data rate

The data rate is actually a quite important feature for a DP position reference system. This is because DP weighting is a function of reference system update rate. This is a linear relation, with 5 seconds update giving only 1/5 weight. Increasing the update rate above 1 Hz will however not increase the weight. The decreased weighting has become an increasingly problematic issue for acoustics over the years as more and more operations are being done in deeper waters. The speed of sound in water is approximately

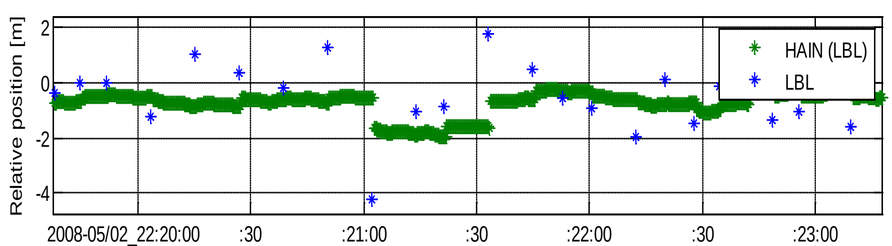

Figure 3: HAIN working with slow rate LBL

1500 m/s, meaning that maximum depth allowing 1 Hz updates is 750 meters, as the signal has to travel back and forth. One can counter this in several ways:

- Have several pings in the water at once, and by time or signal solve the ambiguity that arises.
- Use synchronized clocks, and/or some automatic triggering to get only one way path. (There are commercial systems available utilizing such features).

It is our experience that the most practical way to improve date rate of acoustic positioning is to add an inertial system that will provide 1 Hz updates regardless of water depth or other acoustic issues. See example in Figure 3, where the LBL update rate is on average 0.1 Hz, whereas INS provides a stable position with update rate of 1 Hz. The water depth was 1150 meters. The standard deviations of the inertial positions are shown in Figure 4.

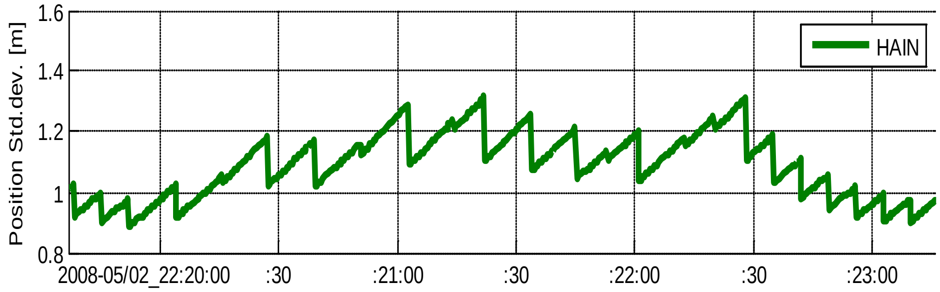

Figure 4: Position standard deviation at slow rate LBL

With the INS making sure the acoustic based position reference system is providing 1 Hz, the user can play around with the interrogation intervals a lot more. This can potentially result in large savings of battery life and subsequent operations to change or recharge the batteries. An example of using a ping per 30 seconds is shown in Figure 5. The water depth in the area is about 1000 meters.

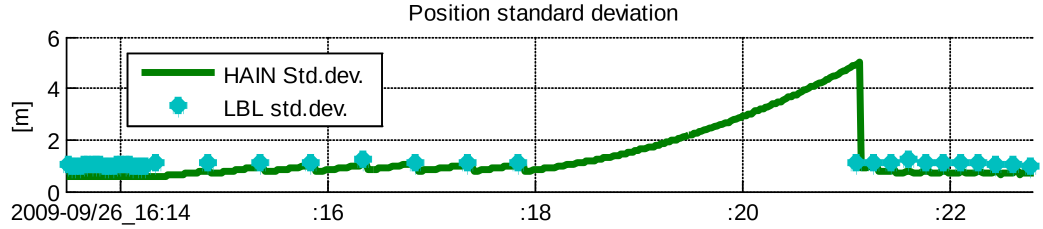

Figure 5: Standard deviations of slow rate and drop out

Accuracy

INS will not only improve the update rate, but also the accuracy of the measurement. In Figure 6 the standard deviations of the LBL measurements of Figure 3 and Figure 4 are shown. The INS accuracy is at worst about half of the standard deviation, often considerably better.

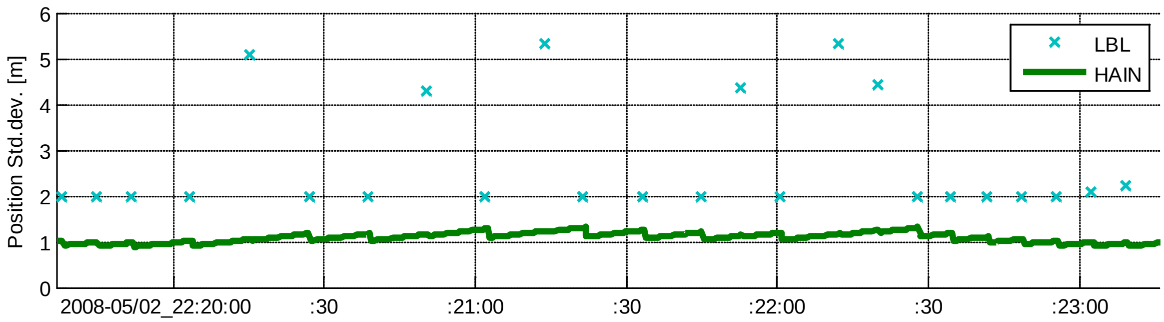

Figure 6: LBL standard deviation with slow rate

The standard deviations of the position measurements are also important in the weighting in the DP. References having a standard deviation better than 1 m will be given maximum weight (provided the data rate is at least 1 Hz). There is a quadratic relation between the weight in the DP and the reference's standard deviation. A standard deviation of two will thus give a weighting of only ¼ of the maximum obtainable weight.

Acoustic aids

HAIN is normally used with HiPAP SSBL or HiPAP LBL, so most experiences are from those. The most asked questions in that respect is: "How deep can SSBL with inertial go?" We have tested with SSBL successfully at water depths of about 3000 meter. However our experience is that HAIN aided with HiPAP SSBL will not continuously provide maximum DP weight at depths beyond 2000 meters. This is because you have less margins for errors such as thruster noise, speed of sound issues, transponder failures and similar.

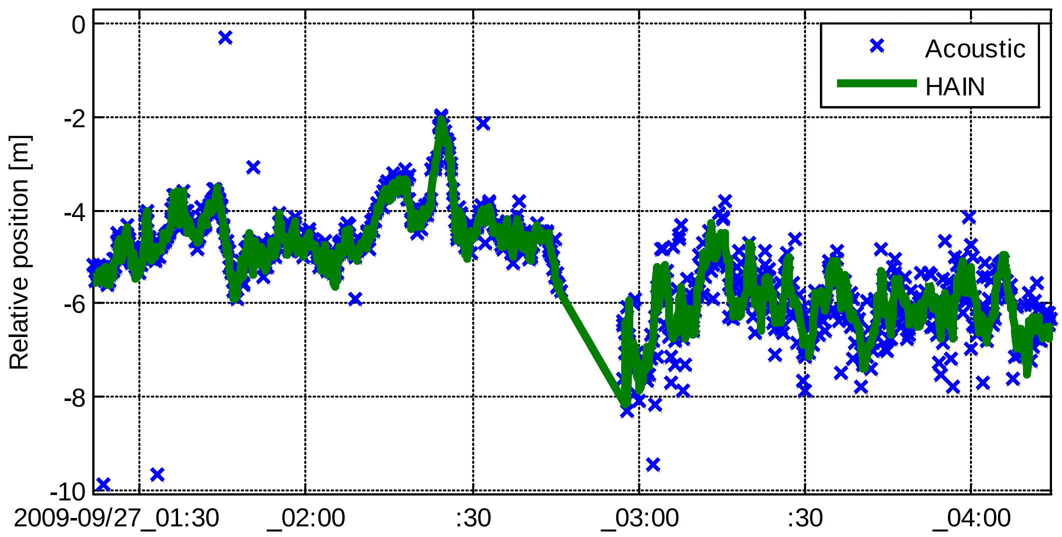

Figure 7: Positioning of LBL (before 02:45) and SSBL (after 02:55) aiding

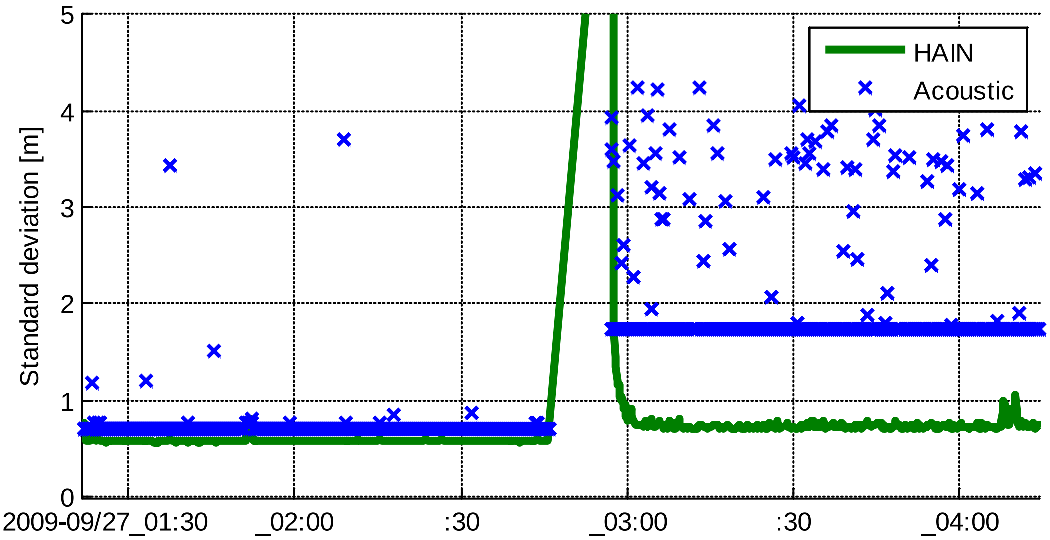

Figure 8: Standard deviations of LBL (before 02:45) and SSBL (after 02:55) aiding

SSBL and LBL exhibit quite different behavior, with the SSBL being noisier and often at maximum update rate compared to the more stable and often slower update rate LBL. However the main experience is that the outputted inertial position exhibits pretty much the same behavior with both LBL and SSBL.

This is seen in Figure 7 and Figure 8 where aiding position is switched from LBL to SSBL and restarted at about 02:55 o'clock. The water depth is approximately 1000 meters. As the accuracy is often less in SSBL than LBL, the accuracy gained is often larger in SSBL, but then again the benefit from increased update rate is often more important with the LBL.
HAIN has also been used successfully with aid from the obsolete HPR-400 system. The system is not as accurate and lack many features of today's generation of acoustic systems. HAIN was able to mitigate the lack of accuracy in many ways. Data from usage with HPR-400 is shown in Figure 9, and the water depth at the location is just exceeding 300 meters.

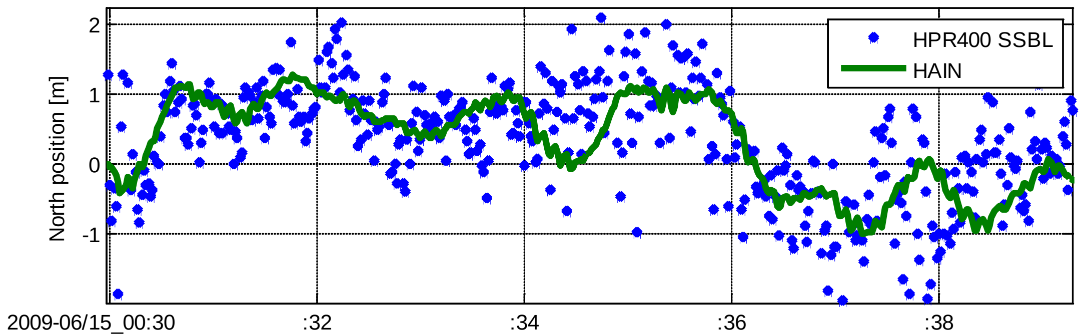

Figure 9: Performance of HPR 400 and INS

In general INS is well suited for any type of vessel. We have experience from running acoustic aided INS on drill rig, drill ship, tankers, ferry, AUV, ROV, and more. Although they exhibit quite different dynamics, this has little effect on performance of the INS. In fact we can take and actually have taken an INS used on an ROV (with quite erratic behavior) and placed it on a drill rig in calm water without re-configuring other things than the aiding source.

Hardware

In terms of the inertial measuring equipment, it is the gyroscope that attracts most attention. They are generally more expensive and harder to manufacture than the accelerometers. For use in acoustic aided INS, they are normally ring laser gyros (RLG), fiber optic gyros (FOG) or micro mechanical engineering systems (MEMS). Kongsberg Maritime have delivered successful acoustic aided navigation based on all three principles. It is not yet possible to purchase MEMS-sensors to the high levels performance that we can with RLGs and FOGs. Of the latter two there really isn't much separating them normally. FOGs have a slightly better MTBF, at least on paper, but RLGs are better in varying temperature. RLGs are not to be put in manned spaces as it makes an annoying high pitch noise.

Installation

You can arrange the INS and the acoustics in two ways. Either the INS can be factory mounted directly on the frame of your transducer, or it can be delivered freely to be mounted elsewhere on the vessel. Transducer mounted means that lever arm and alignment can be determined at factory, and that the lever arm from transducer head (measuring point) to INS center is (almost always) smaller. The free mounting means you can place the INS in a serviceable and friendly environment. Inertial measurements are normally sensitive to especially changes in temperature; that can give a loss of performance. The free mounting means that it is easy to supply the INS as an add-on to existing system, and even older types of such (see also Figure 9). Having the INS not attached to a particular transducer also means it is straight forward to change the transducer providing positions for a particular INS. This yields added redundancy, even on vessels where you have redundant INS and acoustics.

Our experience is that the distance between the transducer and the INS normally does not affect performance. We have successfully had systems with both short and long lever arms, with the largest being almost 150 meters long on tankers. One would often survey in the position of the IMU with reference to the vehicle's common reference point (CRP). Our experience is though that this is most times not necessary. Often the person installing can look around for position of a known object in the vicinity and measure the offset from there. Due to the often slow heading changes, and small roll and pitch values of DP vessels, you can have large errors in lever arms without actually seeing any resulting errors in INS output. Often the easiest way to determine location of the INS is from the vessel drawings, which provide adequate accuracy.

Although actually not necessary, we find it a good idea to align the axes of the INS with that of the ship. This makes both supervising and troubleshooting easier. This will also in some cases help on accuracy. The alignment is done on two levels. First level is mounting: We make sure that the INS is mounted such that its axes correspond fairly well to the axes of the ship (forward, starboard and down). It is not necessary to make a big effort here, as a manual visual observation that the unit is facing forward and level with the ship is quite enough. It is though important the unit has a rigid connection to the ship, otherwise navigation will fail. Second level is doing an alignment process. This takes a few hours while navigating off two or more seabed transponders. It is normally not necessary to do any tuning of the system. After the system is completely set up, a few validations tests are normally run. One test is to turn the position aid off, to observe the correct response both in the DP and in the acoustic SW. This also tests the INS on how quickly it diverges from the truth without aid. FMEA tests are also performed if appropriate.

In essence our experience suggests that both transducer and free mounting work fine, and this is sort of confirmed by the quite equivalent GPS-INS solution. Most of these deliver the GP antenna and INS to be mounted separately.

Time to market

The first sea-trials of HAIN Reference were held on-board the Seaway Osprey in 2003. Although the tests were successful it turned out to be a long way from that to any market success. Since the acoustic and inertial was a new combination as a DP reference, a lot of ground work was needed to make sure this new reference system was safe according to class requirements. The end result is summarized in chapter System integrity. This process took quite some time as a result it took a more than a year to get the product ready for sale. Even though the product was ready, it took another couple of years before it made impact in the market. It was quite opposite when we released INS into the market of subsea vehicles. No ground work was necessary, and the first sales came soon after the release. The same effect is also evident in the requirements put forward by the respective clients. INS has been required by survey clients for years, whereas drilling clients have started to require acoustic aided INS in theirs specifications over the last few years.

Technical problems

Initially there were some problems with the performance of the inertial measurement units (IMU) we used. An IMU is an assembly of accelerometers and gyroscopes, providing inertial measurements (angular rates accelerations in all three dimensions) for the INS to rely on. These problems resulted in not so good results in terms of both drift and lack of integrity. However with the set of IMUs used in the last 7 years, these problems have diminished. With these IMUs it's we never see poor performance, they either work well or don't work at all (indicated by bad status or no output). When they no longer work, they have to be repaired or replaced. So whenever there is a performance problem this is almost always related to the acoustic system not producing positions of the expected standard as shown in the examples in this chapter

One of the challenges for the INS is validating the incoming acoustic position measurements. Accepting an erroneous measurement leads to wrongful positions, are sent to DP. On the other hand not accepting valid position will lead to poor performance and can in turn lead to accepting wrongful positions. The validation is not a problem when the acoustic system itself detects a problem due to signal to noise ratio, signal level, or other acoustic phenomena.

Figure 10 shows the problem of not detecting outliers. The red outliers are marked in hindsight. The positions have a reported standard deviation of about 4 meters, and thus they are within the acceptance area. The INS is clearly seen drifting wrongfully off as a result of accepting the outliers.

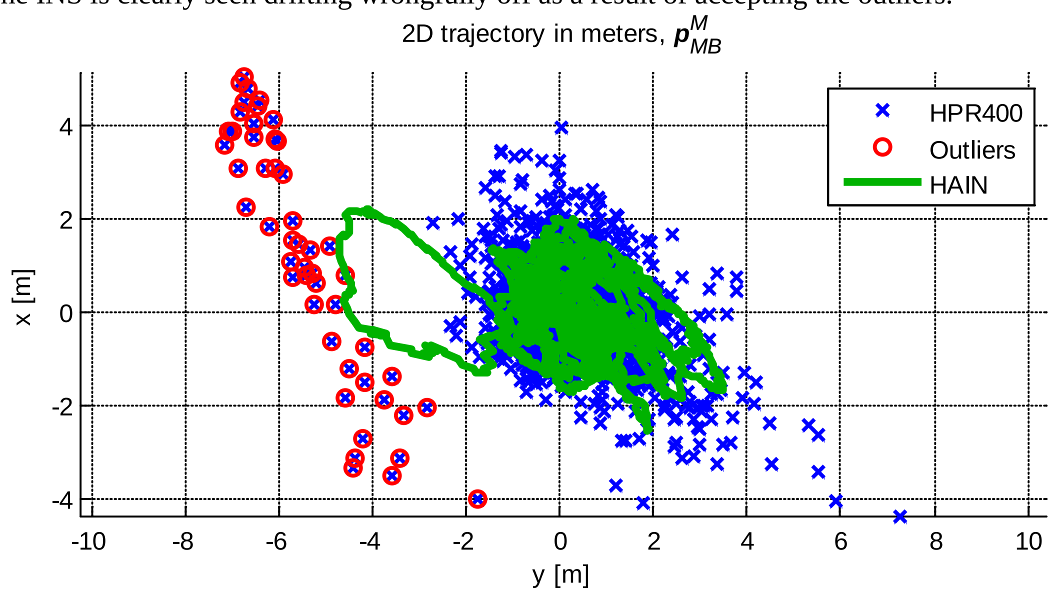

Figure 10: Effect of not detecting outliers

Figure 11 shows another example of hard to detect errors in the positioning. For the INS it is not so hard to detect if the position measurements suddenly change location, but detecting that the positions slowly moves away from the correct position is much harder. The measurements in Figure 11 will therefore be accepted one by one as they are within the acceptance area of the INS. The end result is though that they will drag the INS off. The reason for this event turned out to be a faulty transponder. Examinations revealed that such an error can be detected by the acoustic system, and will in the future be marked as bad status and not used by the INS.

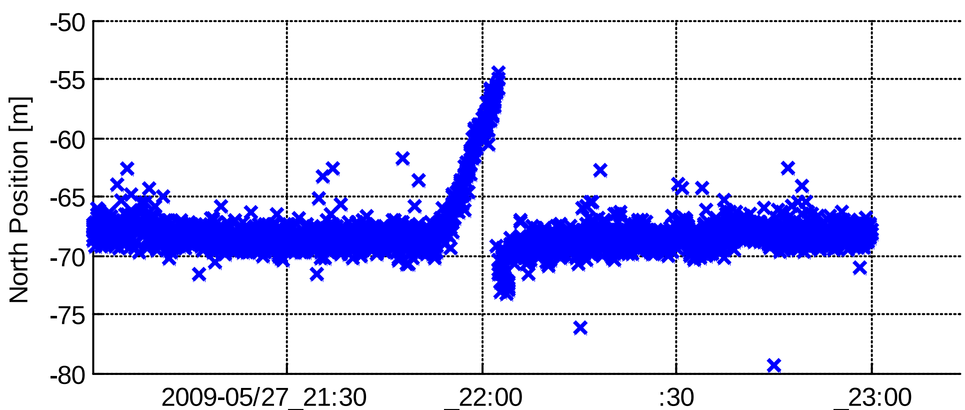

Figure 11: Drifting position

We have also had a situation where there were no outright error in the acoustic system; it was just performing badly. This is shown in Figure 12. The acoustic has a time varying bias (Slowly varying part), with magnitude and time scale that is problematic. The slowly varying part can be thought of as a moving average. Had the time scale been short, the error would have averaged out, like white noise errors. We normally estimate the slowly varying part to be smaller than half a meter, but in this case it was many times that value. The INS can be setup to mitigate for such poor input, if you cannot resolve the problem with the acoustics. It is just a matter of configuration. However performance of the INS with such an input will not be able to reach the 1 meter standard deviation mark that gives full weighting in DP.

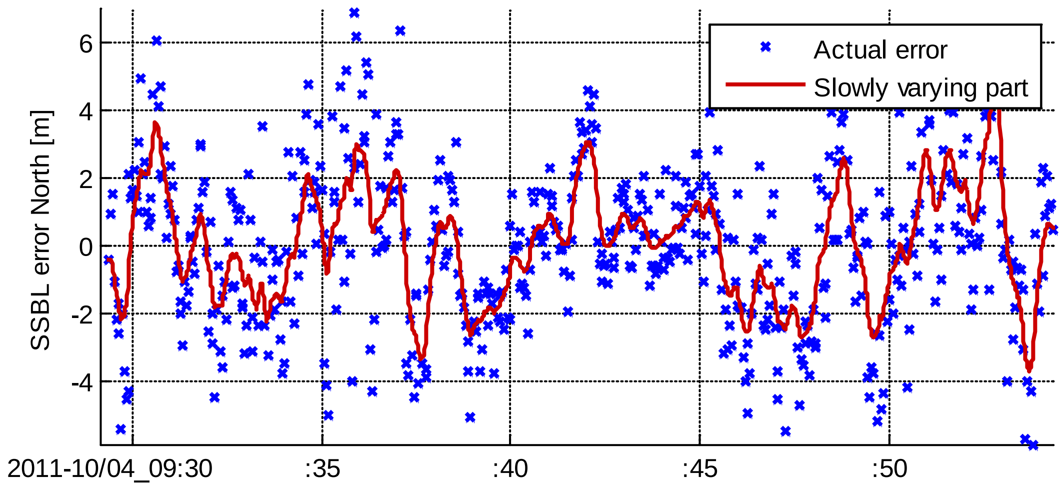

Figure 12: Uncharacteristic error in acoustics

Every so often it is the INS's low noise and high DP weighting; that make the operator able to see the error. Although the same error is also present in the pure acoustics, it wouldn't have been recognized if that and not the INS was input to DP. Normally these acoustic problems can be physically explained as errors in speed of sound, malfunctioning transponders, thruster induced noise, air at the transducer or other. Since these problems are not detectable by the acoustic system, it is important that INS can both detect that the aiding position has a problem and mitigate it.

We have found it invaluable to always store all the measurement for the INS on disk. This means that we can examine quite well what actually happened and also that we can test improvements or solutions to problems on the actual data. Replaying the actual data works fine because there is no feedback for the INS; its outputs does not affect its inputs. If it had been, we would require an extensive simulator such as is necessary when testing the DP controller. Obtaining the logged measurements is not always easy, though, as the normal amount of data produced by the INS is on the scale of 2-3 GB/day. If you have larger time spans for investigations, the most sensible thing is to hand carry the data on disk and send it by regular mail.

In general the HAIN creates considerably less service requests per operational unit than for instance in HiPAP. This goes for both routine assistance and system problems. The INS for use on subsea vehicles on the other hand creates more requests per operational unit. As a DP reference the INS benefit from both few problems on board and the fact that it requires little user interaction. For instance the vessels often change location across the world without requiring other changes than the transponder(s) to use as aiding position. Most installations will go years between each time they see a problems with the INS, such as the ones discussed here, and with the further development of both INS and acoustics it is likely that many installations will never see them.

Export restrictions

Inertial measuring equipment of the quality levels used in INS for DP applications is almost always export restricted. This is though rarely a problem as acoustic systems are covered by the same rules. High accuracy inertial sensors from American suppliers have an additional control measure in ITAR (International Traffic in Arms Regulations). This gives more paperwork, such as in advance getting approval of where to use the unit. Some American suppliers also offer the same products, but of lesser quality, that are not ITAR controlled. It is our experience that the best commercially available IMUs are under ITAR control, but that INSs based on non-ITAR components also work well. However in many cases the increased performance is worth the ITAR hassle.

Life of field

By coordinating the use and placement of transponders for the entire life of a field there are savings to be made. This boils down to using the same transponders for construction, drilling, survey, maintenance and the other tasks, instead of setting down new transponders for every task. In such a scenario, the INS will often play a vital role, both as DP reference and for subsea positioning. This will normally allow reducing the number of transponders, and/or the ping rate of them, and still have more accuracy and redundancy than without the INS.

Conclusion

INS aided by acoustic positioning efficiently improves the performance of acoustic based DP reference systems. In deep waters it is currently the only way to get acoustic based positioning, with accuracy and update rate comparable to GNSS systems, and thus giving true balanced redundancy in DP positioning. The accuracy of the INS is always better than the acoustics, and often this difference is substantial. INS can be used on pretty much all types of acoustic reference systems, and it requires little or no attention from the on-board crew. It works both installed together with the acoustic system and after mounted on existing installations.

Acknowledgements

We would like to thank the HAIN customers for making available and allowing the use of navigation data taken from their vessels.