DYNAMIC POSITIONING CONFERENCE
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Sensors

HAIN

An Integrated acoustic positioning and inertial navigation system

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1 INTRODUCTION

Exploration on deeper water puts high requirements on underwater positioning for both DP operations and survey applications. Acoustic positioning systems are continuously improved to meet new requirements. Development carried out during the last years for the HUGIN AUV has brought new technology available for combining acoustic positioning with inertial navigation. Based on this the HAIN system is developed as an extension to the HiPAP and HPR systems.

HAIN Position Reference

The HAIN system for vessel positioning is an aided inertial navigations system. The position drift that is inherent in Inertial Navigation Systems is limited by the acoustic position measurements relative to transponder(s) on the seabed. The system can be used both with SSBL or LBL position input. The HAIN provides an improved position of the vessel which both has increased accuracy and higher update rate than the original position from the acoustic measurements. This extends operational water depth and reduced battery consumption. Position output during acoustic dropout will be maintained.

HAIN Subsea

The system is also available in a version for ROV positioning for survey applications. In this version the system also is interfaced to a Doppler velocity log and a pressure sensor.

The complementary solution

Acoustic and Inertial positioning principles in combination is ideal, since they have complementary qualities. Acoustic positioning is characterised by relatively high and evenly distributed noise and no drift in the position, whilst Inertial positioning has very low short-term noise and relatively large drift in the position over time.

2 INERTIAL NAVIGATION

2.1 Principles of Inertial Navigation

An Inertial Navigation System (INS) integrates the output of three accelerometers and three gyros to compute the position, the velocity and the attitude.

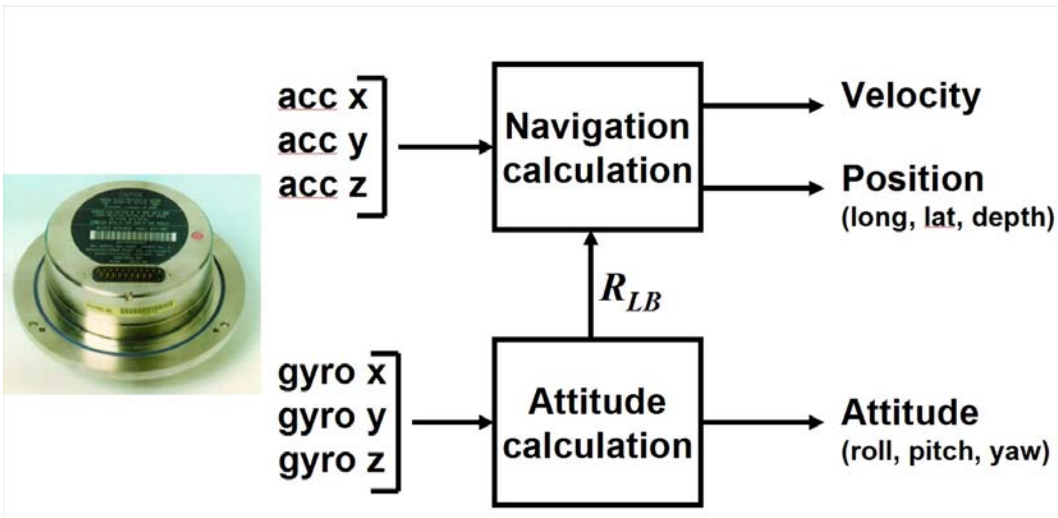

Figure 1. The sensors in the Inertial Measurement Unit

The three accelerometers are mounted perpendicular to each other. Each accelerometer measures the acceleration relative to the inertial space. Integration of acceleration gives velocity, and integration of velocity gives position.

The three gyros are also mounted perpendicular to each other. Each gyro measures the angular rate relative to the inertial space. Integration of angular rate gives attitude, i.e. roll, pitch and heading.

The accelerometers and the gyros are contained in an Inertial Measurement Unit (IMU). The figure above shows a picture of a Honeywell HG-1700 IMU.

Most Inertial Navigation Systems to-day are strap-down systems, with the IMU rigorously connected to the body that is positioned. For HAIN, the body is either a surface vessel or an ROV. The integration of the accelerometers gives the velocity in the body co-ordinate frame. The integration of the gyros gives the attitude, which is used to convert the acceleration/velocity from the body co-ordinate frame to an earth-fixed co-ordinate frame.

The basics described so far is simple. Complexities arise because the navigation is done on the Earth and not in the inertial space. Different co-ordinate frames, Earth gravity and Earth rotation must be handled. This is done in well established strap-down navigation equations.

Complexities also arise because all measurements have noise added to them. The noise consists of a white part and a colored part. The white part is random Gaussian noise. The colored noise is often referred to as a bias on the measurement. The bias changes slowly, with a time-constant of many minutes.

2.1.1 Initial values for the integration

An integration gives a change from an initial value. Integration of acceleration gives change in velocity. Integration of angular rate gives change in attitude.

2.1.1.1 Attitude

It is possible to calculate the initial attitude based on the IMU sensors, by using the knowledge about the Earth gravity, the Earth rotation and an approximate value for the latitude. The IMU sensors must be of good quality to manage this task, because the Earth rotation is slow compared to the movements of the body.

2.1.1.2 Position

It is not possible to calculate the initial position based on the readings from the IMU sensors. An Inertial Navigation System must therefore get a position aid from outside.

2.1.2 External measurements

In addition to the gyro and accelerometer readings from the IMU, an Inertial Navigation System gets external measurements.

The external measurements to the HAIN are

- The aiding position in latitude longitude and depth.
  It is used both to get an initial value for the position and to limit the drift that is inherent in Inertial Navigation Systems.
- The heading.
- The velocity.

The external measurements are used by a Kalman filter to compute corrections of the filter's estimates. It is expained in more detail in the next chapter. The corrections are weighted according to the expected accuracies of the measurements and to the filter's estimate of its own accuracies.

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2.2 HAIN processing

The figure below shows how the readings from the IMU and the external sensors are used.

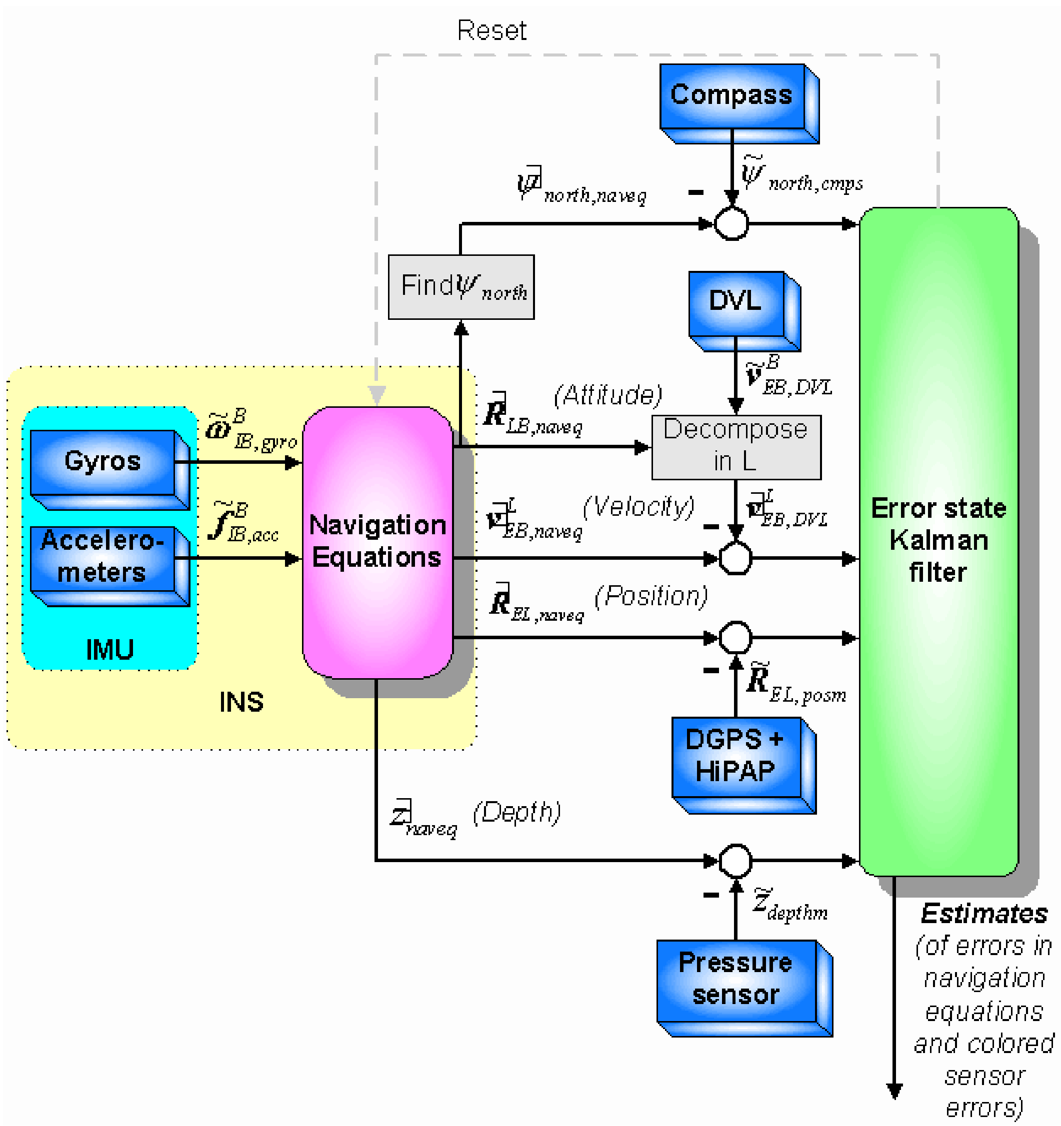

Figure 2. HAIN processing block diagram

To the left we see the IMU with its gyros and accelerometers. The navigation equations read the three gyros and the three accelerometers with 100 Hz. Based on these readings, the navigation equations calculate the change in position, velocity and attitude. Due to noise and errors in the readings, errors in the calculation increase with time if not corrected for.

The to right we see the Kalman filter. It estimates both the attitude, velocity and position and the sensor biases. It also calculates the accuracy of each estimate.

The input to the Kalman filter is the difference between the values calculated by the navigation equations and the external measurements. We can look at the depth measurement as an example. The pressure sensor on the ROV measures the depth. The measured value is subtracted from the depth calculated by the navigation equations. The difference is read by the Kalman filter. The filter knows the expected accuracy of the depth sensor, and it knows the accuracy of its own estimates. The depth correction is weighted based on this knowledge, and the estimates of the filter is updated. New values for the position, velocity and attitude are sent to the navigation equations.

The position aid in the figure is named “dGPS + HiPAP”. The other alternatives for HAIN position aid is “HiPAP” and “LBL”, as explained later. In all cases, the latitude longitude of the aiding position is subtracted from the latitude longitude calculated by the navigation equations. The difference is processed by the kalman filter, as just explained for the depth.

The filter executes each time an external measurement is read. It updates its estimates based on the external measurement, and transfers the new position, velocity and attitude to the navigation equations. This transfer is often referred to as a “reset”. Therefore the values calculated by the navigation equations and those estimated by the Kalman filter are very close to each other.

The graphs shown later in the paper use the same colours as the figure above. Blue is used for measurements, magenta for the navigation equations and green for the Kalman filter.

The Kalman filter shown in the figure is often referred to as the forward filter. It is executed in real time, and does not have any knowledge of the measurements ahead in time. When the measurements are post-processed with the NavLab, the forward filter is first executed. Then a backward filter is executed. It uses the measurements both back and forward in time. This gives a significant improvement in accuracy and stability. The result from the backward filter is displayed in red on the graphs.

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2.3 Acoustics used as Position Aid

2.3.1 The complementary solution

The noise on acoustic positions is dominated by the white noise. There is almost no correlation between the noise on one measurement and the noise on the next measurement.

The noise on Inertial Navigation systems without position aid is dominated by coloured noise, i.e. a position drift.

This is illustrated on the next figure.

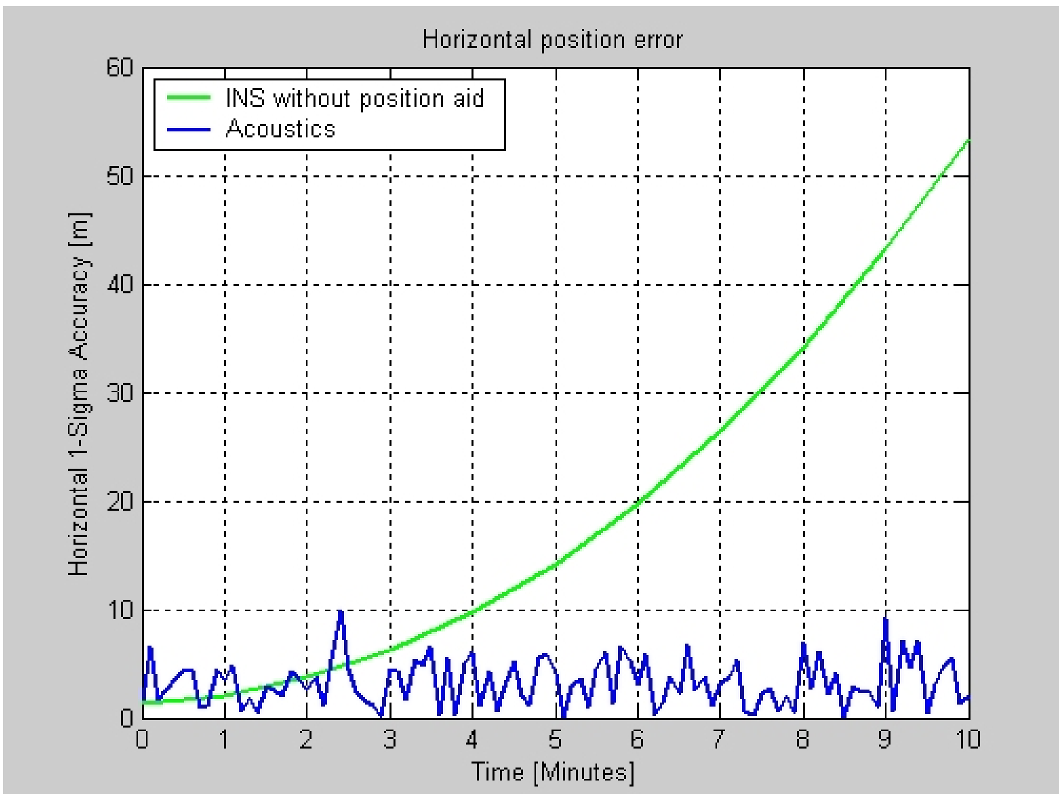

Figure 3. INS position drift and noise on acoustic positions

The noise on inertial navigation without position aid and the noise on acoustic positions are complementary. Acoustic positions are therefore ideal as position aid for inertial navigation. The white noise of the acoustic positions is reduced because the inertial navigation has a small white noise. The coloured noise, i.e. the position drift, of the inertial navigation is strongly reduced by the acoustics, which has almost no coloured noise

2.3.2 The position aid for HAIN Vessel and HAIN Subsea

For HAIN subsea pos, the depth is measured by a pressure sensor on the ROV. For HAIN vessel pos, the depth is the depth of the reference point of the vessel. The depth is in both cases processed as an external measurement.

For HAIN vessel pos, the aiding position is the position of the vessel in latitude longitude. It is generated either by a SSBL measurement or by an LBL measurement. In both cases the position of the seabed transponder(s) must be known in latitude longitude. The SSBL transponder must have been boxed-in, and the LBL array must have been calibrated geographically. This must be done before the HAIN vessel positioning is started. After this, the HAIN vessel pos is independent of the dGPS.

For HAIN subsea pos, the aiding position is the position of the ROV in latitude longitude. When the ROV is positioned with SSBL from the vessel, the latitude longitude position is a combination of the acoustic position relative to the vessel and the dGPS position of the vessel. When the ROV is positioned with LBL, the LBL array must have been calibrated geographically in beforehand.

3 HAIN POSITION REFERENCE

The HAIN position reference system provides:

- improved acoustic position accuracy

The HAIN system will typically improve the accuracy some 2-3 times. Example: If the “ping to ping” deviation is 6 meters, the HAIN will reduce this to approximately 2 meters.

- higher position update rate

The HAIN calculates a new position every 1 second regardless of water depth.

- extends operational depth capabilities

Since both the accuracy and the position update rate are improved, the HAIN allows operation in deeper waters.

- longer transponder-battery lifetime

The HAIN position update rate allows slowing down the acoustic update frequency. This will result in less “ping” per hour, and thereby longer battery duration.

- position update during acoustic drop-out

The HAIN gives continuity in position output even though the acoustic position should fail to operate in periods of limited time.

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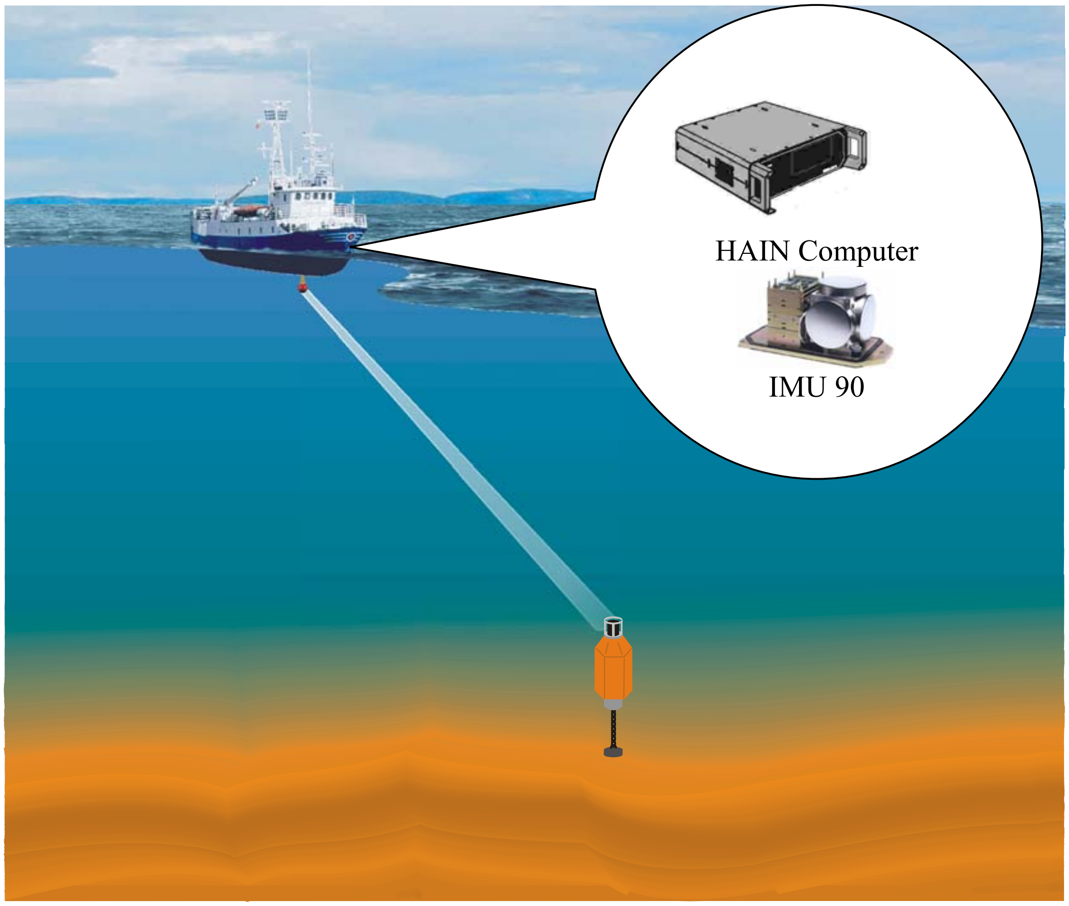

3.1 System description

The figure below shows the HAIN used with a HiPAP system.

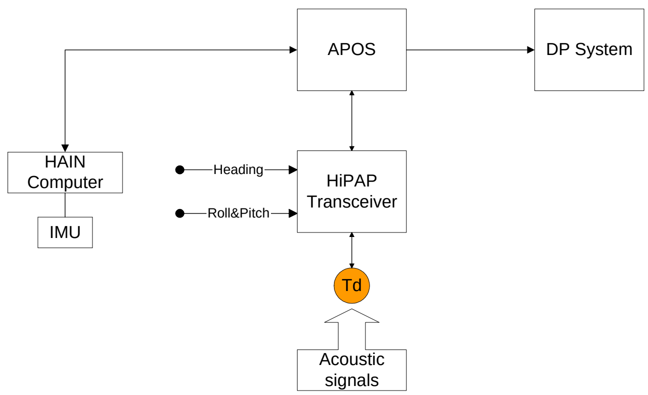

Figure 4 HAIN Position Reference System Diagram

The HAIN positioning system can be used on any vessel equipped with acoustic positioning system.

3.1.1 Inertial Measurement Unit - IMU

The IMU consists of three accelerometers and three Fibre Optic Gyros measuring the vessel’s accelerations and rotation in three axis very accurately.

3.1.2 HAIN Computer

The HAIN Computer executes the navigation algorithm, which consists of Strap-down navigation equations and a Kalman Filter. The unit is interfaced to an Inertial Motion Unit (IMU) and to the APOS (Acoustic Positioning Operator Station).

The HAIN Computer receives the aiding positions (latitude and longitude) from the APOS and will limit the position drift that is inherent in inertial navigation systems. Vessel position, attitude, speed and expected accuracy of the data are sent back to the APOS at 1 Hz update.

3.1.3 Operator Station - APOS

The HAIN system is operated from the Acoustic Positioning Operator Station.

The information received from the HAIN Computer is displayed and sent to external computer(s). APOS can request status information in the HAIN Computer to be displayed, which helps the operator to check the system in real-time.

3.1.4 Accuracy

HAIN combines the acoustic measurements and the readings from the IMU sensor installed onboard in an optimum way. The navigation equations update the vessel position, velocity, heading and attitude almost continuously based on the readings from the IMU. The Kalman filter corrects these values when new acoustic positions are available. This result in improved position accuracy compared to the acoustic measurements, as illustrated in the figure below.

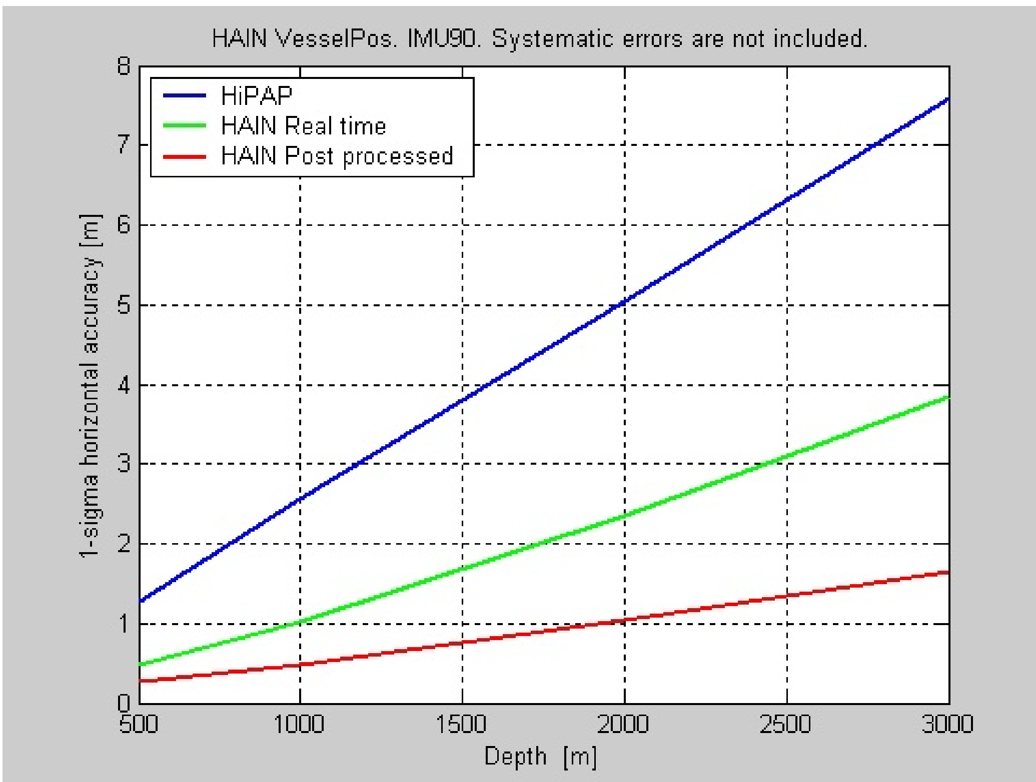

Figure 5 HAIN Position Reference Accuracy figures

The simulations for the expected accuracy are based on the following accuracy figures:

- HiPAP angle accuracy 0.1° in x and y
- dGPS position white noise 0.15m in North and East
- dGPS position colored noise 0.10m
- Motion Sensor white noise 0.02° in roll and pitch
- Motion Sensor colored noise 0.1° in roll and pitch
- Accelerometers random walk 15µg/√(Hz)

- Accelerometers colored noise 0.5mg
- Gyro random walk 0.0025°/√(h)
- Accelerometers colored noise 0.05°/h
- Compass 0.01°

3.1.5 Data Logging

Data logging can be done on two levels:

The HAIN Computer is logging all measurements on its hard disc. These data can be post-processed.

The APOS can log measured and calculated vessel positions, attitude and velocity on its hard disc.

All measurements and positions in the log files are time-stamped. The APOS clock and the HAIN Computer clock are both synchronised with the GPS clock (1pps).

The Technology

The HAIN product is based on technology from the advanced navigation developed in the HUGIN AUV programme.

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4 HAIN SUBSEA

The HAIN Subsea solution provides:

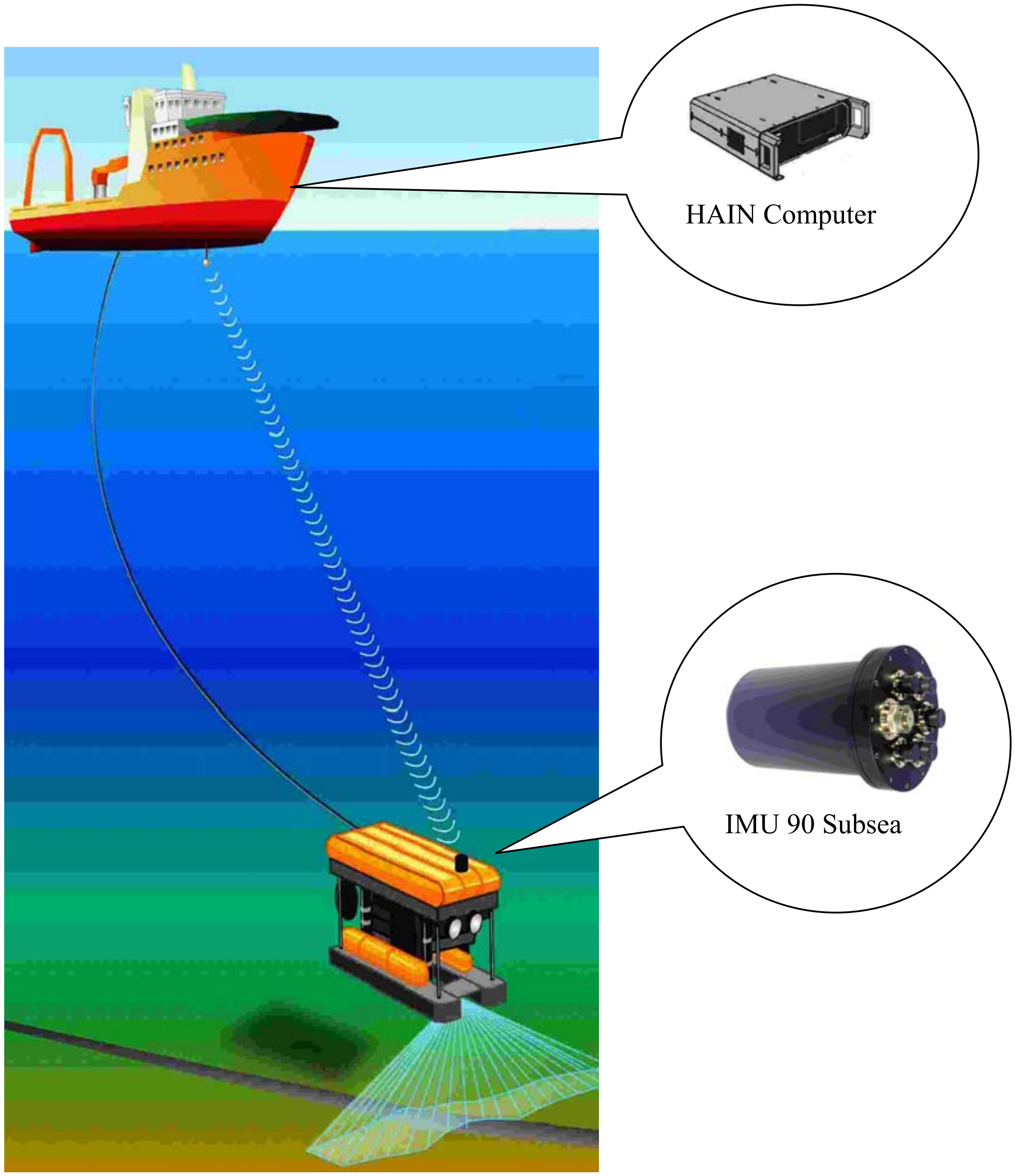
- improved acoustic position accuracy
- higher position update rate

The **HAIN system** onboard the vessel comprises;

- HAIN computer with interfaces to ROV sensors
- Operator Station
- HAIN software
- Vessel position input from dGPS
- ROV position input from an acoustic system.

Hydroacoustic Aided Inertial Navigation

The HAIN Subsea system can be used on ROVs and other underwater cable-connected units.


HAIN Computer
IMU 90 Subsea

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4.1 System description

The figure below shows the HAIN used with a HiPAP system and an optional LBL system.

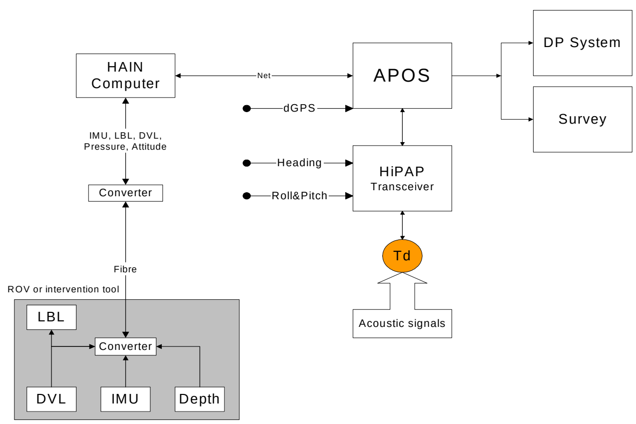


Figure 6 HAIN Subsea System Diagram

4.1.1 HAIN Computer

The HAIN Computer executes the navigation algorithms, which consists of Strap-down navigation equations and a Kalman Filter. The unit is interfaced to the sensor signals coming from the ROV-umbilical system. These signals come from; Inertial Motion Unit (IMU), Doppler Velocity Log (ROV Speed), pressure sensor and heading sensor (Compass). The HAIN computer may interface different types of sensors giving these aiding measurements.

The HAIN Computer receives the aiding positions (latitude and longitude) from the Acoustic Positioning Operator Station (APOS) over an Ethernet interconnection and will limit the position drift that is inherent in inertial navigation systems. ROV position, attitude, speed and expected accuracy of the data are sent to the APOS at 1 Hz update. The source of the aiding position can be SSBL or LBL.

4.1.2 Inertial Measurement Unit - IMU

The IMU comes in a pressure container and contains three accelerometers and three Fibre Optic Gyros measuring the vessel's accelerations and rotation in three axis very accurately.

4.1.3 Operator Station

The HAIN system is operated from the APOS and has three main functions:

- Controls the HAIN system
- Integrates dGPS and local acoustic ROV position
- Displays position and sends position and status data

The information received from the HAIN Computer is displayed and sent to external computer(s). APOS can request status information in the HAIN Computer to be displayed, which helps the operator to check the system in real-time.

4.1.4 Accuracy

HAIN combines the acoustic measurements and the readings from the sensors onboard the ROV in an optimum way. The navigation equations update the ROV position, velocity, heading and attitude almost continuously based on the readings from the IMU. The Kalman filter corrects these values when new acoustic positions and when readings from the other ROV sensors are available. This result in improved position accuracy compared to the acoustic measurements, as illustrated in the figure below.

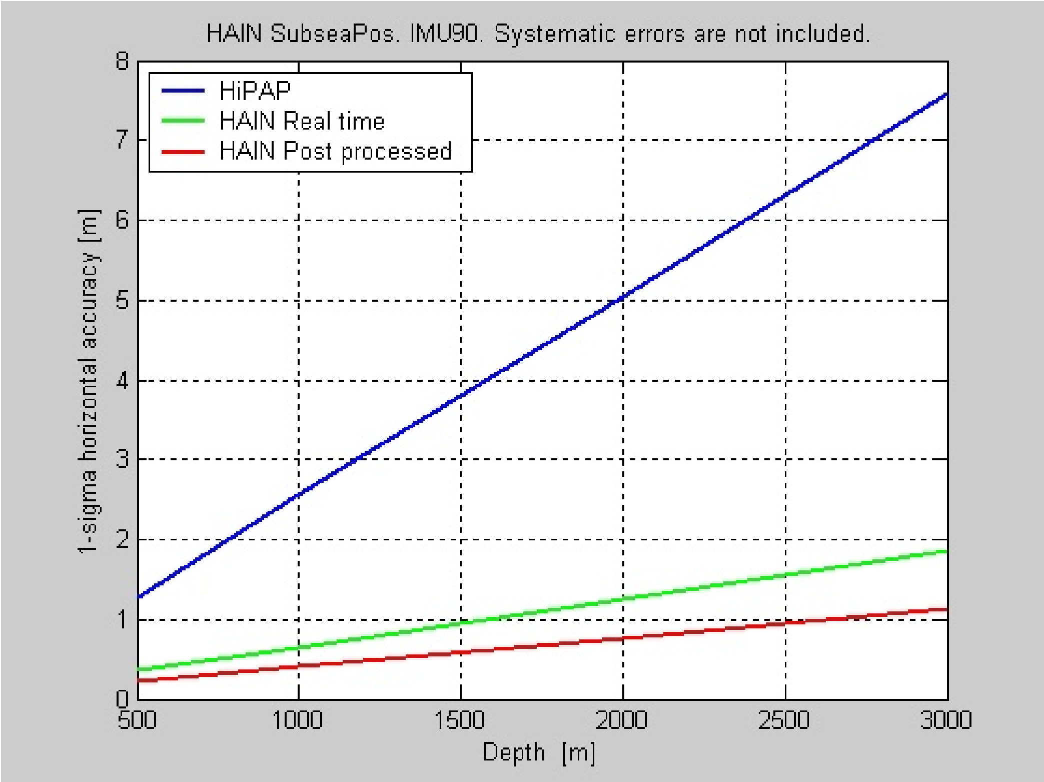


Figure 7 HAIN Subsea Accuracy figures

The simulations for the expected accuracy are based on the following accuracy figures:

- HiPAP angle accuracy 0.1° in x and y
- dGPS position white noise 0.15m in North and East
- dGPS position colored noise 0.10m
- Motion Sensor white 0.02° in roll and pitch
- Motion Sensor colored noise 0.1° ° in roll and pitch

• Accelerometers random walk	15µg/√(Hz)
• Accelerometers colored noise	0.5mg
• Gyro random walk	0.0025°/√(h)
• Accelerometers colored noise	0.05°/h
• Depth sensor	0.1m
• DVL white noise	0.02m/s
• DVL colored noise	0.015m/s
• Compass	0.01°

4.1.5 Data Logging

Data logging can be done on two levels:

The HAIN Computer is logging all measurements on its hard disc. A new file is generated each 15th minute with binary data. These data can be post-processed.

The APOS can log measured and calculated ROV positions, attitude and velocity on its hard disc.

All measurements and positions in the log files are time-stamped. The APOS clock and the HAIN Computer clock are both synchronised with the GPS clock.

4.1.6 Post Processing Software - NavLab

The NavLab post-processing tool reads the files logged by the HAIN Computer. When calculating the ROV position, it uses measurements both in the past and in the future, giving a better quality than can possibly be achieved in real time. In this process NavLab detects wild-points in the measurements, which can be excluded from the processing. NavLab exports the results to files for use by the survey SW. NavLab can post-process with other settings than you used during the mission. It can process with offsets in the sensor readings, and thereby compensate for constant errors in the sensors that were detected after the ROV mission.

The Technology

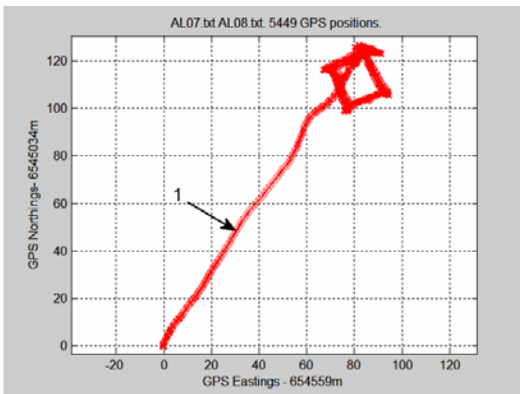
Both the HAIN and NavLab products are based on technology from the advanced navigation developed in the HUGIN AUV programme.

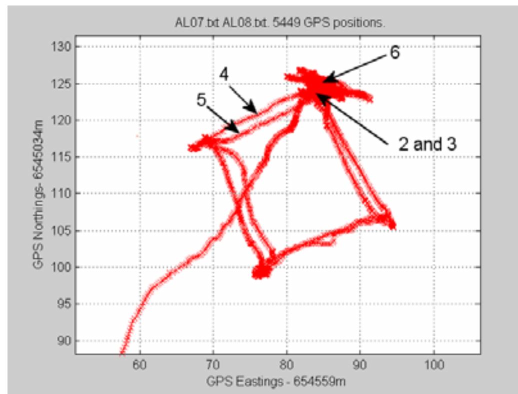
5 FIELD RESULTS POSITION REFERENCE

The HAIN position reference system has gone through several sea trials on our own vessel, "Simrad Echo". The trials are done for debugging purposes and accuracy analysis.

A short trial on an offshore DP vessel has also been carried out.

The plots below are from the offshore trial.





The scatter plot above show the vessel position during the test, as logged by the dGPS.

1. Sails backwards 150 m with HiPAP update rate 20s
2. Stationary with HiPAP update rate 10s and then 20s
3. Changes heading first CCW 40° and then CW 70°, with HiPAP update rate 20s.
4. Sails a square with HiPAP update rate 20s.
5. Sails a square with HiPAP update rate 5s.
6. Removes the HiPAP position aid from the HAIN for 10 ½ minute.

DP used HAIN as the reference during operations 1 to 5. DP used dGPS as reference during operation 6, and just logged the drift in HAIN.

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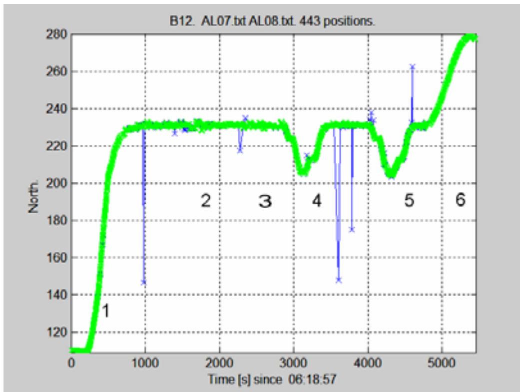

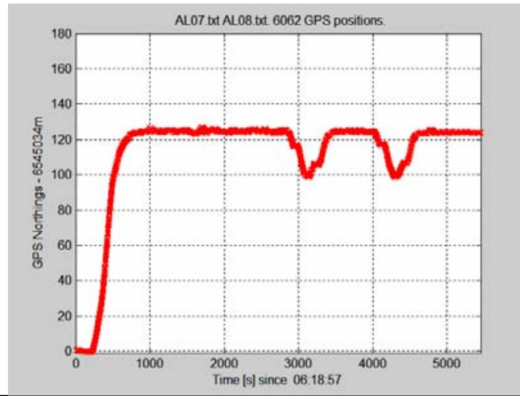

The time-plot to the right shows the dGPS North co-ordinate from the scatter plot on the previous slide.

The time-plot to the left shows the HAIN position in green and the HiPAP positions in blue. The update rate of the HiPAP positions varies between 20 s and 5 s. In the last 10 ½ minutes there is no HiPAP positions. The update rate of the HAIN positions is 1s.

The north axis in the HAIN plot has the transponder position as the origin. The north axis in the dGPS plot is in UTM. (If more questions about the axes, tell that UTM north is not the same as geographical north, and that an UTM meter is not exactly one meter.)

We see that there are some wild-points in the HiPAP measurements. The position QA test in the HAIN has rejected these positions in real-time.

We see that there is a good correlation between the plots, except during the 10 ½ minute interval (6) without position aid. In this interval the vessel is stationary, as shown on the dGPS plot. The HAIN position drifts 50 m in the North direction.

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6 FIELD RESULTS SUBSEA POSITIONING

6.1 Pipeline route survey

The HAIN Subsea system has been used for positioning an ROV on a pipeline route survey in the North-sea. The water depth was from 100 to 850 meters. The system was mobilized on Normand Mermaid for the survey company DeepOcean. In this project the HiPAP SSBL system was used as the acoustic aiding position.

The screen dump shown below represents a snapshot of the data that is post-processed and shown on next page. The ROV is finished with a line, it has stopped, moved to the next line and started the new line.

The blue line is the HAIN history track. The grey line is the HiPAP history track.

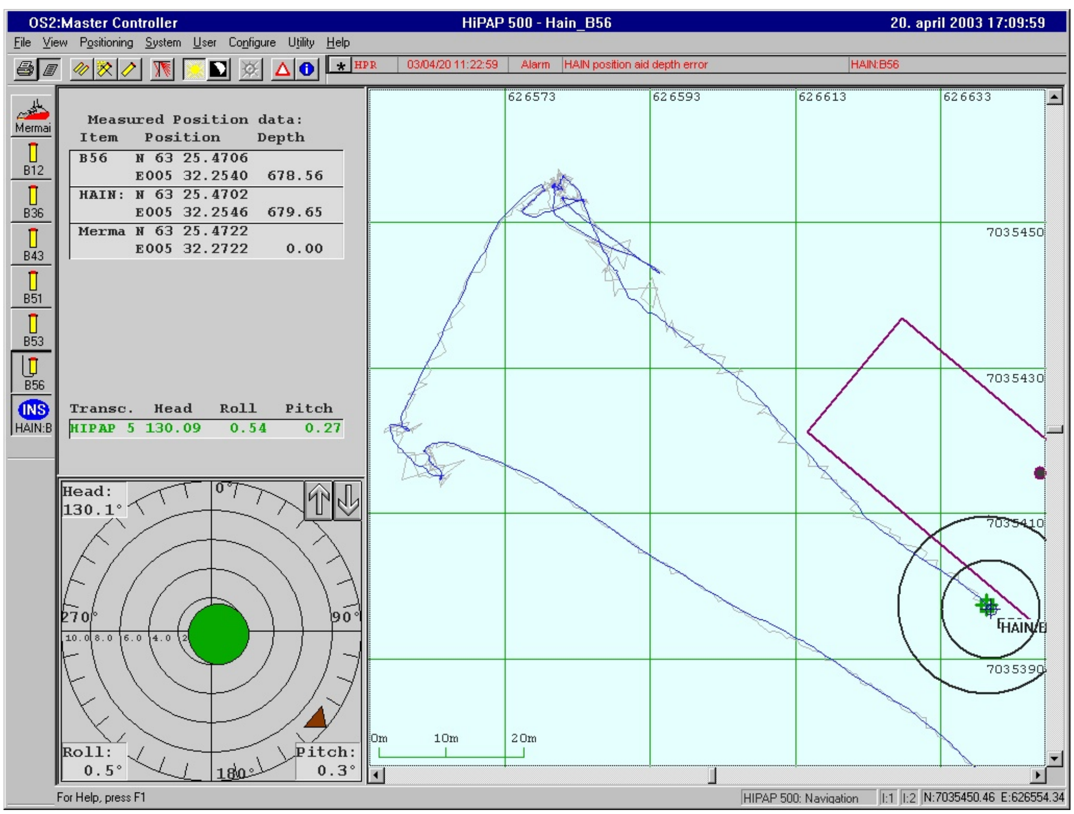

Figure 8 HiPAP/HAIN Screen Dump

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As we will see later, the HiPAP measurements were not as stable in the turn as when the ROV/Vessel sailed the lines. It is probably caused by more use of thrusters in the turn.

The scatter plot below is zoomed in the first corner of the turn, when there was some noise on the HiPAP measurements.

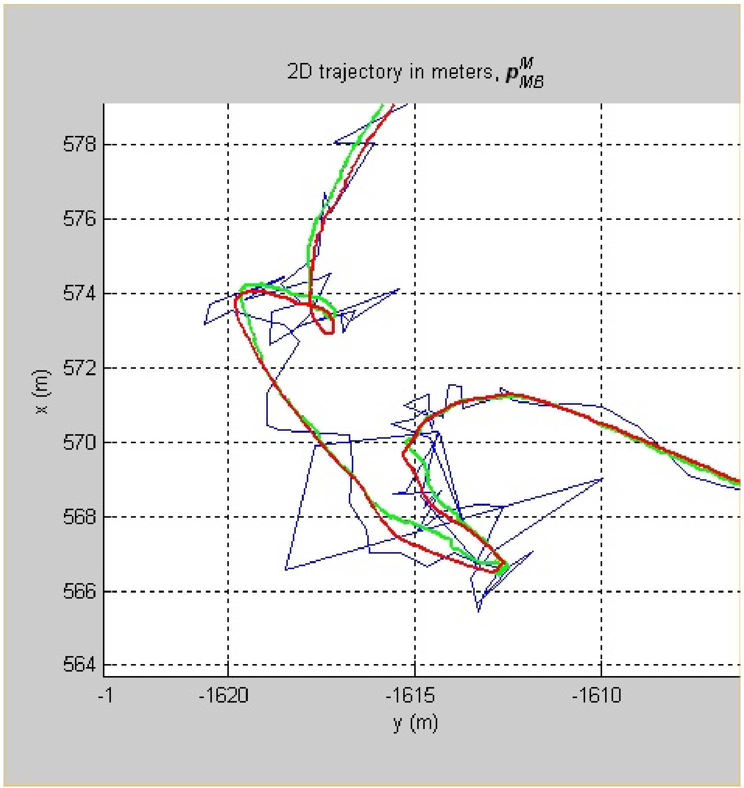

Figure 9 Zoomed scatter plot in turn

Line colours:

Blue – HiPAP real time, Green – HAIN Real Time, Red – post processed

We see the same history track of the measurements and the real time position as in the screen dump. In addition we see the red track from the post processing backward filter, which is the most stable and accurate estimate of the position

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6.2 Seabed mapping survey

The HAIN system has also been used on a 4000 metre deepwater project for Thales. In this project an HPR 400 LBL system was used as the acoustic aiding position.

The plot below shows the positions of the ROV as they where post-processed. The start of each line is marked with a circle.

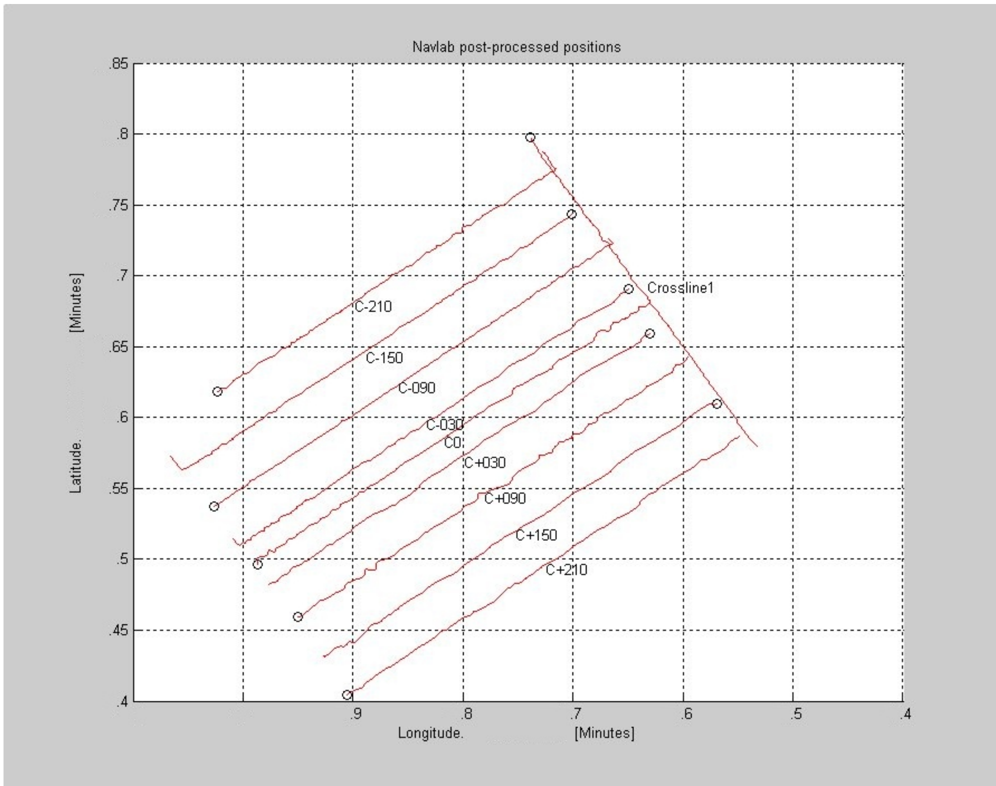

Figure 10 Survey lines Depth 4000m

In order to see the performance of the system we have investigated various sections of the survey. The figure below shows a section where there is some noise on the LBL measurements.

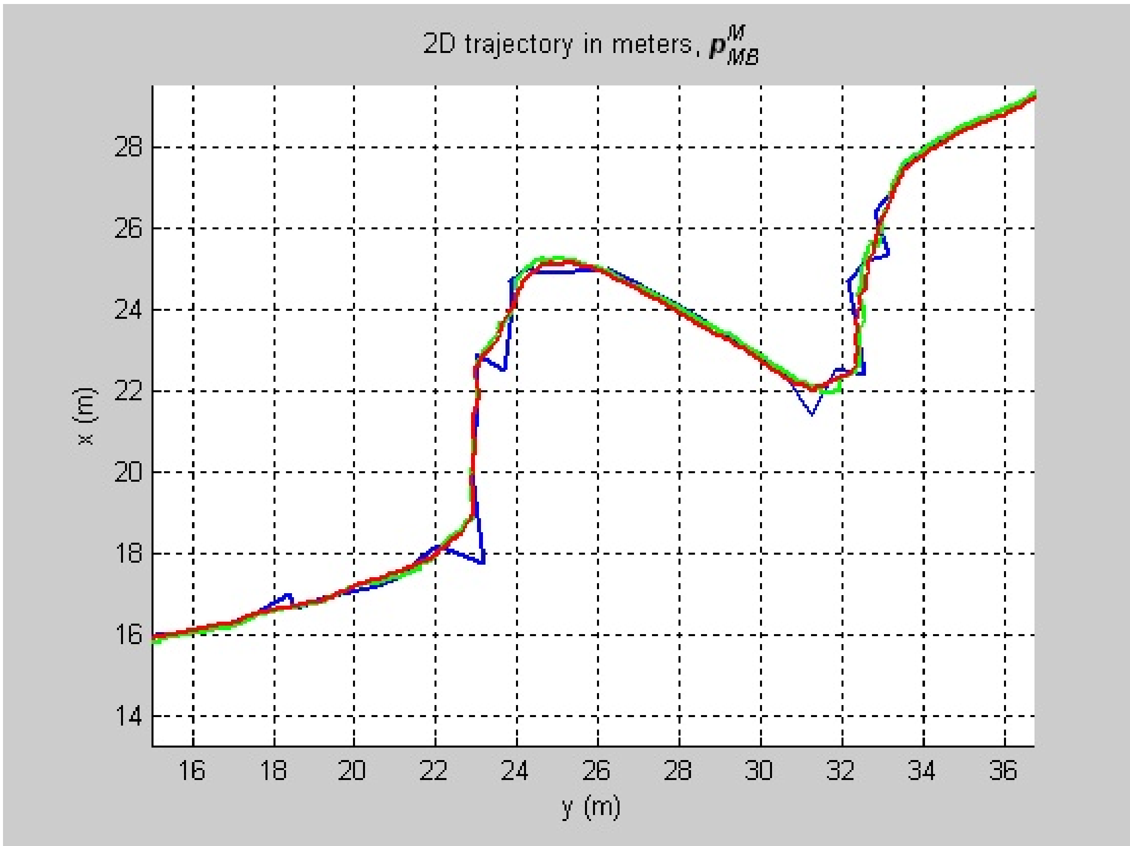

Figure 11 Performance when noisy LBL, Depth 4000m

Line colours:

Blue – LBL real time, Green – HAIN Real Time, Red – post processed

In the middle of the plot, the LBL positions tend to jump almost a metre in the south east direction. It is probably caused by either a reflection on one of the range measurements or a missing range measurement. The jumps do obviously not match with the other input to the HAIN, and the HAIN positions do not follow the jumps

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The next figure shows when there is no noise on the LBL measurements, the difference between the HAIN positions and the measured positions is in the cm range. The water depth is almost 4000 meters.

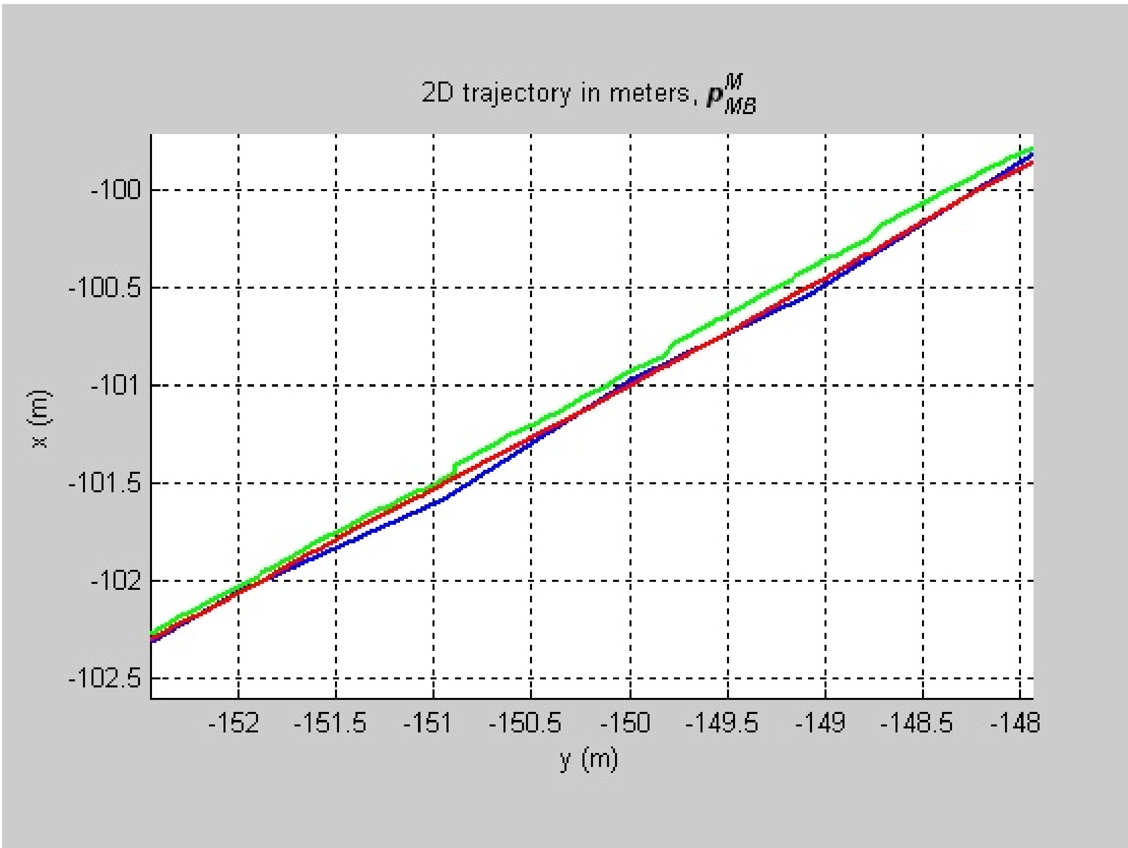

Figure 12 when good LBL, Depth 4000m

Line colours:

Blue – LBL real time, Green – HAIN Real Time, Red – post processed