Benefits of Using High Grade True INS for Hydrography

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Abstract

Over the last number of years the hydrographic community has made intensive use of multibeam echosounders for deriving accurate subsea cartography. Consequently, as the processing of the multibeam data requires reliable attitude and position information, the use of precise motion sensors and positioning systems has massively increased. In this paper, we present HYDRINS: the first fully integrated true Inertial Navigation System (INS) designed to meet all hydrographic positioning requirements. We will present why and how a true INS can be used for hydrographic surveys. It can be used either as an autonomous inertial navigation system or integrated with GPS differential or RTK, or Doppler velocity log (DVL). In this paper, we will review hydrographic positioning requirements and we will explain how HYDRINS was tailored to meet those needs. Moreover, we explain how HYDRINS can cope with GPS dropouts or bad GPS data. We will give some field data and discuss the performance achieved for all parameters during dropouts of GPS data. Eventually, we present an interesting alternative for surveyors, independent from the GPS the joint use of DVL and HYDRINS.

1. Introduction

In 1997, iXSea developed an attitude and true heading sensor known as OCTANS [14] (today OCTANS uses 0.05 deg/hour FOGs (fiber optic gyroscopes)).OCTANS was designed to meet the requirements of the marine and survey communities and provides 0.1 deg heading, 0.01 deg roll and pitch accuracy. Today, more than 500 OCTANS are now operating worldwide, primarily on survey vessels or underwater vehicles.
In 2000, iXSea introduced PHINS, the first commercially available Inertial Navigation System, now a common navigation sensor in many AUVs. PHINS is a true INS. When started without external heading aiding, it can compute survey-grade heading, roll, and pitch with no degradation in both static and dynamic condition. When aided by external aiding sensors on surface (GPS) and subsea applications (USBL, LBL, DVL, …) it can provide a complete and suitable navigation solution to surface and subsea vehicle. In 2004, based on our experience with OCTANS and PHINS, we designed HYDRINS a true inertial navigation system for hydrographic surveys.

During survey work, HYDRINS is able to integrate information from any GPS and from a Doppler Velocity Log. The position drift using only DVL is less than 3 meters per hour at 2 knots and the heading accuracy is better than 0.02 deg. Moreover if for some reasons neither GPS, nor Doppler velocity log is available for a while, HYDRINS is able to keep a good position in pure inertial mode in order to continue the survey work. To satisfy such requirements, HYDRINS relies on the highest inertial measurement unit (IMU) currently available on the commercial market, based on state of the art gyroscopes, the data of which are blended with external sensors data. iXSea has been working on the fiber optic gyroscope (FOG) technology since 1987 and is now producing very high performance fiber optic gyros for space applications [13].

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2. Positioning requirements for hydrographic surveys

- **Practical issues with using multibeam sonar: Attitude and time correction**

Multibeam sonars use sound to measure depth of the ocean. They receive and transmit sound from an acoustic array. The transmit array is usually mounted parallel to the keel of the vessel and the receiver array is orthogonal to the transmit array. Such installation creates beams which are narrow in both fore-aft and athwartship directions. A series of narrow beams are generated and steered (acoustically or electronically) in the athwartship direction. This fan of beams is transmitted and received by the system (see [10][11]). This would be perfect in a static world, however practical limitations may apply. After bottom detection methods are applied to the incoming signals, a series of depths for each ping of the transducer are computed. The obvious issue is the movement of the ship as all these depths must be precisely georeferenced. Therefore, the position and orientation of the sonar at each transmit and receiver times must be known. Practically, on the survey vessel, this drives the need for the installation of sensors to measure horizontal positioning, orientation (roll, pitch, heading), elevation (heave and tide) together with the velocity profile of the water column. Obviously, the global accuracy of the survey is directly correlated to the quality of the different sensors individually as well as the quality of their integration onboard the ship.

A successful integration of these sensors requires a very precise knowledge of:

- the relative location of the sensors within the ship reference frame: Full attitude data and the offset between the antenna and the transducer are needed to apply in real time a correction to the soundings.

- the location of the sensors with respect to the ship reference frame: Roll, pitch, heave offsets will induce both vertical and horizontal depth errors and small attitude biases can create depth and position errors.

- the time delays between the various sensors: Time delay in the positioning sensor will result in an erroneous location and shift the attitude reduction of the data.

- **IHO regulatory minimum requirements**

As described above, the referencing of the multibeam data is obtained by merging attitude information and earth relative position information. The main issue is, what is the accuracy needed in attitude and position (see [15]). The international reference in terms of hydrographical depth measurements is described by the S44 standard, commonly named IHO standard by hydrographers (see [9]). The table below recalls the different accuracy thresholds.

Order	Special	1	2	3
Examples of typical areas	Harbors, berthing areas, and associated critical channels with minimum under keel clearances	Harbors, harbor approach channels, recommended tracks and some coastal areas with depths up to 100m	Areas not described in Special order and order 1, or areas up to 200m water depth	Offshore areas not described in Special order, and orders 1 and 2
Horizontal accuracy (95% confidence level)	2m	5m + 5% of depth	20 m + 5% of depth	Same as order 2
Depth accuracy for reduced depths (95% confidence level)	A=0.25 m B=0.0075	A=0.5 m B=0.013	A=1.0 m B=0.023	Same as order 2
100% bottom search	Compulsory	Required in selected areas	May be required in selected areas	Not applicable
System detection capability	Cubic features >1m	Cubic features >2m in depths up to 40m; 10% of depth beyond 40m	Same as order 1	Not applicable
Maximum line spacing	Not applicable, as 100% search compulsory	3x average depth or 25 m, whichever is greater	3-4x average depth or 200 m, whichever is greater	4x average depth

A = constant depth error, i.e. the sum of all constant errors
B = factor of depth dependent error

- **Murphy's law and the hydrographer: The most stringent requirements apply to the less easily practicable areas**

Today, when it comes to meeting the IHO requirement, the critical problem that hydrographers are facing in order to meet the above requirements are as follows:

- GPS outages in harbor areas

Unfortunately, the IHO special order case corresponds to the places where the GPS coverage is the less efficient even in RTK mode. This comes from numerous obstacles to GPS signal that can be found in harbors or rivers as a result of steep walls, cranes, bridges which cause shadows or multipath to the signal.

- Precise altitude monitoring

The real time monitoring of the vessel altitude is also a critical issue. Both long term (tides) and short term (heave) variations are present in the altitude data. The critical areas mentioned above are also the areas where the hydrographers need the highest altitude accuracy. The best way to have a real time earth ellipsoid reference is to use the RTK GPS system. However you are still very dependent of GPS outages.

- Synchronization of the different sensors

The most disastrous artifacts generated in the data acquisition are due to the inaccuracy of the time synchronization of the different sensors on board. Systems which integrate most of the sensors are best placed to cope with such problems.

3. HYDRINS

- **Principle**

With HYDRINS, the heading accuracy is better than 0.02 deg and the roll or pitch accuracy is better than 0.01 deg. Moreover if for some reasons neither GPS, nor Doppler velocity log is available for a while, HYDRINS is able to keep a good position in pure inertial mode in order to continue the mission. To satisfy such requirements, HYDRINS IMU is based on state of the art gyroscopes and HYDRINS DSP contains a Kalman filter able to optimally integrate external sensor data from any GPS and from a Doppler velocity log. HYDRINS is easy to install and compatible with standard NMEA frames.

- **Positioning solution**

Taking advantage of the merging of GPS with inertial, HYDRINS delivers a high rate (100 Hz) position. In fact, over a short period of time, the GPS is noisy but the INS is smooth, however over a longer period of time the GPS stays accurate, but the INS does drift. The Kalman filter is the optimal mathematic tool to take advantage of both inertial data and GPS data. The HYDRINS Kalman filter allows to have a smooth (no noise) and a non drifting position. Moreover the Kalman filter can also correct IMU errors like bias, to continuously improve the inertial performance.

For details on the theory of Kalman filters the reader can refer to [2] [4] [5] and for the applications of Kalman filtering in navigation the reader can refer to [1][7][12]. The goal of the Kalman filter is to use data provided by external sensor to correct inertial navigation errors.

<u>Robust estimation and rejection of erroneous measurements</u>:
During a long mission it is very likely that some external sensors will provide erroneous data from time to time. In a traditional Kalman filter, such erroneous data could lead to uncontrolled divergence of the estimations. Moreover the divergence of the Kalman filter would be proportional to the error of the external sensor. To cope with this problem we have implemented a robust estimation based on M-estimator in the HYDRINS Kalman filter (see [3][6]). The principle of robust estimation is to replace the linear response function of the Kalman filter by a non-linear response

function (see Figure 1). Each measurement is compared to the corresponding expected standard deviation. If the measurement is in the expected range it is integrated as usual, if it is clearly not in the acceptable range it is rejected and if it is suspect it is attenuated.

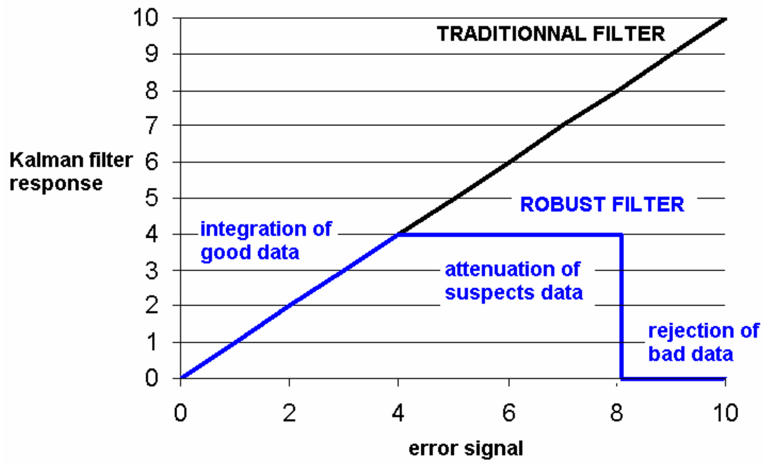

Figure 1: principle of robust Kalman filtering

Figure 2 below, we present the results from a typical survey in a difficult location. The vessel ran survey lines in a narrow estuary, passing under a bridge. It took place near Brest (west of France) on the Elorn River. In this situation, the corrections from the RTK GPS were poorly received, resulting in a 2-minute ''patchy'' GPS data set caused by multipath. However, thanks to its robust filter the HYDRINS continued to give accurate position with the inertial navigation

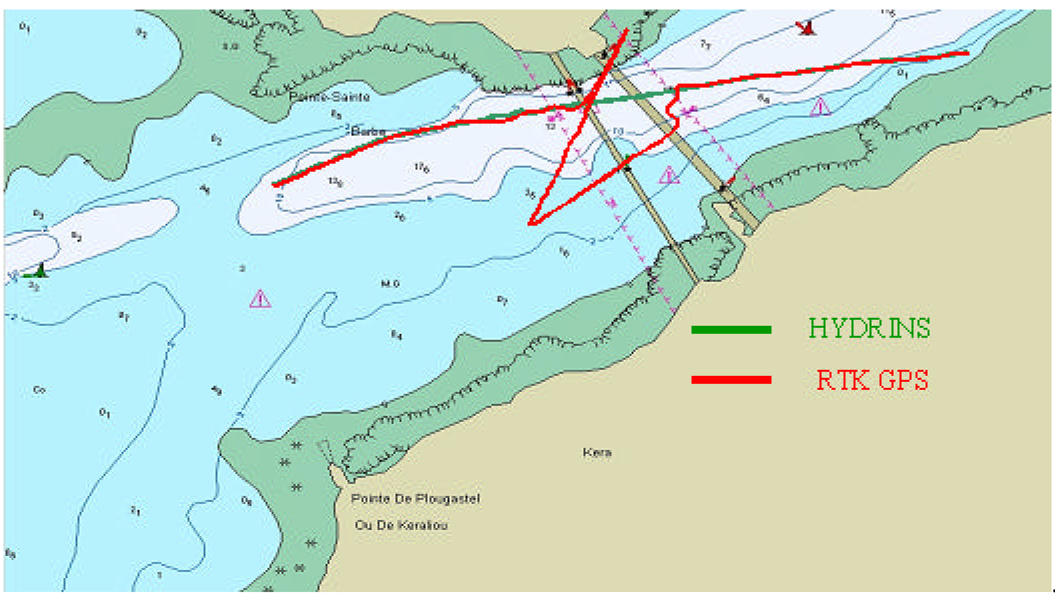

Figure 2 : Robust filter position compared to GPS, Elorn river estuary (Brittany) survey 2 minutes multipath overcame by HYDRINS

Another way to improve the performance of an inertial system is to combine inertial data with speed sensor. Using iXSea's experience in underwater systems, the HYDRINS Kalman filter can also integrate Doppler Log Velocity information in order to improve the drift of inertial navigation. For example; the inertial navigation coupled with a DVL leads to a drifting posing less than 3 meters in one hour. This integration with GPS and/or DVL is performed in the HYDRINS; the user has nothing to do. The HYDRINS, thanks to its Kalman filter, does the entire job taking advantage of the 3 different sources of information: inertial, position (GPS), speed (DVL).

- **GPS outage**

During a drop out of GPS, the HYDRINS computes a position using only the inertial data. However this position will eventually drift due to inertial sensor imperfection. The rate of the drift is depending of the IMU sensor, and of the initial error. To improve the results of inertial navigation, the HYDRINS Kalman filter makes a self-calibration of its IMU sensor. For drop-outs shorter than 5 minutes, the main drifting term is due to accelerometer bias. However, an accurate estimation of the accelerometer bias is impossible without a high class gyroscope (better than 0.1 degrees per hour), because otherwise the Kalman filter can not sufficiently distinguish error coming from accelerometer or from gyroscope. In the next figure we give typical drifts due to either a typical accelerometer bias of 100 migroG only or a 0.01° initial roll error compared to HYDRINS drift.

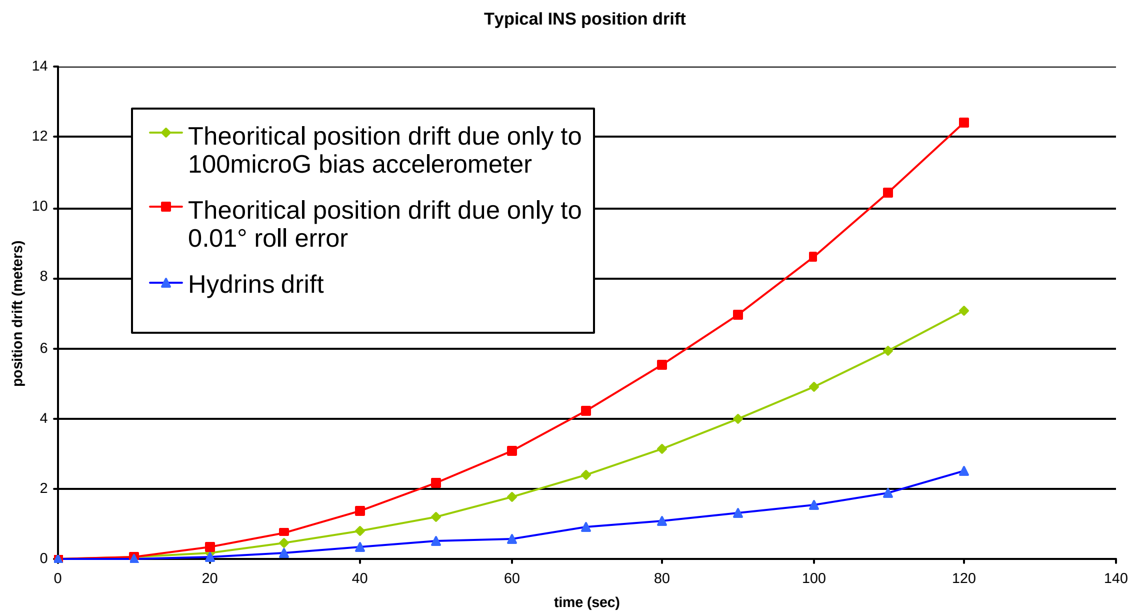

Figure 3 : Typical INS position drift compared to HYDRINS

Several trials have been done to validate the performance of HYDRINS, including laboratory trials (especially for attitude and heading), car trials, trials on specially calibrated tracks and sea trials using GPS RTK for comparison. In this section we present some of the results obtained during these tests. In Figure 4, we compare the temporal drift of different systems with respect to the IHO standards. We can observe that classical dual GPS antenna systems are very dependent on GPS outages which drift very quickly. Higher performance inertial systems like the HYDRINS stay for 100 seconds below the threshold of the IHO special order.
Special applications need centimeter positioning even during long GPS outage. For this case an inertial system alone can not maintain such performance. However, HYDRINS offers a solution which aids the INS with a speed sensor (like a Doppler Velocity Log) and as a result HYDRINS drifts only at 3 meters per hour without any GPS information.

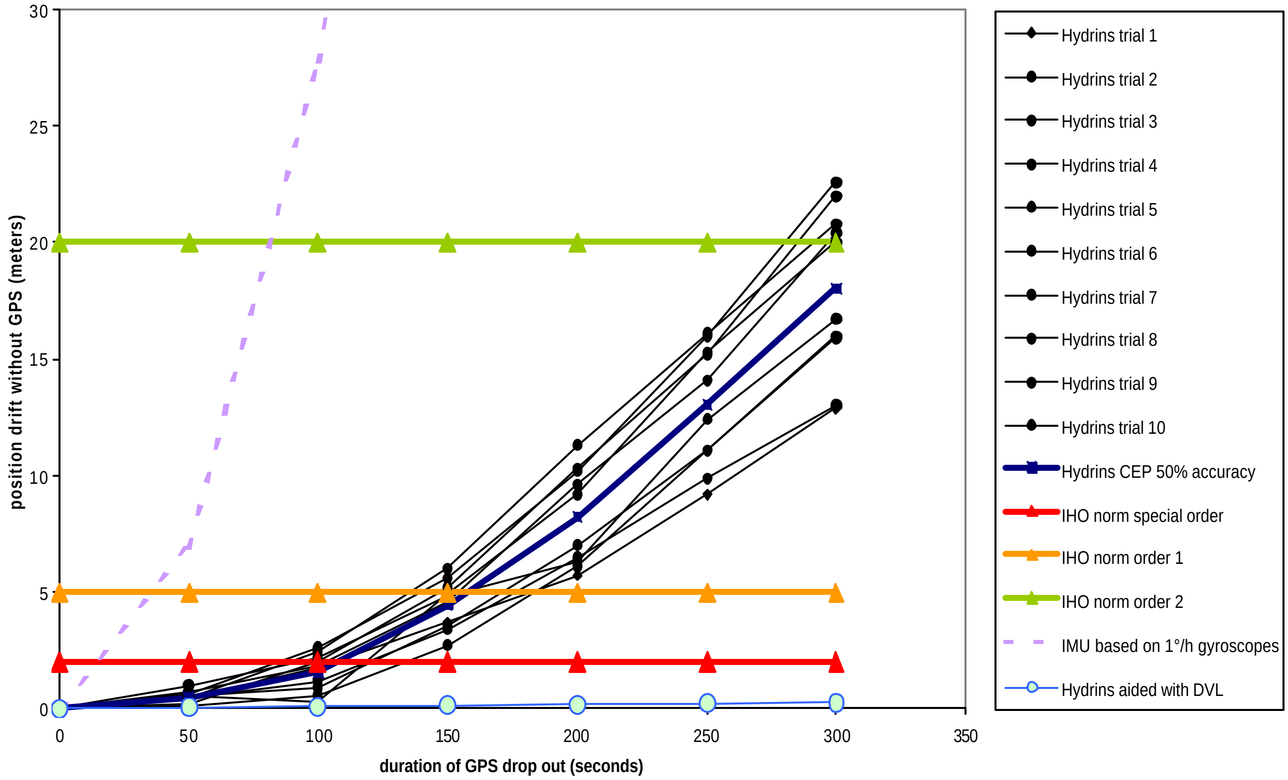

Figure 4: performance of position during GPS drop out

- **Altitude**

During a hydrographic survey, the altitude issue is a serious problem. The only way to have in real time a reference to WGS 84 earth ellipsoid model is to use the RTK GPS. The other solution is to take into account the tide elevation which most likely would result in post processing correction. Additionally, heave must also be addressed as one of the components of altitude.

Once again a smart integration of inertial data and RTK GPS altitude takes advantage of information from both. As can be seen in Figure 5, during the first 20 seconds there were higher waves, but the GPS RTK provides altitude position at slow frequency, so the hydrographer is required to do interpolation. However, using the HYDRINS altitude the hydrographer does not need to do interpolation, the HYDRINS altitude is suitable at 100Hz. HYDRINS takes advantage of its inertial sensor to maintain an accurate altitude. In fact the inertial altitude gives true altitude even during long GPS drop out as seen in Figure 5.

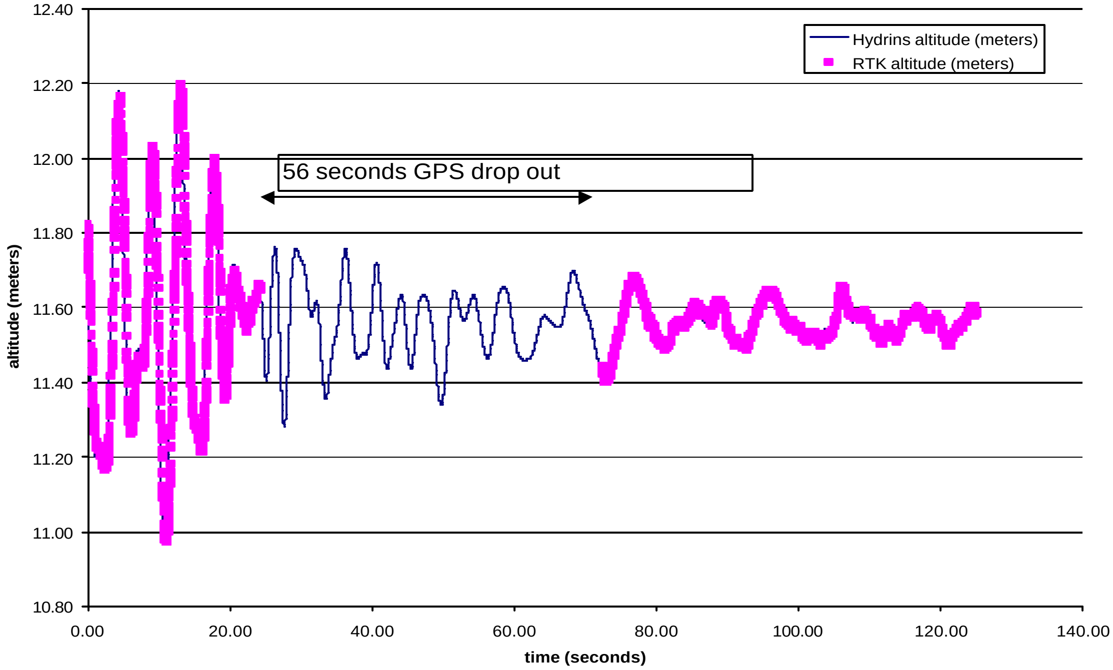

Figure 5 : example of HYDRINS altitude during GPS outage

In case of longer GPS outage, the inertial algorithm cannot provide a geo referenced altitude. In a case like this HYDRINS is still capable of giv ing an accurate relative altitude (heave) by using a specific tuning free heave filter, called SAFE Heave (Self Adaptive Filtered Estimated Heave). This has been included in the HYDRINS system for real time computing.

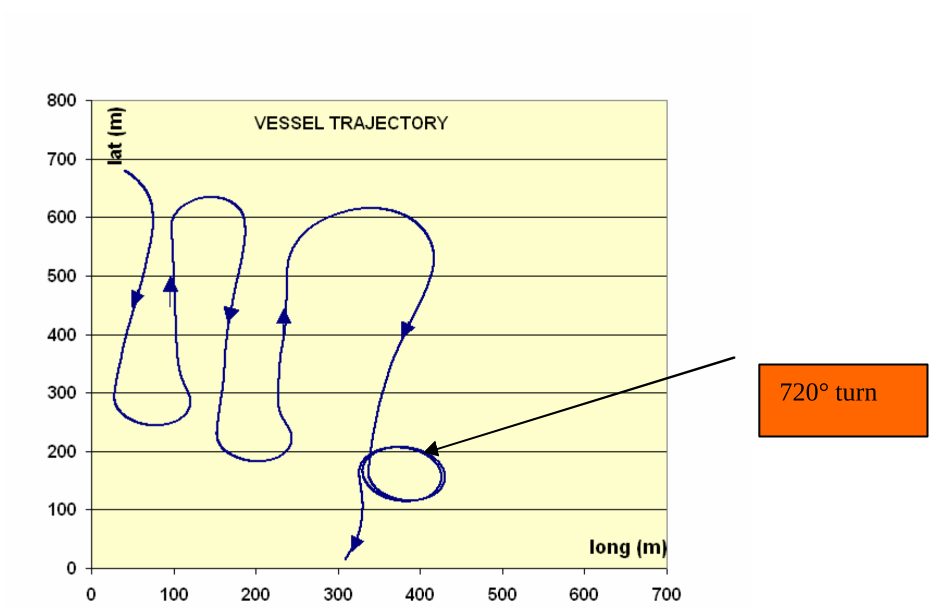

Figure 6 : Vessel trajectory during heave testing: survey lines followed by double turn.

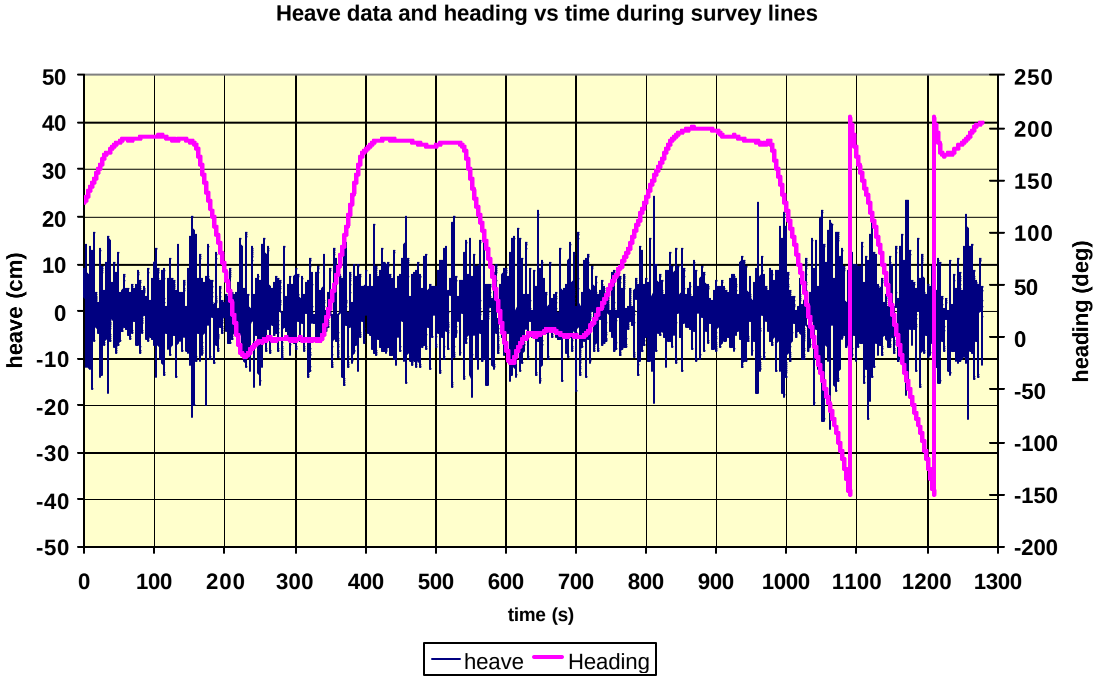

Figure 7 : Heading and heave versus time during survey lines.

This filter is fundamentally a new heave filter concept using the latest progress in mathematical techniques to assess heave filter parameters in real time. As a result, the filter is always optimal, whatever the conditions and regardless of the type of vessel. This algorithm allows several turns without any built-up effect on the heave data as described in Figure 6 and 7. It can be seen on these figures that even when the vessel is changing direction (50 degrees heading changes on first part of the curve, and 720 degrees (two complete turns in a row) at the end of the curve, there is no spikes during or after tum on heave measurement: on that very calm day there were very small amplitude waves that does not change during turns.

- **Synchronization**

For ease of integration, HYDRINS gives all the data useful for a multibeam acquisition system in real time with a time stamp that can be synchronized with PPS. HYDRINS synchronizes itself with the GPS, therefore hydrographers have only one time delay to take into account between multibeam data and HYDRINS data (latitude, longitude, altitude, heave, roll, pitch, heading,, time stamping). This results in significant easiness for installation and use.

4. Conclusions

HYDRINS is the first high performance integrated navigation system based on fiber optic gyroscopes which is able to fulfill hydrographic requirements, even when GPS drops out.

The design of HYDRINS has been possible using iXSea's experience in FOGs and inertial navigation systems. It is able to integrate optimally data coming from external sensor like GPS, and DVL using a specifically designed robust Kalman filter. Several tests have proved that HYDRINS achieves very high performances. Most importantly iXSea offers a new approach for hydrographers to be independent of long GPS drop out.

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