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Sensors

PHINS, An All-In-One Sensor for DP Applications

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ABSTRACT

DP positioning sensors are mainly GPS receivers and acoustics sensors such as USBL or LBL. GPS receivers when used in differential mode are very accurate and very reliable. However, there are cases when they may provide either corrupted measurements or no measurements at all. Acoustic positioning systems usually take a great deal of time to install and to calibrate. The purpose of the present paper is to present some alternative sensors that would resolve some of the difficulties with conventional sensors. They are not intended to replace those sensors but more as supplemental to them to add availability, safety and redundancy to conventional DP system sensors. IXSea manufactures two sensors that may be used for DP applications:

- PHINS, an inertial navigation system capable of data fusion between inertial sensor measurements and GPS data and/or Long Base Line (LBL) acoustic positioning systems and/or Ultra Short Base line (USBL) acoustic positioning systems.
- GAPS, a portable, calibration-free USBL-based positioning system, incorporating a high-performance inertial navigation system.

1 INTRODUCTION

A key element of DP operations is the position reference system. Depending on the DP operation class, up to three position reference systems are required, each providing the requisite level of accuracy. But accuracy is not the only important factor. Availability, integrity and continuity are also characteristics required for secure operation at all times.

GPS receivers are currently the most popular position reference systems. When used in differential mode, they have numerous advantages, among them, accuracy and cost are not the least. However, GPS may be subject to interruption in service due to various effects:

- Some are natural, such as the scintillation effect: solar storms may lead to instability in the ionosphere capable of interfering with GPS signals, making them impossible to track for a period of time.
- Signal masking due to large structures close to the DP vessel. This may happen in harbors and close to lighthouses for example.
- Multipath, a GPS signal reflection that causes positioning instability and inaccuracy.

Some of these effects may lead to an undetected position error and some to unavailability of GPS data. In all cases either the system availability or integrity will be diminished.

Far from doing away with GPS receivers, these being unrivalled in terms of accuracy and cost, the concept here is to add sensors to ensure continuity, integrity and availability whenever the GPS signals are corrupted or temporarily unavailable. Two of these sensors are described below:

- PHINS™ is an inertial navigation system (INS) aided by external sensors whenever they are available. These external sensors may be the differential GPS data, LBL position data or USBL position data or even Doppler Velocity Log (DVL). It contains three Fiber Optic Gyros and 3 accelerometers. Data merging between all measurements is performed using a Kalman filter.
- GAPS™ is a new compact, portable, calibration-free and fully integrated position reference system, which combines in a single housing all the necessary sensors and processing – UBSL 3-D acoustic antenna and broadband spectrum signal processing unit, a FOG (Fiber Optic Gyro)-based inertial navigation system similar to PHINS, a standard GPS receiver, a temperature sensor and Kalman filtering – to provide the best combined positioning of subsea vehicles with high accuracy, high update, and able to overcome acoustic and GPS signal drop-out.

2 PHINS, a Fiber Optic Gyro Navigation System

2.1 Description

Mechanically, PHINS is a 16x16x16 cm^3 box weighing 4kg (Figure 1).

Figure 1: PHINS mechanical design

The box contains a high-performance inertial measurement unit (IMU) and a digital signal processor. Three connectors are provided for external sensors. During the mission, PHINS is able to integrate information from a GPS whenever available, from acoustic positioning systems, and from a Doppler velocity log. The position drift using only DVL is less than 3 meters per hour at two (or less) knots and the heading accuracy is better than 0.02 deg. Moreover, if for some reason neither the GPS, nor the acoustic positioning systems, nor the Doppler velocity log is available for a period, PHINS is able to keep a good position in pure inertial mode in order to continue the mission. To satisfy such requirements, the PHINS IMU is based on state-of-the-art gyroscopes and the PHINS Digital Signal Processor (DSP) contains a Kalman filter capable of optimum integration of external sensor data.

2.2 Kalman Filter Principle

The purpose of the Kalman filter is to use data provided by external sensors to correct inertial navigation errors. Contrary to traditional approaches in which inertial data are replaced by external data when possible (for instance in dead-reckoning inertial speed is replaced by external speed), the Kalman filter tries to estimate not only the error of the inertial system but also the errors of the external sensors. Moreover, it can also correct errors accumulated in the past using newly available information.

During a long mission it is very likely that the external sensors will provide some erroneous data. In a conventional 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 robust estimation based on an M-estimator in the PHINS Kalman filter. This function is key to the safe operation of DP systems: the INS is able to detect any corrupted data from the external sensor, and then rejects it so that it does not corrupt the optimal solution computed by the INS.

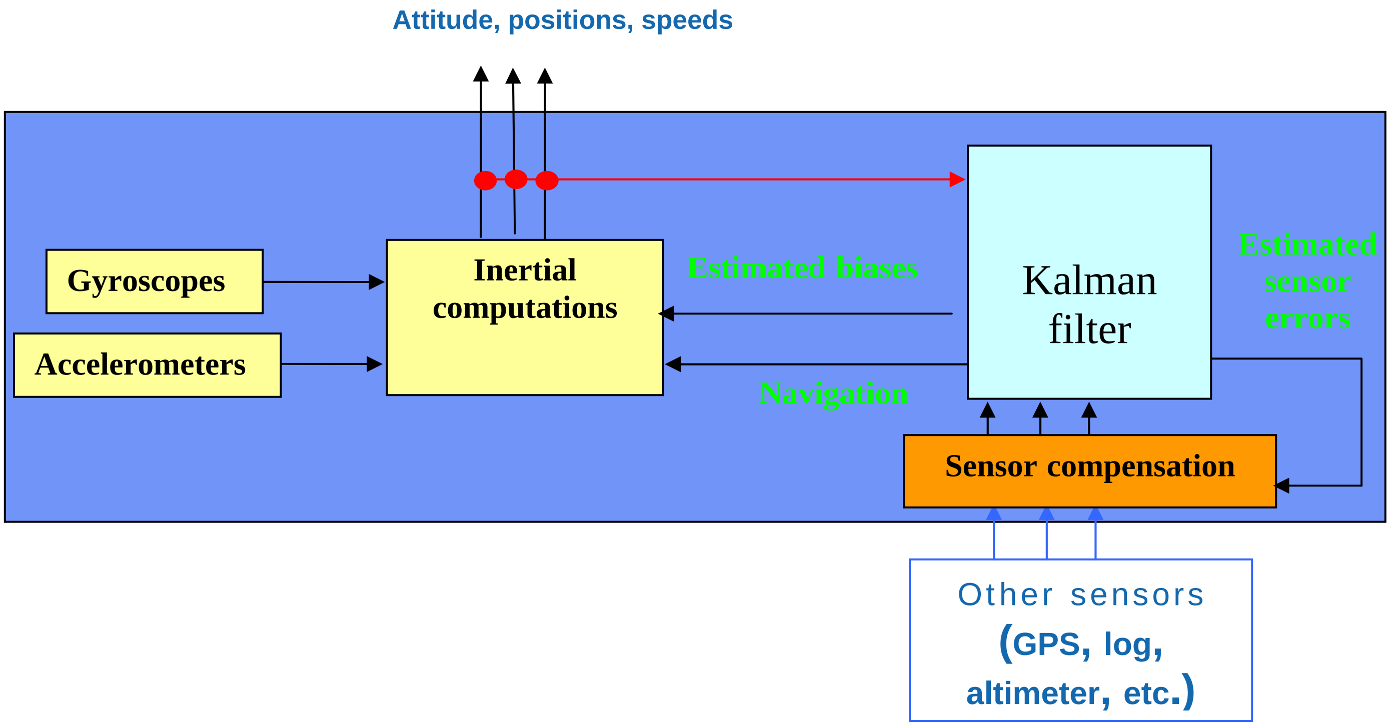

Figure 2: INS Kalman filter principle

2.3 Integration of acoustic sensors

While most inertial navigation systems are designed to merge measured data with GPS data, very few can use acoustic sensors (and in most cases they can accommodate DVL only). The integration of acoustic positioning systems is not straightforward, particularly because of the time delay between the emission of the acoustic signal by a USBL or LBL system and the reception of the corresponding information by PHINS. In this section we will discuss the specifics of acoustic systems and the integration of acoustic data in the PHINS Kalman filter.

2.3.1 USBL

USBL systems are operated from a surface vessel. A standard USBL system comprises an acoustic antenna with four transducers/receivers on the surface vessel and a transponder moored on the seabed (Figure 3). The antenna is oriented with respect to the geographic frame by inertial means using a gyrocompass, such as the Octans for example. The position of the surface vessel is provided either by GPS

or by a combination of GPS and inertial means. The alternative to the standard USBL system is the GAPS™ fully integrated system from Ixsea, which contains all the necessary sensors and merges their data within a single housing (see para. 3).
Due to the relatively slow speed of sound in water, the position measured by USBL is delayed for a duration equal to twice the transit time between the transponder and the antenna. For instance at a range of 3000m, the position provided by USBL will be delayed by at least 4 seconds.
The integration of delayed data in a Kalman navigation filter is not a traditional procedure. To cope with this problem, IXSea has designed a specific algorithm. Broadly speaking, the underlying concept of the algorithm is to compare delayed external data with delayed inertial data before integrating them into the Kalman filter (account of course also needs to be taken of covariance variations and corrections to the inertial navigation based on other sensors). Using this algorithm, the PHINS Kalman filter can integrate external data with up to 30s delay with no loss in accuracy, which is amply sufficient in real-life applications.

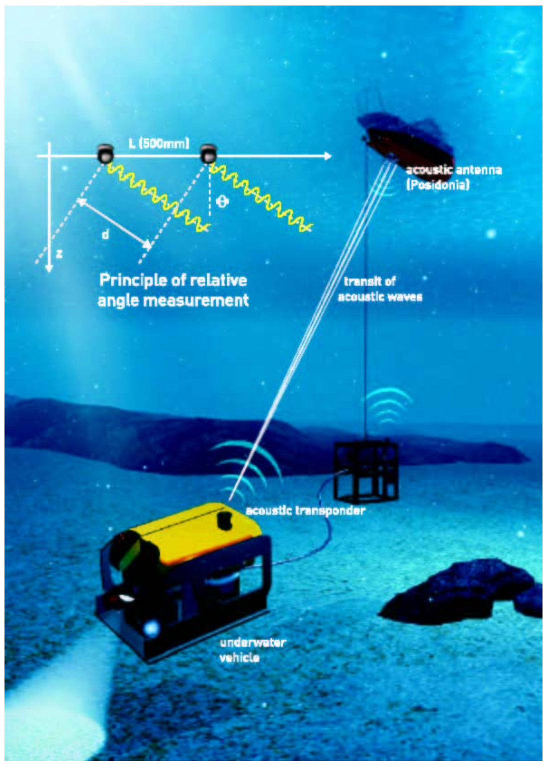

Figure 3: principle of USBL systems

2.3.2 DVL

To use a Doppler velocity log in conjunction with an inertial navigation system it is first necessary to compute very precisely the misalignment between the two sensors. This is done automatically by PHINS using a specific procedure. If the DVL is mechanically connected to the PHINS the misalignment calibration needs to be performed just once and it will remain valid for subsequent missions.
In certain situations the DVL is not able to compute speed relative to the sea bottom (for instance when the altitude of the vessel above the seabed is too great). However, in this case, the DVL can provide the speed relative to the water layer. This means that it can be used for navigation purposes if the speed of the current has been estimated beforehand. For example, the estimate of current velocity is possible when USBL or GPS and DVL water track data are available at the same time or when bottom track and water track measurements from DVL are simultaneously available.

To integrate the estimation of current velocity into the Kalman filter, we have added new states corresponding to east and north current velocities.

2.4 PHINS test results

2.4.1 Pure inertial mode (no aiding sensors)

Sea trials were performed in November 2003. Several tests were carried out to check PHINS accuracy during GPS outages. During the trials the vessel speed was between 2 and 4 knots. No effect of the speed or the maneuvers of the vessel on position drift were observed. The results are shown in Figure 4. PHINS position accuracy during a GPS outage stays within GPS accuracy for a period exceeding 150s. The mean position drift after a 50s GPS outage is less than 0.5m.

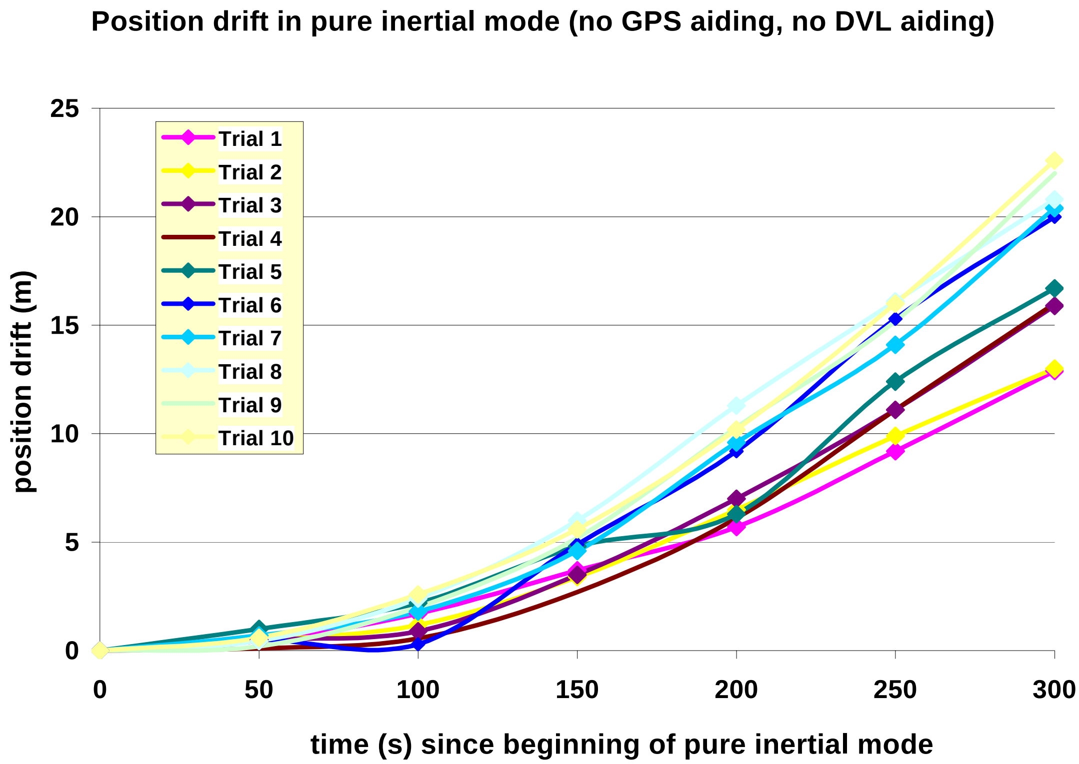

Figure 4 : PHINS performance in pure inertial mode

2.4.2 GPS multipath rejection

In many situations, GPS systems can be used to obtain a very accurate absolute position. However, in principle, there are many areas where GPS cannot be used effectively because of multipath errors (for instance in harbors or, generally speaking, in noisy environments). In these cases, the PHINS Kalman filter, since it is based on robust statistics, is able to reject automatically GPS outliers and continues to provide a very accurate position. Figure 5 presents the basic operating principles of the robust PHINS Kalman filter and shows the typical behavior of PHINS versus GPS in a noisy environment. During a bridge crossing, the GPS satellite signals are reflected on the bridge and GPS position is affected by multipath errors; the PHINS rejects bad GPS data and provides a metric position throughout the whole sequence. When the GPS data are once again valid, PHINS automatically integrates them.

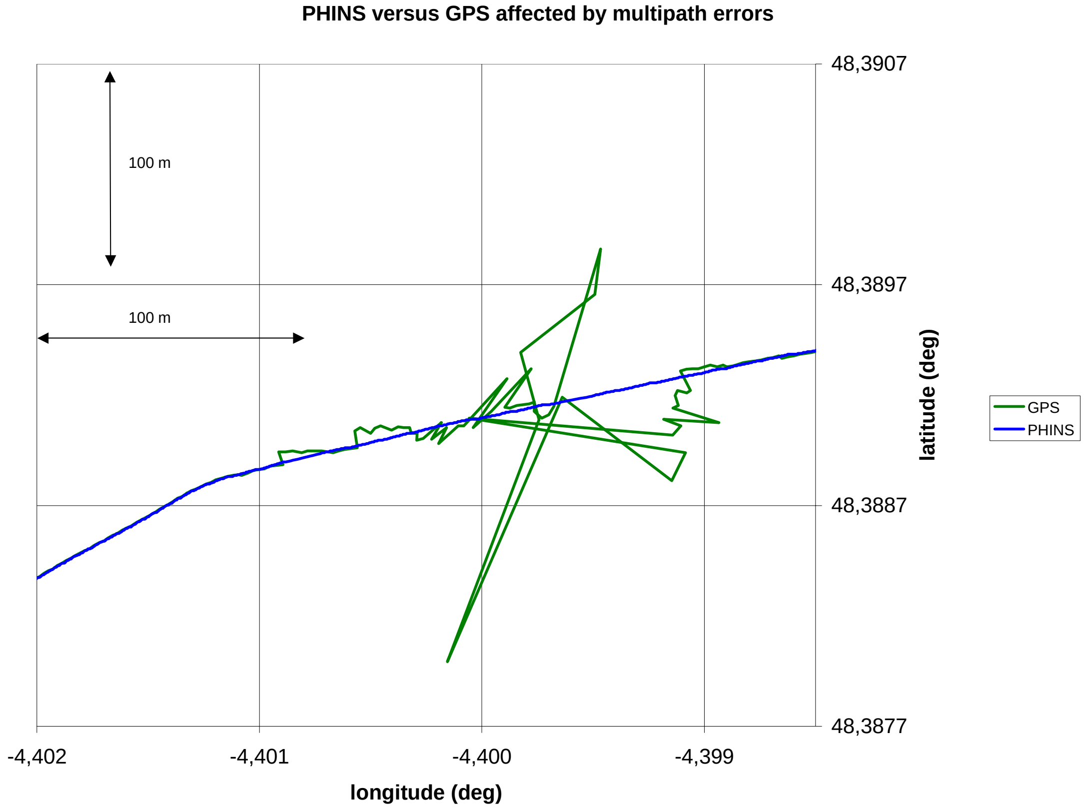

Figure 5 : PHINS trajectory measurement vs. erratic GPS positioning when passing below a bridge

2.5 How can PHINS help in safe DP operation?

The use of a an INS aided with GPS and possibly USBL would provide a much more robust positioning system:

- the system would be able to detect and reject eventual jumps in GPS position,
- it would be able to maintain the GPS accuracy for approximately 2 minutes, during GPS dropouts or even simply during a loss of differential GPS mode
- if USBL is available, it would provide a solution that would be completely independent from GPS, therefore eliminating any common mode errors or failures,
- compared to USBL used alone, INS aided by USBL would provide data at a much higher refresh rate (up to 100 Hz) and there would be no latency in position data: this would provide a much more robust control system (data latency is a factor for instability).

A possible architecture could be as shown in Figure 6.

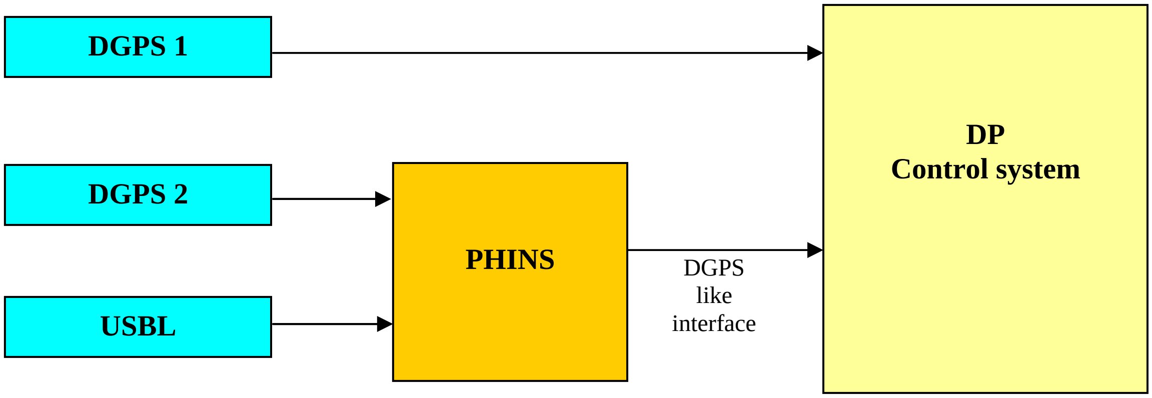

Figure 6 : System architecture

3 GAPS USBL

3.1 Introduction

GAPS™ is a new compact, portable, calibration-free and fully integrated position reference system, which combines all necessary sensors and processing within a single housing– USBL 3-D acoustic antenna and broadband spectrum signal processing unit, a FOG (Fiber Optic Gyro)-based inertial navigation system similar to PHINS, a standard GPS receiver, a temperature sensor and Kalman filtering – to provide the best combined positioning for subsea vehicles with high accuracy, high update rate, and capable of overcoming outages in acoustic and GPS signals.

Figure 7: GAPS™ mechanical design

GAPS™ is not simply an underwater positioning system, it is also an inertial navigation system, able to provide Heading, Pitch and Roll of the surface vessel fitted with GAPS™.
Its portable, plug & play and calibration-free design concepts make this equipment flexible and especially suitable for quick installation on board any vessel of opportunity, thus reducing cost and vessel mobilization time.
It has been developed with a design-to-cost approach, taking into account customer requirements in terms

of hardware price and cost savings, as made possible by the plug-and-play concept. The complete success of this design-to-cost approach is based on (i) optimized design in terms of acoustics, inertial hardware, materials and size, (ii) total in-house mastery of the key technologies.

This system merges within a single, compact watertight housing in titanium, a complete range of key technologies:

- 3-dimensional Acoustic Array and temperature sensor
- broadband spread-spectrum signal processing
- a state-of-the-art, embedded INS system with Fiber Optic Gyro, with an added GPS receiver
- state-of-the-art data integration based on Kalman filtering and associated techniques.

The incorporation of these key technologies brings benefits to improve overall performance and helps to address the increasing demands of the industry for reliable and accurate subsea positioning.

Figure 8: GAPS sea trials off the Atlantic Ocean

3.2 Main features and Performances

The GAPS™ system is able to integrate data from the embedded INS system, GPS and acoustic USBL array to provide an all-in-one solution for precise, fast and more robust positioning of multiple underwater transponders, as well as for very high-accuracy data for surface vessel attitude, heading and position.

A proprietary Kalman filter has been specially developed to supply the best combined real-time positions with no delay, high and adjustable output rate up to 10 Hz and reduction of acoustic positioning jitter.

This system is also designed to offer compatibility with a wide range of existing medium-frequency, industry-standard transponders.

It automatically provides telegrams for the subsea vehicle's position, attitude and vessel's position messages using industry-standard protocols, to any survey system or dynamic positioning system.

GAPS™ operates in the 19-30 kHz medium-frequency bandwidth, with up to 4000m operational slant range and is able to maintain a 0.2% rms accuracy for slant range (or 0.12 deg angle accuracy) over the 200 deg coverage below the acoustic array and close to the surface, thanks to the 3-D concept of the antenna.

3.3 Key advantages

The principle benefits of the ship-borne GAPS™ systems include:

- Single, minimally sized housing holding all sensors and eliminating the need for separate conventional USBL system hardware
- Free of calibration as no mechanical alignment is required after installation
- Plug & play
- Improved accuracy and higher acoustic position update rate
- Short time update of subsea positions during acoustic drop-out
- Complete acoustic coverage with tracking close to surface
- Robust to GPS outage
- Cost savings and outstanding value-for-money for hardware and performance.

3.4 GAPS test results

Figure 9 presents the trajectory of the vessel around a moored transponder. The transponder was at a depth of 1250 meters. Therefore the average slant range to the vessel was 1500 meters when the vessel performed an eight-trajectory around the transponder. GAPS, using the vessel position and the USBL measurements computed the position of the moored transponder.

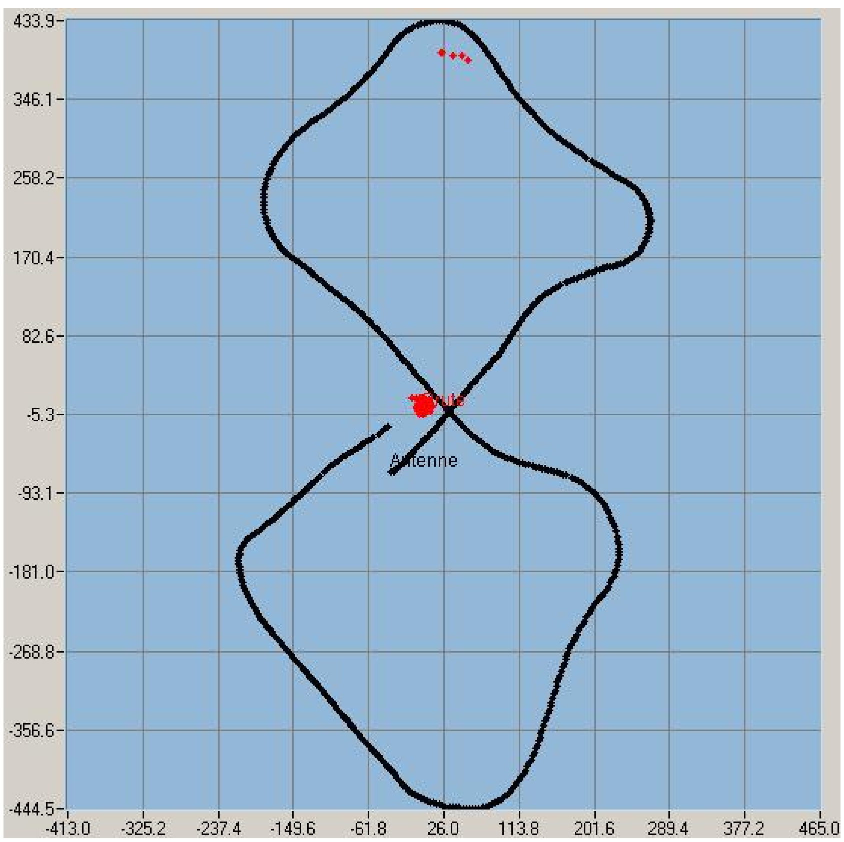

Figure 9 : Vessel trajectory around transponder

Figure 10 presents the position accuracy of the transponder as computed by GAPS. It can be seen that at a slant range of 1500 meters, the rms accuracy is 2 meters, i.e. less than 0.2% of the slant range.

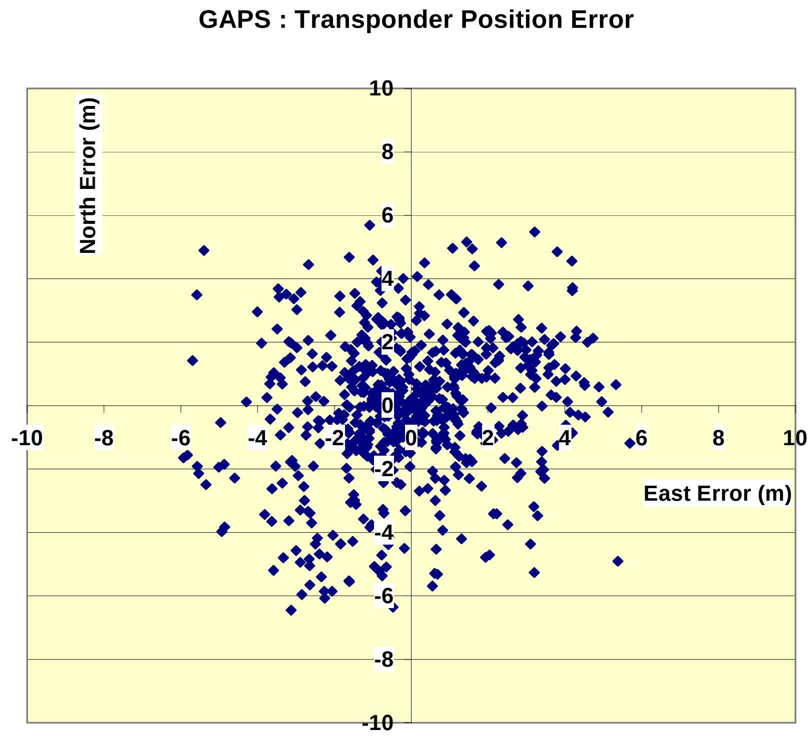

Figure 10 : Transponder position error

3.5 How to use GAPS in a DP vessel?

Since GAPS is a not a simply a USBL, given that it also includes an INS, it is able to perform different functions that are not possible with a conventional USBL:

- As long as DGPS data are available, using the vessel position computed by the Kalman filter of the INS contained in the equipment, GAPS is able to compute the transponder position with a very good accuracy with no calibration. This saves considerable time, which can be used for operational work rather than for installation,
- Immediately the DGPS position ceases to be available, GAPS will determine the vessel's position using the previously computed transponder position.
- At any time, the INS contained in the system will provide data at a very high refresh rate and without delay thanks to the coupling between INS and DGPS and USBL position.

4 CONCLUSION

PHINS or GAPS are two alternatives providing enhanced integrity in the position reference system for DP operations. These two systems are complete solutions containing state-of-the-art technologies, thus providing the very best performance. They add to the DP system's integrity, availability and redundancy.