Technical Report

MARPOS®

Doppler-Inertial Positioning System

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Preface

This report describes the Doppler-Inertial positioning system known as MARPOS®. MARPOS® has been developed for the Autonomous Underwater Vehicle MARTIN® but having direct applications also for tethered deep-sea vehicles (ROV's and ROTV's).

The initialisation procedures and the performance for typical site surveys and line surveys are described.

The accuracy of the positioning system has been tested verified by an extensive sea test programme in 1998-1999. The results of the sea tests are included.

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1. Introduction

Maridan's high-accuracy doppler-inertial positioning system MARPOS® is designed to provide robust high precision positioning of underwater vehicles at all times during its missions. This is achieved through the use of advanced state-of-the-art ring-laser-gyro (RLG) technology and the intimate fusion of Inertial (INS), Doppler (DVL) and Differential GPS DGPS) data in a Kalman filter architecture.

MARPOS® is an aided inertial navigation system that uses external sources to improve positioning accuracy. Positions relative to a known starting point (the Initial Position, IP) are continuously calculated by dead reckoning (DR) using the Kalman filter to process the INS and DVL measurements. If only relative positions are needed any location at the seabed can be used as the IP.

Compass course (heading) is determined by MARPOS® in an alignment process wherein the Kalman filter uses the gyros and accelerometers to sense the centre of gravity and the rotation of the Earth. Alignment can be performed either statically or on a moving base using DGPS and DVL aiding.

The IP can be established by MARPOS® itself or from an external source such as USBL or LBL.

During the survey MARPOS® computes position continuously to a very high accuracy using the high performance INS in combination with the DVL which is operated in bottom-track mode.

1.1 Free-Inertial navigation

The INS can be used to calculate relative positions by integration of accelerometer measurements into velocity and subsequently displacement. Using the INS without input from additional sensors is called free inertial navigation.

The main drawback of free inertial navigation is the limited long-term accuracy due to initial velocity uncertainty and accelerometer imperfections. Despite this the very high accuracy of the gyros and accelerometers used in MARPOS® allow free inertial navigation to be performed over comparatively long mission durations.

1.2 Aided inertial navigation

To maintain high performance over several hours MARPOS® combines the INS with additional motion sensors such as DGPS and DVL. The DGPS is used to aid the INS while at the surface by measuring absolute position and North/East speed over ground with extremely high precision. When submerged the system combines the INS data with either water-track or bottom-track DVL aiding depending on the altitude. Continuous measurement of salinity, pressure and temperature provide the ability to damp the vertical channel error and determine a refined value of the speed of sound and hence to optimise the DVL data.

The DVL measures speed through water and over ground. To measure speed over ground the DVL must be relatively close to the seabed (30 – 200 meters, depending on its transducer frequency). The DVL velocity measurements are relative to the MARPOS® frame. Thus knowing the orientation of MARPOS® in the earth frame is a pre-condition for using the DVL to calculate absolute position. This also applies for the INS accelerometer measurements.

The error growth in Doppler aided inertial navigation can be approximated as a linear function of time and distance to the starting point.

2. Application of MARPOS®

MARPOS® was developed for use in the Autonomous Underwater Vehicle MARTIN® (Figure 1) but the system can also be used in ROV's (Remotely Operated vehicles) or ROTV (Remotely Operated Towed Vehicles).

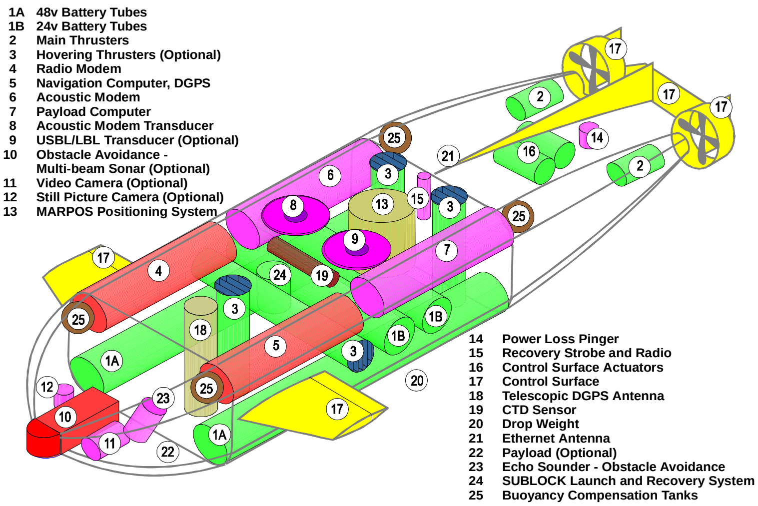

Figure 1: Location of MARPOS onboard MARTIN

At the surface MARTIN® raises its DGPS-antenna to initialise MARPOS® and perform accurate apriori calibration of the sensors. Thereafter MARPOS® can be used as a stand-alone system or with external input under the following conditions without the need to re-surface for position updating:

- **Site survey in shallow water** (upto 300 m). By flying in a "lawnmower" pattern MARPOS® can provide very high accuracy, thus eliminating the need for continuous external updating (LBL or USBL tracking).
- **Site survey in deep water** (300+ m). The relative positions can be provided by MARPOS® to the same accuracy as for shallow water. To bind the relative positions in a global frame the initial position after diving may be provided from an external source (LBL or USBL) or by reference to a recognisable location with known position.
- **Line survey (pipeline and cable inspection)**. The vehicle can follow a pipeline or cable autonomously using an electro-magnetic tracking system in combination with apriori information on the as-laid position of the pipeline or cable. In this way MARPOS® can be updated periodically when passing joints with a characteristic magnetic signature.

3. System Description

3.1 Mechanical design

A schematic view of the MARPOS® cylindrical pressure housing are shown in Figure 2.

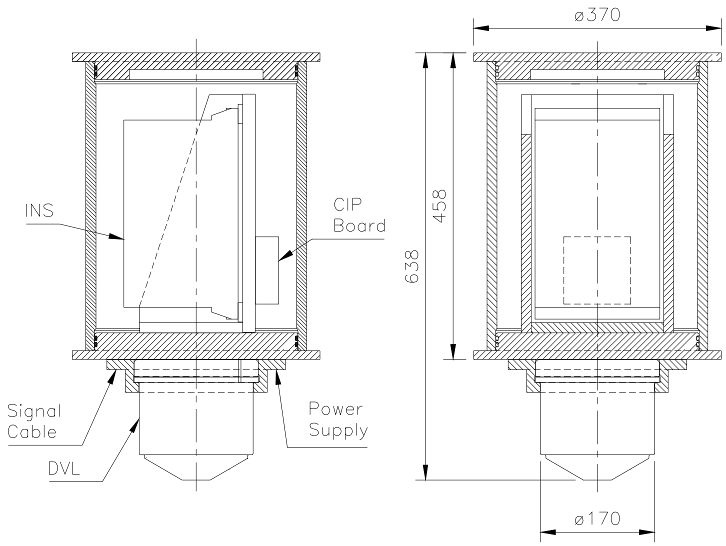

Figure 2: MARPOS® Pressure housing

3.2 Integration of MARPOS® in MARTIN

MARPOS® is an integrated positioning system including the INS and external navigation sensors (Figure 3). The sensors are connected in a network that includes a PC (the Main Positioning Computer). The network is based on a serial bus (CAN-bus) via a micro-controller board called CIP (ref. 1). The CAN Bus is extended to all electronics onboard the vehicle.

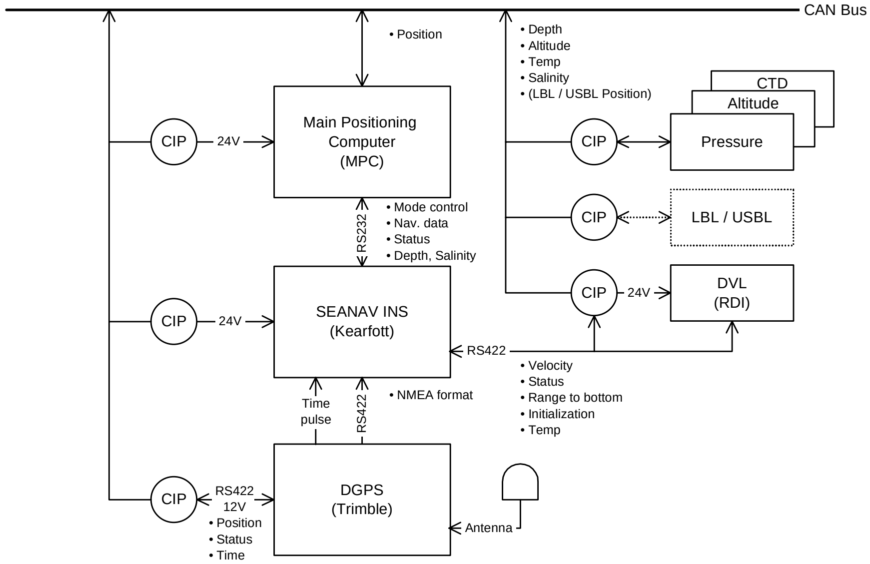

Figure 3: Configuration of MARPOS

3.3 *Inertial Navigation System (INS)*

The kernel of MARPOS® is the KN5053 inertial navigation unit from Kearfott G & N Corp. (New Jersey, USA). The KN5053 is a full strapdown inertial sensor incorporating an advanced monolithic 3-axis ring-laser-gyro and a triad of high performance single-axis pendulous accelerometers providing inertially derived position, velocity, attitude and attitude rate in all six axes of linear and rotational freedom. The KN5053 utilises additional inputs from differential GPS and DVL, using a sophisticated and proven Kalman filter, to compute optimal high accuracy data throughout the operation of the vehicle. The typical performance of the KN5053 is summarised as follows:

Positioning 0.03% of Travelled Distance ($CEP_{50)}$ for Site Surveys

Heading 0.03 deg, RMS

Pitch and Roll 0.03 deg, RMS

For applications where this level of dead reckoning is not mandatory MARPOS® can be provided with the lower performing version of the KN5053 known as the KN5051. This INS is "form, fit and function (F-cubed)" interchangeable with its KN5053 counterpart and gives flexibility to the customer in the choice of configuration for the required mission. The KN5051 based performance is as accurate as the KN5053 in pitch and roll but has a heading accuracy of 0.5 deg, RMS, and a typical positioning performance of 1% of distance travelled, $CEP_{50.}$

As well as reporting precise position and attitude data MARPOS® provides high integrity motion data (Heading, Roll, Pitch) to the Autopilot ensuring a precise path following system for the AUV.

3.4 Navigation sensors

In addition to the KN5053 inertial system MARPOS® includes the following sensors:

- A Doppler Velocity Log for measuring vehicle speed over the seabed (bottom-track mode), vehicle speed in water (water-track mode), altitude and depth.
- A Differential GPS receiver for calibration and updating of the positioning system when the vehicle surfaces. The DGPS receiver is mounted on a telescopic mast that can be erected at the surface allowing the AUV to maintain satellite contact during the time required to receive the update. When diving the DGPS receiver is retracted into the hull.
- A CTD (Conductivity, Temperature, Depth) sensor for measuring parameters to compute the sound velocity.

The following table summarises the specification for the sensors included in MARPOS®:

Sensor	Model	Manufacturer	Specifications
INS	KN5053 or KN5051 RLG INS	Kearfott G & N Corp. (New Jersey, USA)	Position 0.03% or 1% of distance travelled respectively
DVL	Workhorse 1200 KHz	R.D. Instruments (San Diego, CA)	Bottom track: 1-30 m altitude
DGPS		Trimble	Accuracy 1 m (CEP_{95}), 8 satellites.
CTD		Falmouth Scientific (San Diego, CA)	Pressure range: 0-20 bar (optional)

3.5 Input to the INS

To initialise the INS and bound position error the Kalman filter integrates the following input from the external sensors:

Input to INS	Sensor	Operating requirement
Position	DGPS	At surface
Ground Speed	DGPS	At surface
Ground Speed	DVL 1200 kHz	Max altitude 30 m
Speed through water	DVL 1200 kHz	In water
Pressure	CTD	In water
Salinity	CTD	In water
Temperature	CTD	In water
Position (optional)	USBL	Within USBL range
Position (optional)	LBL	Within LBL range

For some of the parameters redundant measurements are provided.

3.6 Output from MARPOS®

When using MARPOS® as a stand-alone system the following performance is typically provided:

Output	Accuracy[1]	Operating requirement
Position (Lat/Lon)	3 m/hour[2] (CEP_{95})	Max altitude 30 m
Depth	0,05% FS (RMS)	
Altitude	1% (RMS)	Max altitude 30 m
Heading	0.03 degree (RMS)	
Roll/Pitch	0.03 degree (RMS)	
Horizontal velocity[3]	0.01 m/s (RMS)	Surface or max altitude 30 m
Vertical velocity[3]	0.01 m/s (RMS)	
Linear Acceleration	NA	
Angular Rates	NA	

[1] after heading alignment as described in the following section.

[2] Line survey, 1 m/s. This is equivalent with an accuracy of 0.1% of travelled distance.

[3] Either body frame velocities or Geographic frame velocities may be selected for output via EEPROM settings.

The standard system includes a programmable RS-232/422 interface. Output rate is selectable to a maximum of 100 Hz. Other interfaces, such as ethernet or CAN-bus, are optional. Output is programable in a user-defined protocol.

4. Operational procedures

This section describes the initialisation procedures required to obtain optimal performance. Initialisation is necessary to provide initial position, to perform heading alignment and to calibrate the sensors and their boresight alignment within the system. If MARPOS® is operating as a stand-alone positioning system the heading alignment can be carried out in three different ways:

- Stationary alignment (on land or dockside)
- GPS alignment (at the surface)
- Doppler alignment (max altitude 30 m)

Stationary alignment or GPS alignment are be performed prior to diving. Doppler alignment can be performed after diving to further improve the accuracy.

4.1 Stationary alignment

After switch-on MARPOS® enters heading alignment establishing its orientation with respect to the local gravity vector and the earth's axis of rotation.

Stationary alignment (on land or dockside) would typically require between 15 and 30 minutes depending on the geographic latitude. If required the stationary alignment could be carried out after diving by parking the vehicle on the seabed.

4.2 GPS alignment

GPS-alignment allows the system to North-align on a moving vehicle and to improve the accuracy because of the applied dynamic input that allows further refinement of the Kalman filter.

After launch from the mothership, the vehicle performs a prescribed navigation pattern at the surface. This process will establish the following information:

- Initial position at the surface (provided by the DGPS onboard the vehicle)
- Attitude (pith, roll, heading, i.e. vehicle orientation relative to the local gravity vector and earth's axis of rotation)
- Refinement of the sensor calibration

The optimum navigation pattern for the GPS alignment includes a "boxcar" manoeuvre consisting of 4 legs of straight lines with 90 degree turns every 5-10 minutes (a poor pattern would be a constant circular motion). GPS alignment may typically require up to 40 minutes.

Doppler calibration is an additional initialisation procedure that is required only if the DVL and the INS has been separated, or if the environment differs significantly from that of the previously calibration.

Once completed, the GPS alignment allows the vehicle to dive and initiate its operational mission without the need for continuous updating.

4.3 Doppler alignment

The purpose of the Doppler alignment is to improve the accuracy of the inertial heading and the DVL scale factor.

The Doppler alignment can recover a part of the "free inertial" drift during the dive and thereby reduce the error of the initial position after the dive.

If the mission starts with a site survey with repeated U-turns, the “lawnmower pattern” in itself will provide the same accuracy improvement as the Doppler alignment. Improving the heading accuracy by performing Doppler alignment is of particular interest for short line surveys where optimum gheading accuracy may eliminate the need for USBL tracking.

4.4 Doppler calibration

Doppler calibration is an additional initialisation procedure that is required if the DVL and the INS have been separated.

The Doppler calibration includes a combination of “boxcar” manoeuvres with different speed and length for each leg. This will allow the Kalman Filter to determine scale-factor and bias-errors of the DVL and compensate for any boresight misalignment between the INS and the DVL.

5. Error predictions

The positions provided by MARPOS® are calculated by dead reckoning (DR) relative to a reference point called IP (Initial Position, Figure 4). After establishing the IP co-ordinates (with an error called the IP-error) the vehicle is ready to approach the survey trajectory.

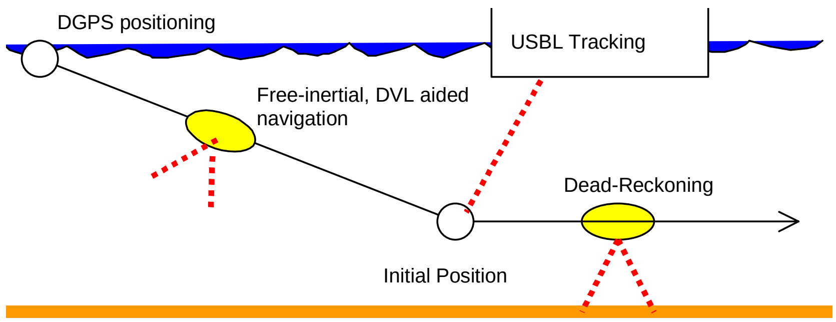

Figure 4: MARPOS determines positions relative to a reference point called IP

The error of a position relative to the IP is called the DR-error. The primary sources of the DR-error are heading error and Doppler scale factor error. The DR-error depends on the survey pattern as well as geographic latitude, updating intervals and the time available for apriori calibration of the system at the surface prior to dive.

The errors of the subsequent survey positions provided by MARPOS® (i.e. the Total Survey Error) will be a combination of the IP-error and the DR-error.

The IP co-ordinates can be provided by MARPOS® itself or via an update from an external source. The external source could be an acoustic positioning system (USBL) onboard the mothership or any feature with a known location at the seabed.

5.1 MARPOS® used as a stand-alone system

In-transit to the bottom MARPOS® utilises the less accurate “free-inertial” performance of the KN5053 with DVL aiding in water-track mode where appropriate. For extended dives the accuracy depends of the temporal and spatial variations of the sea current.

It is important to minimise the duration of "free-inertial" navigation by diving as fast as possible. As a rule of thumb the non-recoverable position error will increase by 1 m per minute until the DVL has established bottom contact. When the DVL has established bottom contact it automatically enters bottom-track mode whereby much of the accrued drift error will be eliminated.

The selection of the DVL for MARPOS® is a trade-off between low IP-error and low DR-error,

- The 1200 kHz DVL selected for the prototype MARPOS gives the lowest DR-error (0.15% of travelled distance). It requires less than 30 m altitude to achieve bottom track mode.
- The optional 600 kHz DVL gives a higher DR-error (0.3% of travelled distance). It can achieve bottom contact at a higher altitude (90 m) thereby reducing the IP-error by 1 m (assuming the free inertial time is reduced by one minute).
- The 300 kHz DVL can measure bottom referenced velocity at an altitude of up to 200 m but is probably less accurate and consume more power.

5.2 MARPOS® used in combination with USBL

The IP-error increases with the water depth. For deep surveys the IP can be determined by positioning MARTIN from the mothership using a USBL system (for example Simrad Hipap (ref. 5).

Having established an accurate IP, MARPOS® can be used as a stand-alone positioning system providing very low DR-errors.

5.3 MARPOS® use in combination with LBL

If the survey lines are very long (several kilometres) or if the site survey is continued over the maximum period within a battery cycle (typical 12 hours) it may be necessary to bound the error growth by integrating the MARPOS® system with an LBL system. This would bind the error to the error of the LBL system (typically 1 m).

5.4 Site surveys

For a site survey (bathymetry, sub-bottom profiling, etc.) most of the systematic error growth will cancel out due to the geometry of the survey pattern. Furthermore, the inherent dynamic input provided to the Kalman filter by the U-turns continuously calibrates the MARPOS® system. Therefore, the error drift will be extremely low and **MARPOS® can be used as a stand-alone sensor for site surveys without the need for a continous LBL (long baseline) acoustic positioning system**.

5.5 Line surveys

Line surveys are carried out frequently for inspection of cables (for damage) or pipelines (for free span). The accuracy is heavily dependent on the calibrated DVL scale factor for "along track" error and the residual inertial heading for "cross track". The predicted performance will depend upon the type and quality of additional information available as described in the following examples:

Correlation with Pipeline Position

If the distance between discernible features on the pipeline are known with respect to each other these points can be used as relative position fixes to aid the real time calibration of the sensors and bound error growth. The resultant accuracy of the solution will be dependent on the scale factor of the relative position (i.e. the relationship between the distance and the accuracy with which it is known).

Periodic Updates from the mothership

For a long survey (typically 100+ km) it is assumed there will always be a mothership within 2 km from the vehicle. It is thus assumed that a periodic USBL position fix can be transmitted to the vehicle to eliminate accrued error growth. The combination of MARPOS and a USBL system is expected to provide unsurpassed accuracy deep water surveys.

6. Sea tests

A test program has been carried out to verify the positioning accuracy under different operating conditions. All tests were carried out in shallow water with MARPOS® one metre below the surface where DGPS could be used as independent instrumentation to verify the accuracy provided by the MARPOS® system. Throughout the test MARPOS® and DGPS data are time tagged and stored for further analysis.

6.1 Site surveys

This section shows a representative example of MARPOS® accuracy when used for site surveys. The trajectory is a 750x750m “lawnmower” pattern with a line spacing of 50 m preceded by a small 150x250m trajectory with a line spacing of 10 m (Figure 5).

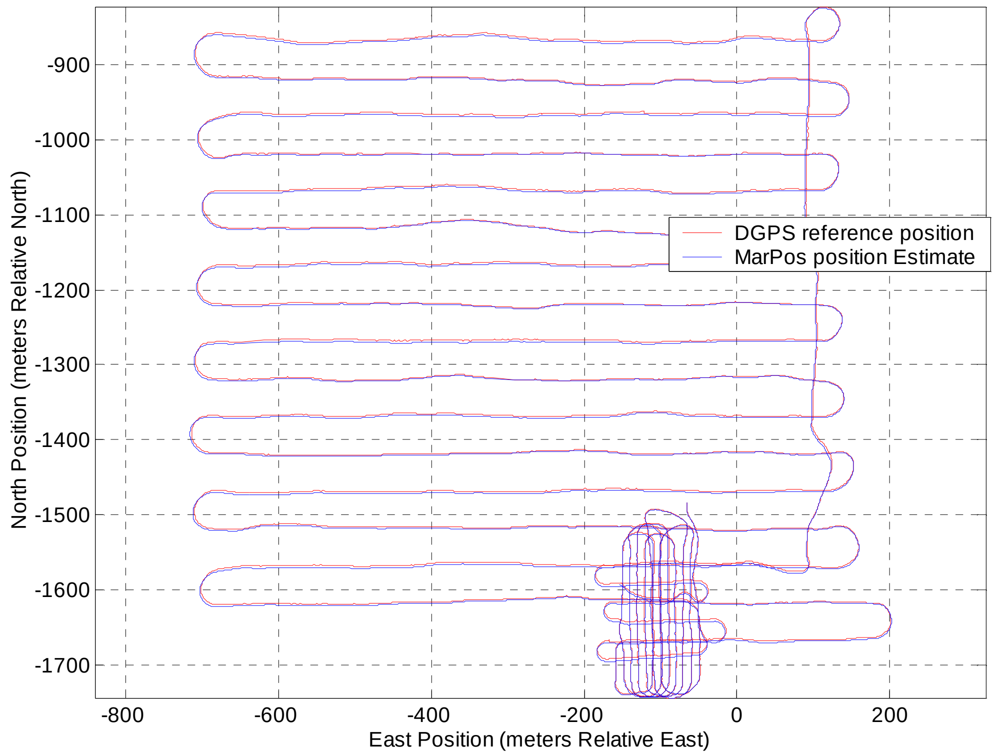

Figure 5: Site survey trajectory

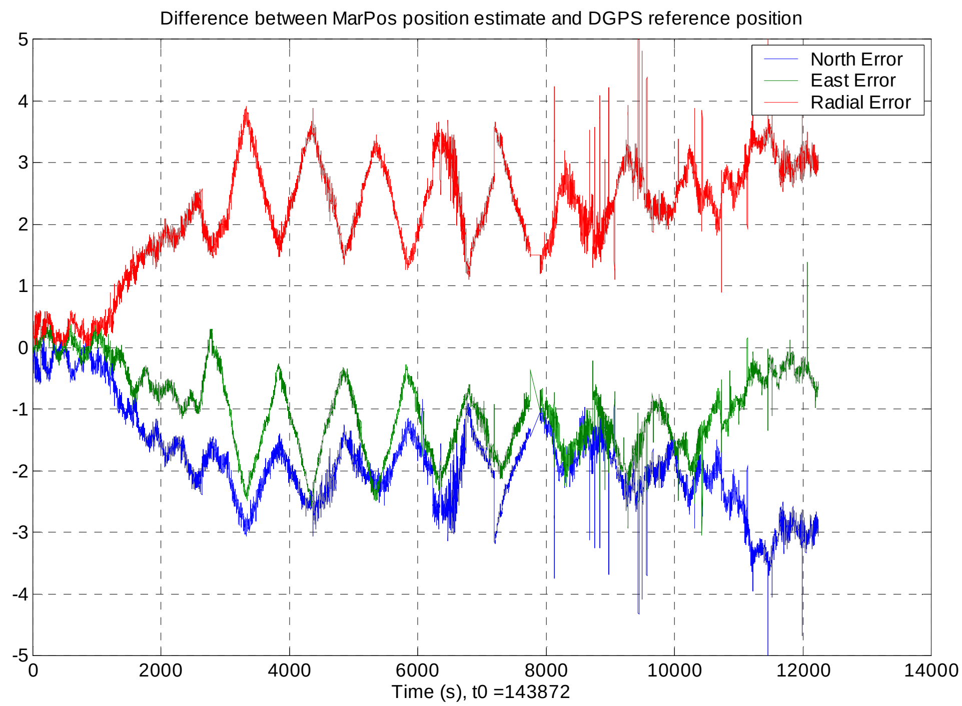

Figure 6: Site survey. Error growth vs. time

The duration was 3h 20 min and the total distance travelled ~20 km. Figure 6 shows the position error as a function of time. The position error at the end of this survey was ~3m, equal to ~ 0.015% of distance travelled or 0.9m/hour.

The actual survey trajectory is not important, as long as the distance from the origin is small compared to the total distance travelled. When the survey is confined to a restricted area some of the most important sources of position error cancel out due to geometry. This is why site survey accuracy is usually better than the accuracy of comparable length line surveys.

6.2 Line surveys

As a representative example of the high accuracy obtained by MARPOS® as a stand-alone positioning system the results of a 14-km line survey is shown (Figure 7: Line survey trajectory). The path generated by MARPOS® was compared to the path generated by an independent DGPS reference.

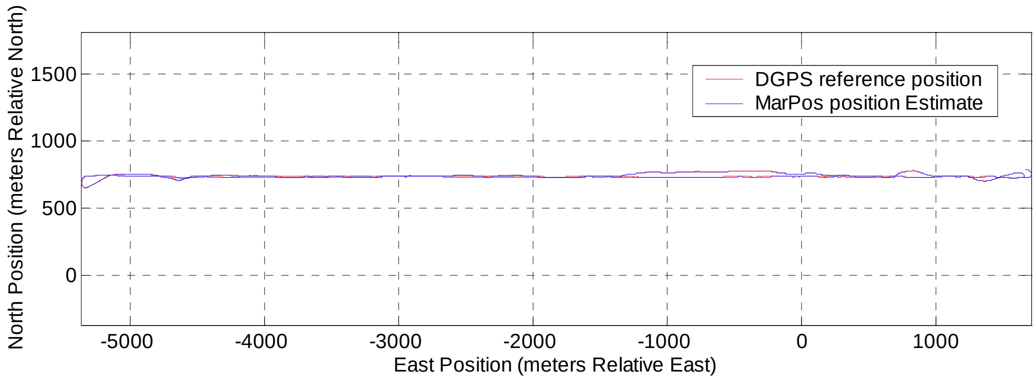

Figure 7: Line survey trajectory

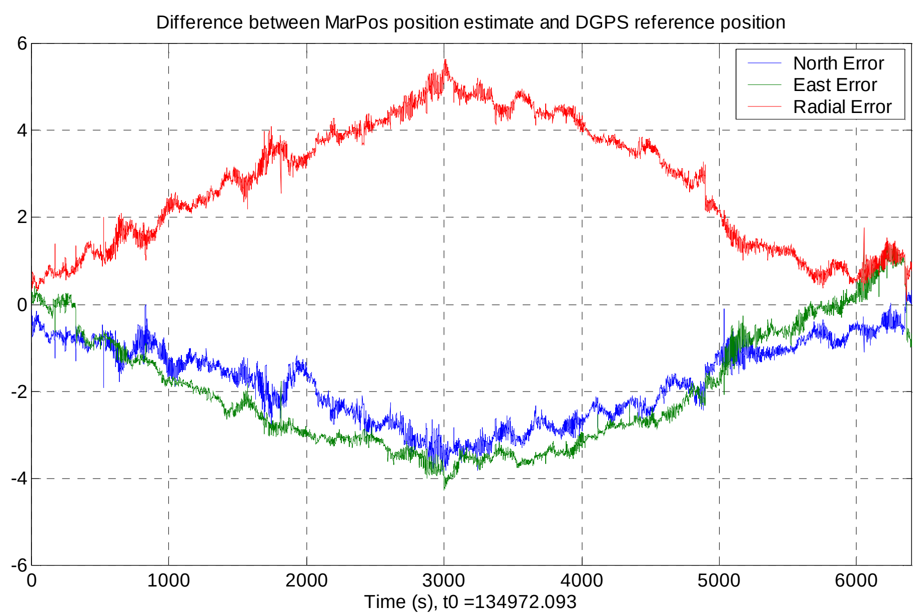

Figure 8: Position error vs. time for a 14-km line survey

After navigating along a 7 km straight line and back the accumulated survey error was ~1 m with respect to the DGPS reference (<0.01% of distance travelled), Figure 8. At the turning point the position error was 5m (~0.07% of distance travelled). The high frequency noise is caused by scatter of the DGPS reference positions and not by MARPOS, which is much more accurate than DGPS in short term.

6.3 Summary of sea test results

A total of six site surveys and three line surveys has been performed. There has been some indication that wave induced roll and pitch motion has negative influence on performance. Thus the results should be regarded as a conservative estimate of MARPOS® accuracy when used in an AUV. The tests were performed at typical AUV velocities ranging from 1.2 - 2.2 m/s using a small surface vessel.

Line Survey	**Travelled Distance (TD)**	**Max radial position error (CEP)**	**CEP / TD (%)**
SL990815*	8 km	17 m	0.21%
SL990817	7 km	5 m	0.071%
SL990824	7.5 km	2 m	0.027%
		$\mu \approx$ CEP50**	**0.10%**

* Very bad weather causing strong wave motion. Since a small surface vessel was used for the test, the wave motion may have degraded performance significantly.

** Assuming the max radial position error follows a Rayleigh distribution

Site Survey	**Travelled Distance (TD)**	**Max radial position error (CEP)**	**CEP / TD (%)**
NT981124	16 km	4 m	0.025%
NT990818	13.2 km	6 m	0.045%
NT990821	25 km	6 m	0.024%
NT990822	20 km	4 m	0.020%
NT990825	22.4 km	3 m	0.013%
NT990826	15.4 km	5 m	0.032%
SL990817*	14 km	1.5 m	0.011%
SL990824*	15 km	3 m	0.020%
		$\mu \approx$ CEP50**	**0.024%**

* Starting point repeatability of straight line test used, i.e. position error after returning to the origin.

** Assuming the max radial position error follows a Rayleigh distribution

The results of the sea tests are summarised in the following table:

Max. position error (CEP50) during survey	Error (% of Travelled Distance)	Error growth at survey speed 1.5 m/s	Error after 10 km survey
Line Survey	0.10%	5 m/hour	10 m
Site Survey	0.024%	1.3 m/hour	2.4 m

7. Conclusion

MARPOS® is a high-accuracy doppler-inertial positioning system developed by Maridan for it's Autonomous Underwater Vehicles MARTIN® but having direct applications also for tethered deep-sea vehicles (ROV's and ROTV's).

MARPOS® can be used as a stand-alone positioning system or it can be used in connection with external positioning systems such as USBL and LBL.

A sea test program has been carried out to verify the accuracy under different operating conditions. The results are indicated in section 0. The table can be used to predict the positioning accuracy for specific surveys.

8. References

1. AUV technology, Maridan, September 1998 (Internal report)
2. MARPOS specifications. Statement of Work, Maridan, (October 1997, internal report, under revision).
3. Interface Control Document for integration of the SEANAV ICD in MARPOS, Kearfott (August 1997, internal report, under revision).
4. Acoustic Doppler Current Profilers, RD Instruments, October 1996.
5. Simrad HIPAP USBL, ref. Hydro International July/August 1998, Vol 2, No 5.

9. Glossary

Ring-laser gyro(RLG)	Non-mechanical gyro for high-precision angular rate measurements
Inertial Measurement Unit(IMU)	Motion sensor including 3 gyros and 3 accelerometers
Kalman Filter	Statistical method often used to minimise the error when combining input from multiple sensors (sensor fusion).
Inertial Navigation System (INS)	Navigation instrument including an IMU and a Kalman filter

Strapdown INS	INS with “no moving parts” (unlike gimballed gyro-stabilised Inertial Platforms that are kept horizontal in moving ships)
Doppler Velocity Log (DVL)	Speed sensor based on measuring the Doppler frequency shift of the echoes from 3 or 4 acoustic beams
MARPOS®	Integrated positioning system including a strap-down INS and a DVL
Dead Reckoning (DR)	Positioning relative to a known starting point
Free Inertial Navigation	Dead reckoning using the INS without the DVL).
Doppler Aided Inertial Navigation	Dead reckoning using the INS together with the DVL.
Acoustic transponder	Unit to be located at the seabed with a transducer that responds by sending a ping when activated by a ping.
Ultra-short baseline (USBL)	Acoustic positioning system based on a single transponder mounted on the object to be positioned. The transponder can be tracked from a surface vessel.
Long baseline (LBL)	Acoustic positioning system based on a spread of seabed transponders.