ATLAS Research Project

SUMMARY of RESULTS

30-SEP-2014

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Principal Investigator: Francisco José Curado Mendes Teixeira
Principal Contractor: Universidade de Aveiro
Participating Institution: Instituto Superior Técnico
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COMPETE
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1. High-resolution bathymetry and magnetometry

1.1. Task objectives and expected results

The objective of this task is to produce the reference maps that are used in the theoretical studies, computer simulations, and experimental trials of geophysical navigation. The expected output is the production of high-resolution bathymetric maps and high-resolution magnetic data maps (total field and gradients) of a test site.

1.2. Work developed and results obtained

The site chosen for the project tests is a shallow-water lake with an area of approximately 300m*200m located at *Doca do Oceanário* in *Parque das Nações,* Lisbon; see **Fig.1**.

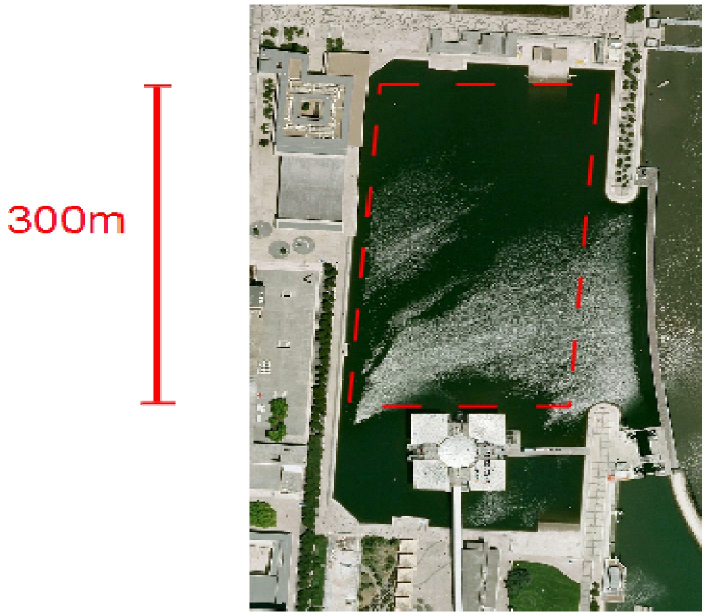

Fig.1: Aerial view of the experimental test site located at *Doca do Oceanário* in *Parque das Nações,* Lisbon.

The availability of this site, which is easily accessible by land and located close to other IST facilities, was an important contribution to the project given the good conditions of operation in the water at the area, even with adverse weather conditions. The logistics necessary to start operating at the site were more complicated than expected initially because the lake can only be accessed by land. This limitation made particularly difficult the deployment of the boat used for one the main bathymetric survey, imposed an additional cost to the survey, and delayed the start of some tasks. The following is a list of the main activities performed and the results obtained with this task:

- A preliminary bathymetric survey of the test site was performed using the range measurements provided by a Doppler velocity logger (DVL) which is also the instrument proposed to implement terrain-aided navigation of the AUV. The objective of this survey was to assess the interest of the trial area for GN tests. Although DVL systems are not normally employed to execute bathymetric surveys, it was relevant to explore this possibility, given the versatility of these systems, their relative low cost, and their widespread employment in marine robotic vehicles. The data obtained with the DVL had to be processed for filtering of outliers and other artifacts, prior to map building. This bathymetric survey is documented in the Technical Report [1] and the associated signal processing tasks are documented in the Technical Report [2] ; see the localization of the survey trajectories in **Fig.2** and the preliminary map obtained in **Fig.3**.

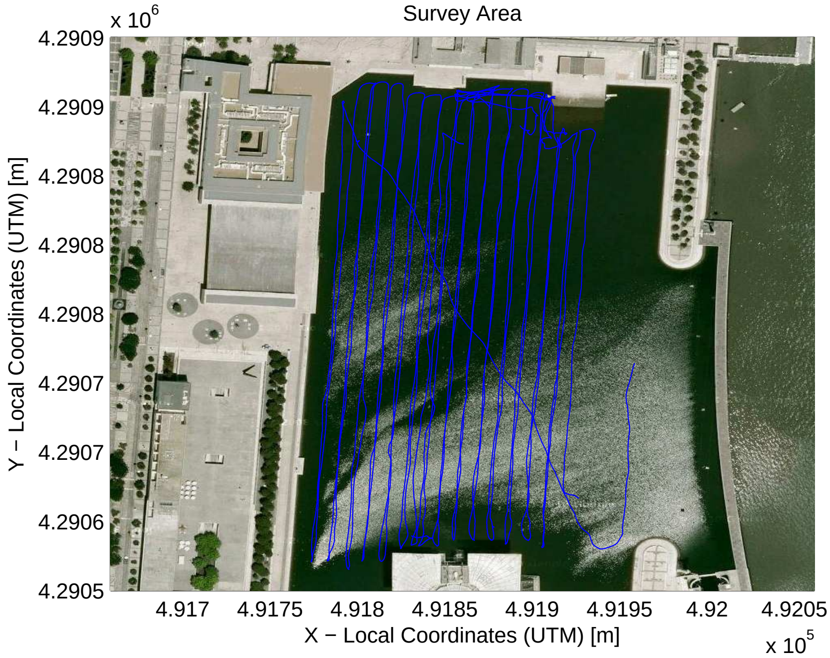

Fig.2: Trajectories used for bathymetric data acquisition with the Doppler at the test site.

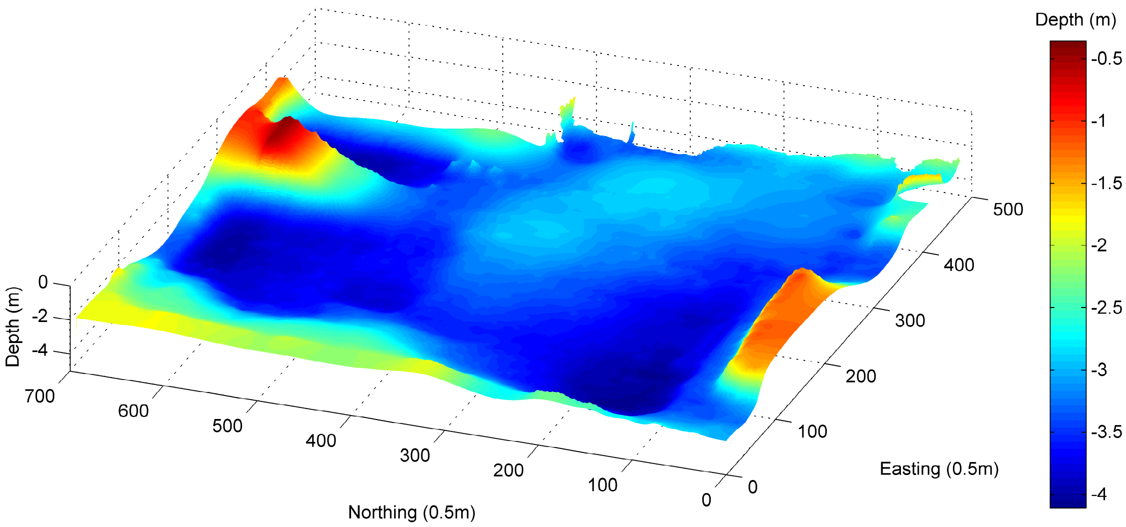

Fig.3: Bathymetric map acquired with the Doppler at the test site.

- Given the promising results of the first survey, a second bathymetric survey was performed with a very high-resolution multi-beam sonar to obtain the reference maps used in navigation; see **Fig.4**. This map involved substantial work of signal processing that is documented in the Technical Report [3].

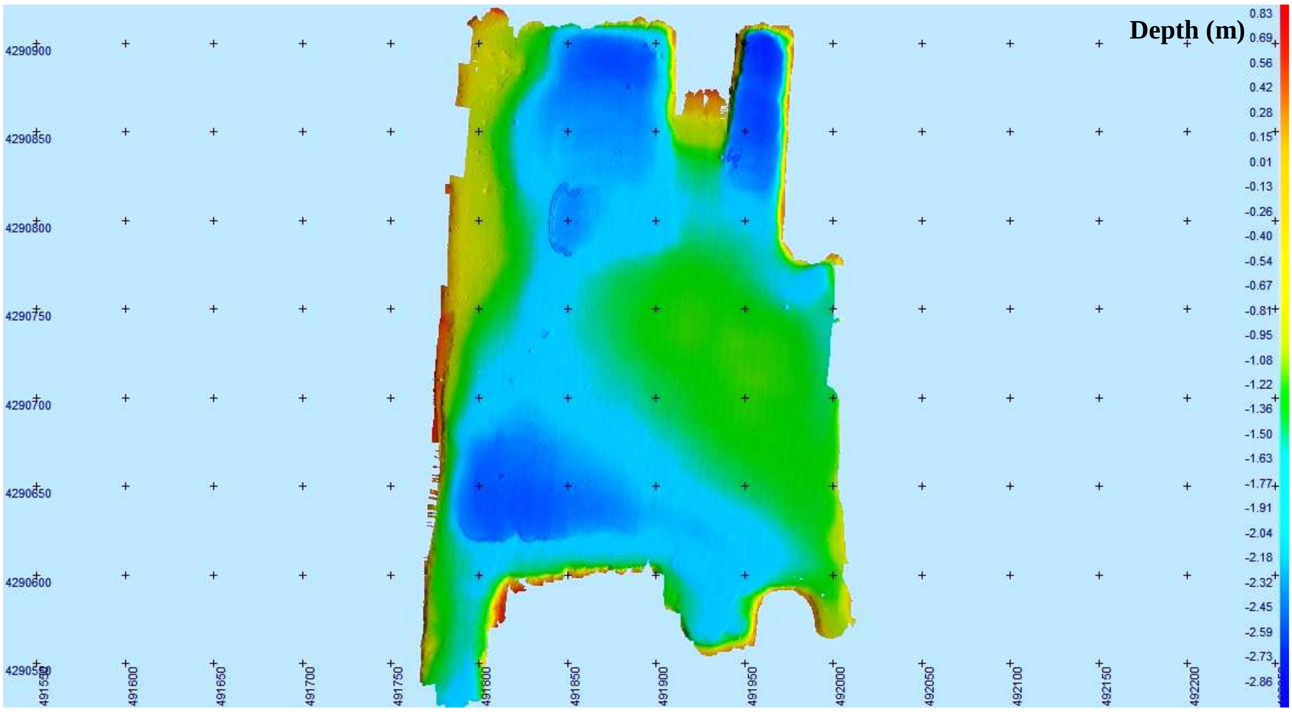

Fig.4: High-resolution bathymetric map of the test site acquired with a multi-beam sonar (UTM Northing and Easting coordinates in meters).

- A preliminary total field magnetic high-resolution map was also acquired in the test area; see the survey trajectories in **Fig.5** and the final map produced in **Fig.6**. It was planned to survey this site later with magnetic vector gradiometers to support the tests of new navigation algorithms based on magnetic gradient data.

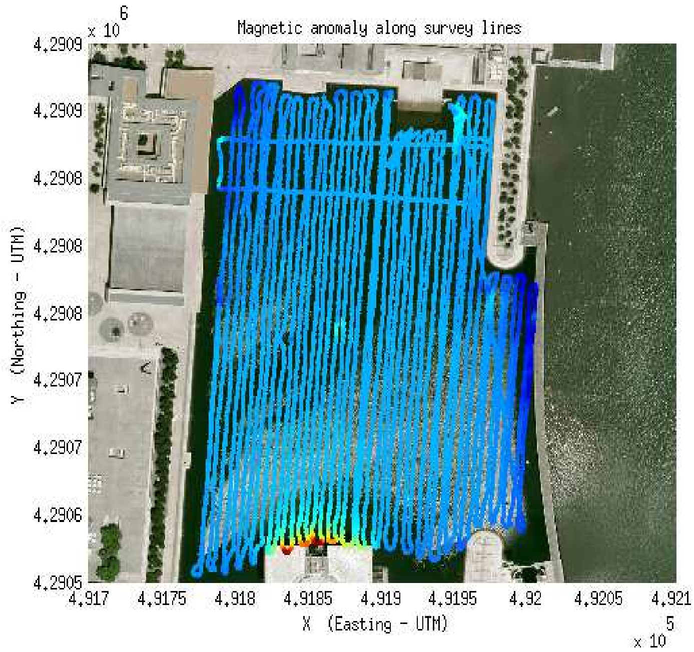

Fig.5: Magnetic survey performed with a scalar magnetometer at the test site and preliminary profiles of the magnetic anomaly observed. A second, identical scalar magnetometer was used as a base-station to allow for correction of diurnal variations of the Earth's magnetic field.

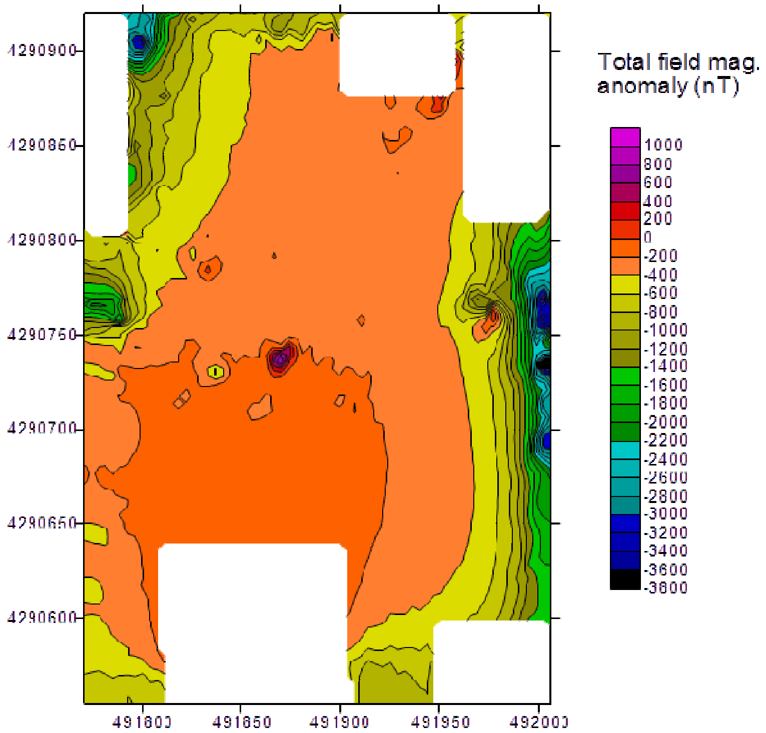

Fig.6: Magnetic anomaly map of the trial site. Some areas are blanked in the map since they are not useful in terms of geophysical navigation and their high amplitude prevents showing enough detail in the areas of interest.

2. Simulation of Geophysical Navigation and map assessment

2.1. Task objectives and expected results

The objectives of this task include: tuning the navigation algorithms and assessing their efficiency in simulations with real bathymetric data; studying the requirements of the geophysical navigation algorithms in terms of map resolution and accuracy; evaluating the survey and map requirements for GN in terms of terrain information, spatial resolution and measurement accuracy, and establishing efficient methods for representation of maps used by the GN subsystem. The results expected consisted of a suite of refined algorithms for GN, the specifications for accuracies and spatial resolutions of the prior maps, and quantitative measures of performance of GN algorithms.

2.2. Work developed, results obtained, and publications

This work relied essentially on computer simulations where the navigation algorithms developed have been applied to real geomagnetic data. The main results have been presented at international conferences and published in conference proceedings with peer review [4-7]. The superior performance of the estimation algorithms developed for geophysical navigation is illustrated in **Figs.7** and **8**, which show the estimation errors obtained by the novel algorithms (MPF and PPF) and the conventional (SISR) navigation methods compared with the theoretical lower bound (CRLB) obtained in simulations with real data as reported in [6]. **Fig.9-a-b** puts also in evidence some fundamental properties of the new methods in terms of robustness to terrain symmetries and measurement outliers that constitute the main cause of failure of the conventional navigation filters. The main developments and the results of this task were:

- Test and performance evaluation of novel navigation algorithms based on Monte Carlo methods (Particle Filters).
- Specifications of maps required for GN.
- A new data fusion method for integration of conventional dead-reckoning methods using Doppler velocity measurements with terrain-based localization based on DVL range measurements.
- Research on alternative navigation methods that integrate bathymetric terrain navigation with complementary sources of information for precise localization [8].
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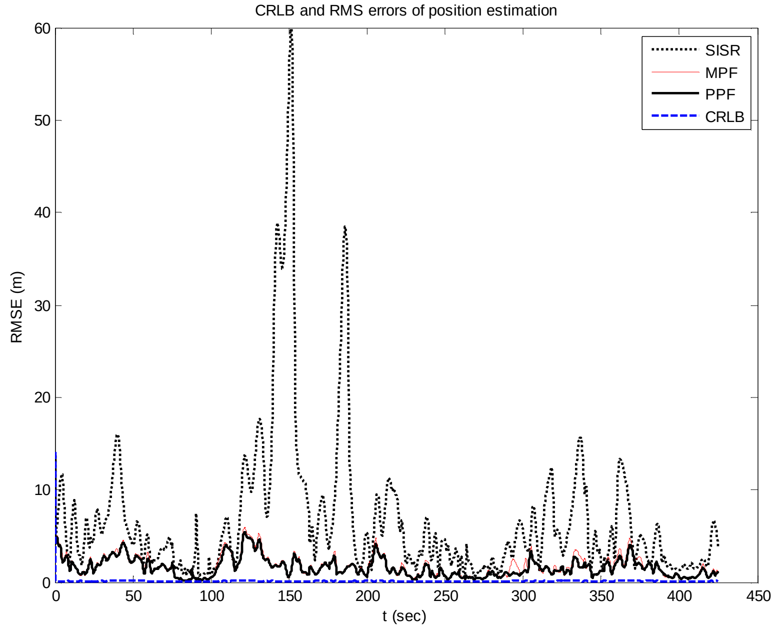

Fig.7: Position estimation error obtained by the new (MPF and PPF) and the prior (SISR) navigation methods compared with the theoretical lower bound (CRLB) obtained in simulations with real data.

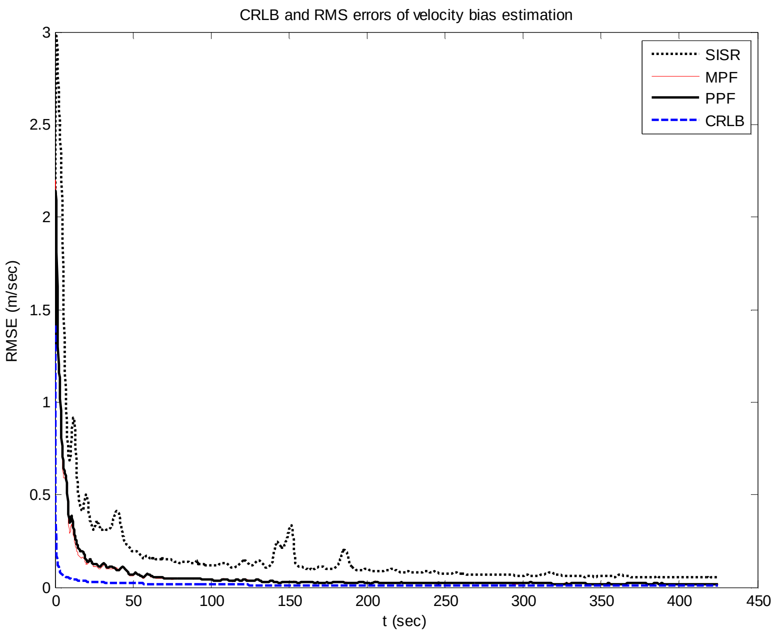

Fig.8: Velocity (bottom) estimation error obtained by the new (MPF and PPF) and the prior (SISR) navigation methods compared with the theoretical lower bound (CRLB) obtained in simulations with real data.

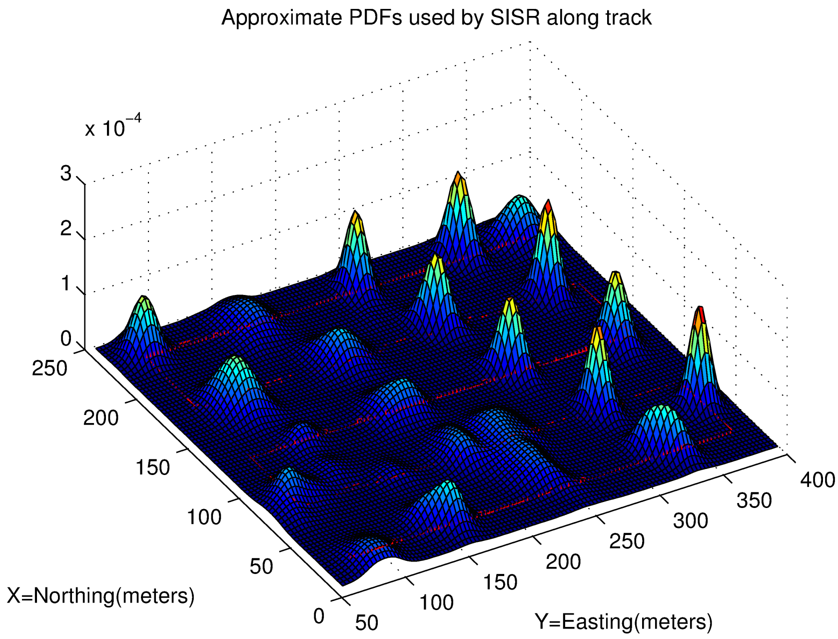

Fig.9-a: Probability density functions (PDFs) used by the standard Particle Filter SISR. Compare with the following figure and notice the biased estimates and much larger uncertainty of the standard filter SISR shown here that is caused mainly by terrain symmetries and areas of flat terrain to which the PPF proves to be very robust.

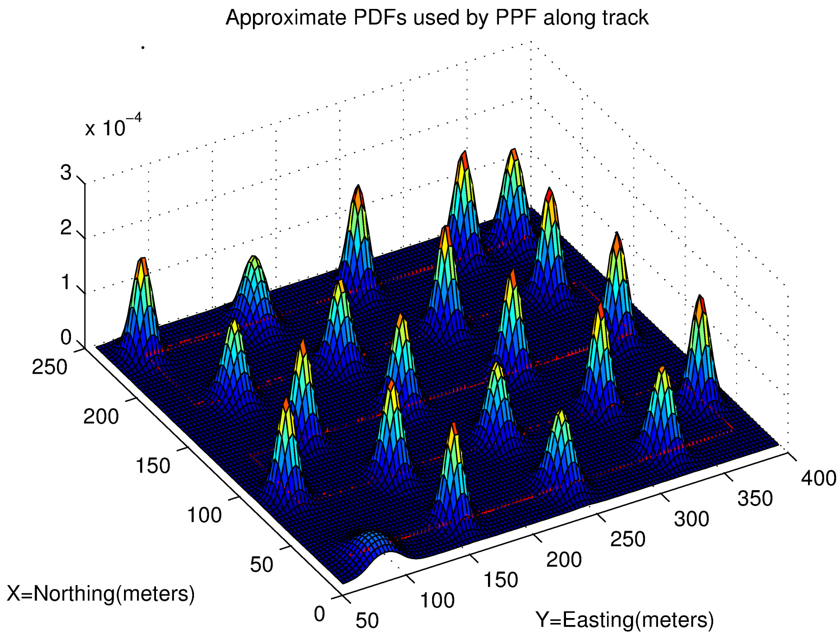

Fig.9-b: Probability density functions (PDFs) used by the novel PPF filter.

3. Sonar sensors' setup

3.1. Task objectives and expected results

The objective of this task was to install and test a suite of sonar sensors to perform trials of Geophysical Navigation at sea with the AUV. It was decided to make all the experimental tests in an initial phase in enclosed, shallow waters. The project proposed to use a Doppler velocity logger (DVL), which is a standard navigation sensor in many underwater robotic vehicles, as the main sonar system for the acquisition of altitude data, instead of using dedicated sensors for that purpose; see **Fig.10**.

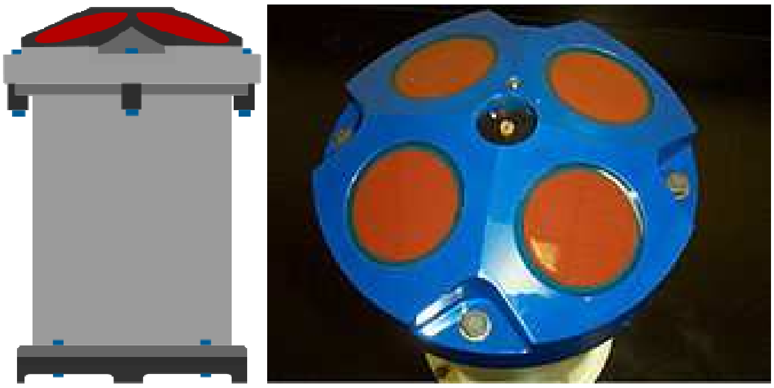

Fig.10: Side view diagram (left) and head view (right) of the Doppler velocity logger (DVL) used in the tests of geophysical navigation. Notice the arrangement of the four sonar transducers which allow for the acquisition of 4 simultaneous range measurements.

3.2. Work developed and results obtained

The robotic platform used in the experimental tests is an autonomous vehicle of the class *Medusa*, developed by the Institute for Systems and Robotics of Instituto Superior Técnico. The *Medusas* can be configured as autonomous surface vehicles (ASV) or autonomous underwater vehicles (AUV). The ASV configuration includes an external GPS antenna that can be used to track the vehicle using real-time kinematics (RTK) GPS; see **Fig. 11-a-b**. It is worth noting that the GPS data collected by the ASV in these tests is used only for ground-truthing, i.e., for comparison of the real localization of the vehicle with the position estimated by the navigation algorithms, in order to assess the performance of the GN software. The DVL was used for terrain navigation as proposed. The vehicle has also installed a sonar altimeter which can be used to implement a low-cost GN system which explores complementary sources of positioning data such as magnetometry or range measurements provided by fixed-position single-beacon; see the work reported in [8] and consult the last Section of this report for details.

The acoustic system used to acquire the altimetry data required by the TAN algorithms is a LinkQuest NavQuest 600 Micro Doppler velocity logger with a classical Janus four beam configuration. This DVL is a relatively inexpensive system which is installed as a standard navigation instrument of the *Medusa* ASV. Besides providing velocity measurements used for dead-reckoning, the unit can acquire four depth measurements at each ping, with an approximate accuracy of 10cm; the DVL is also equipped with a motion sensor which provides relatively noisy measurements of the sensor attitude. An additional motion reference unit, that provides more accurate measurements of attitude and angular velocities, is installed on-board the vehicle: a VectorNav VN-100 Inertial Measurement Unit (IMU) and Attitude Heading Reference System.

The configuration implemented allowed to obtain the expected results which consisted of:

- A functional sonar sensor suite installed in the AUV.
- An experimental dataset collected with the sensors installed in the vehicle that permitted their characterization in terms of resolution and accuracy.

These results were fundamental for the execution of realistic simulations and the subsequent experimental work in the water.

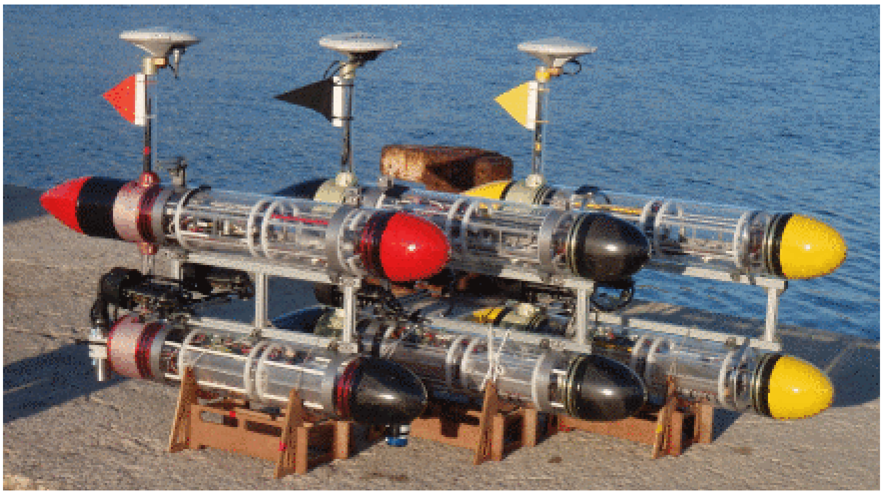

Fig.11-a: Medusa ASVs ready for deployment at the test site in Lisbon.

Fig.11-b: Medusa ASV in the water at the test site in Lisbon.

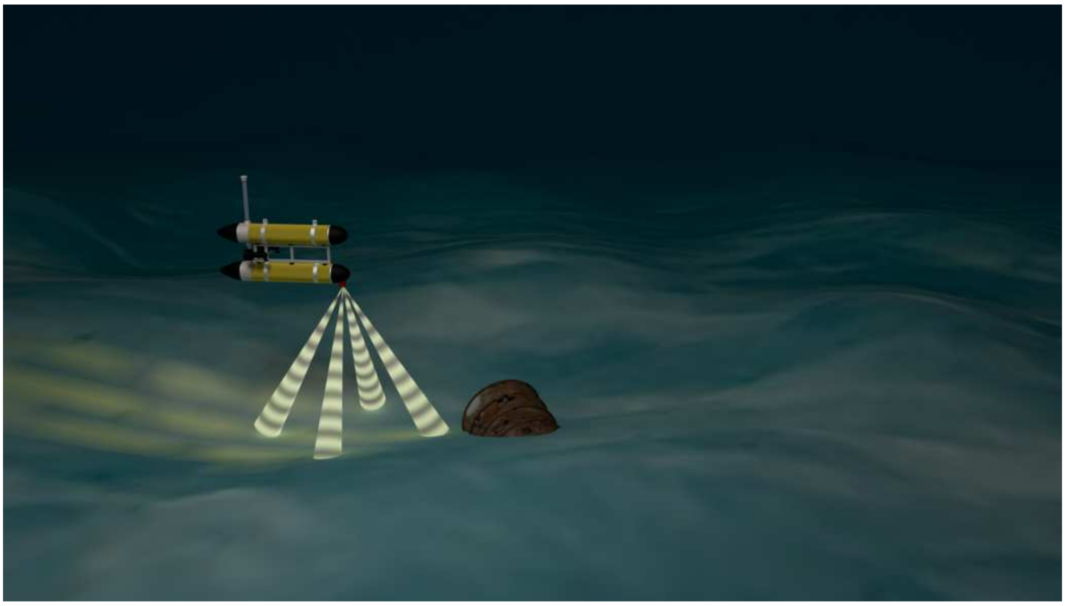

Fig.12: Terrain Aided Navigation using a Doppler velocity logger.

4. Integration of GN with GNC subsystems

4.1. Task objectives and expected results

The objective of the task is to integrate the geophysical navigation system with guidance, navigation, and control systems installed in the vehicle.

4.2. Work developed and results obtained

The navigation software developed for simulations using Simulink/Matlab has not been tested experimentally in the real vehicle due to limitations of time but has been converted to a modular architecture that can easily be integrated in the guidance, navigation, and control (GNC) system of a real AUV; the architecture of the software is depicted in **Fig.13**. One of the main advantages of this modular TAN package is the possibility of using a simulator (see Physical System blocks in Fig.13) to replace the real system including the vehicle and the sensors. To validate its functionality in a real application, this software package was used to test the navigation software with the real data acquired by the ASV Medusa, as described in Task B.3.

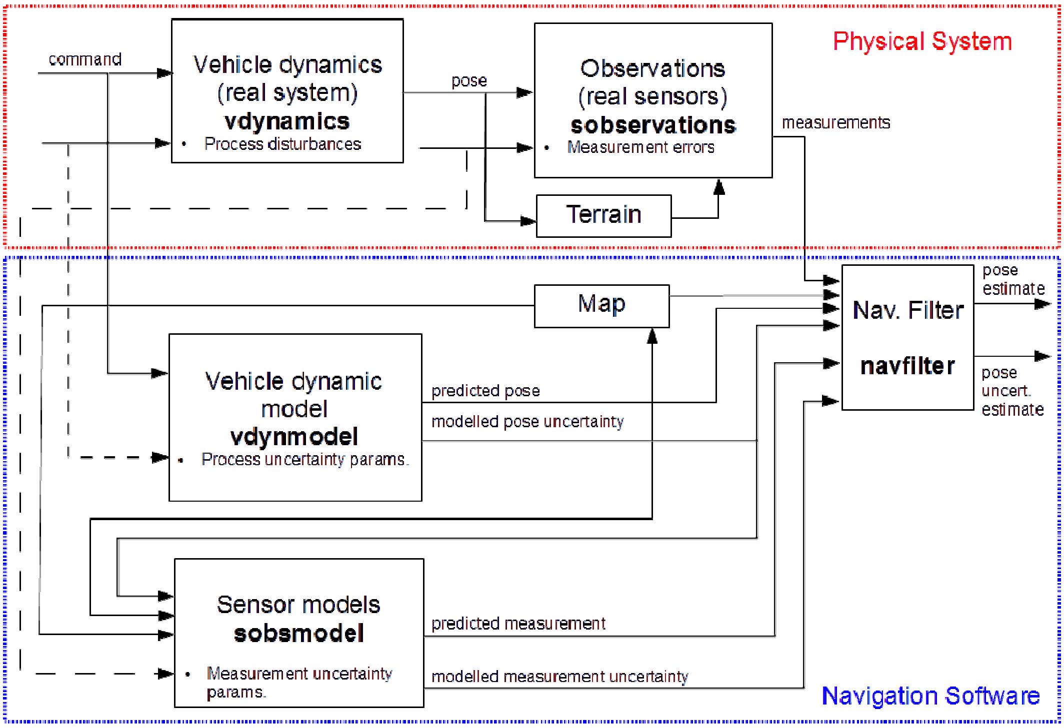

Fig.13: Architecture of the Geophysical Navigation software used in simulations, ready for integration in the AUV.

5. Sea trials of Geophysical Navigation

5.1. Task objectives and expected results

This task aimed at testing geophysical navigation based on bathymetric information using an actual autonomous robotic vehicle in a real environment. As the result of this task it was expected to characterize the different subsystems used in the tests in terms of accuracy and resolution, including the navigation transducers - Motion Reference Unit (MRU) and DVL - and the sonar sensor suite installed in the AUV. As the final result it was expected to derive quantitative measures of performance of geophysical navigation in real applications.

One of the main expected outcomes of the project was the implementation of terrain-aided navigation of AUVs using standard navigation sensors and relying on affordable sonar equipment for real-time acquisition of bathymetric data. For online acquisition of altitude data it was proposed to use the range measurements provided by a Doppler velocity logger which is a standard instrument used for dead-reckoning navigation in underwater robotics. To complement the information provided by the DVL, the proposed GN implementation exploits the attitude measurements acquired by a standard, inexpensive motion sensor installed in the vehicle. The project aimed also at assessing the efficacy of GN methods in different underwater scenarios, including low-informative terrains. The site chosen for the project tests is ideal to assess the real efficacy of the proposed methodology in these conditions. Actually, the trial scenario presents essentially a flat-bottom surface where the execution of terrain-based navigation becomes a considerable challenge.

5.2. Work developed and results obtained

Due to budget limitations it was not possible to make tests at sea as planned but the principal objective of the task was achieved using the confined aquatic environment, the trial site at *Parque nas Nações*, described in Task A.1. This site is very convenient for trials that require repeated operations of deployment and recovery of equipment from the water by human operators, due to the existence of a wide, gently sloping ramp that facilitates the access to the lake. The experimental tests were conducted with the autonomous surface/underwater vehicle *Medusa* described in Task B.1. **Fig.14** represents the paths followed by the vehicle in these trials as tracked by the RTK-GPS receiver installed on board.

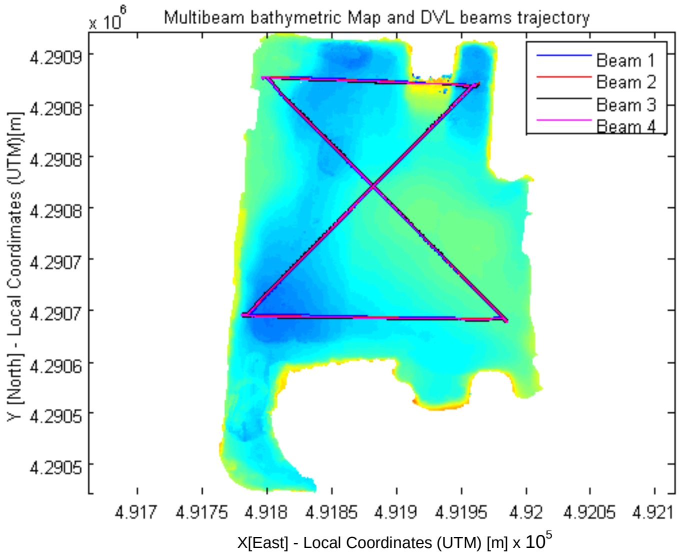

Fig.14: Trajectories of the experimental trials executed by the ASV Medusa at the test site, superimposed on the bathymetric. Notice that each trajectory comprises four simultaneous records of altitudes measured by the four beams of the DVL. The results obtained with this trajectory are illustrated in the following figures.

The data collected in real-time by the vehicle included:

- High-precision global positioning data obtained with GPS-RTK
- Attitude data supplied by two, distinct Motion Reference Units (MRUs)
- Ground-referenced 3-D velocity supplied by a Doppler Velocity Logger (DVL)
- Measurements of altitude relative to the sea-bottom supplied by the DVL (a set of four simultaneous measurements of altitude are supplied by the DVL).

The localization data acquired by the vehicle in real-time using GPS-RTK was used for ground-truthing of the estimate localization obtained by the navigation algorithms. The ground-referenced velocity data acquired by the Doppler and the attitude data acquired by the motion sensors were used for dead-reckoning which is integrated in the GN methods. The altitude measurements supplied by the DVL were obtained in real time by a transformation of the corresponding set of range measurements, using the angles of attitude measured by the Doppler. Given the poor quality of the attitude measuring unit integrated in the DVL, these measurements are corrupted by noise of significant magnitude and is preferable to use an external MRU to obtain the angles of attitude that are used to convert ranges to altitude. As such, it is necessary to invert the transformation implemented by the DVL to recover the original range measurements and to compute a more accurate set of altitude data using the external MRU.

The data obtained in these trials with the *Medusa* ASV using the same sensor suite that is envisioned for practical applications, permits to assess very accurately the efficacy of the navigation methods implemented in the project. The raw altitude data acquired by the vehicle in real time is represented by the profiles shown in **Figs.15a-c**. It is compared in the plots with the profile extracted from the prior bathymetric map obtained with the DVL for the same path. The results plotted show a very good correlation between the data acquired by the vehicle and the prior map, and are indicative of the potential of the proposed method to implement geophysical navigation in a real underwater environment. These data, integrated with the velocity and attitude measurements acquired by the vehicle, have been applied to the navigation filters developed to assess the real performance of the geophysical navigation system implemented. The excellent results obtained, which are described in the sequel, are included in a journal paper which has been submitted recently to the International Journal of Adaptive Control and Signal Processing (Wiley) [9].

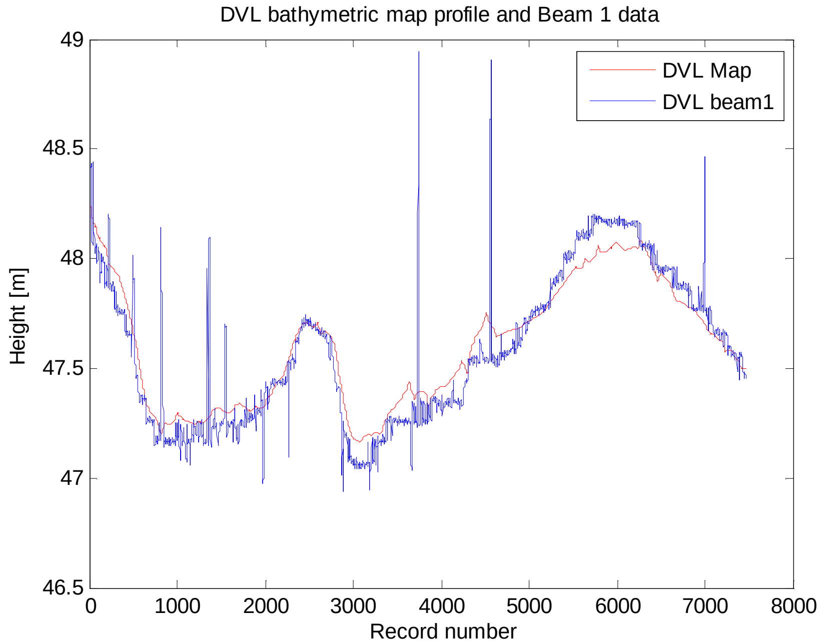

Fig.15-a: Profile of altitudes (expressed in WGS84 datum) measured by DVL beam#1 during the tests with the Medusa ASV along the path shown in Fig.14, superimposed on the corresponding profile of the reference map.

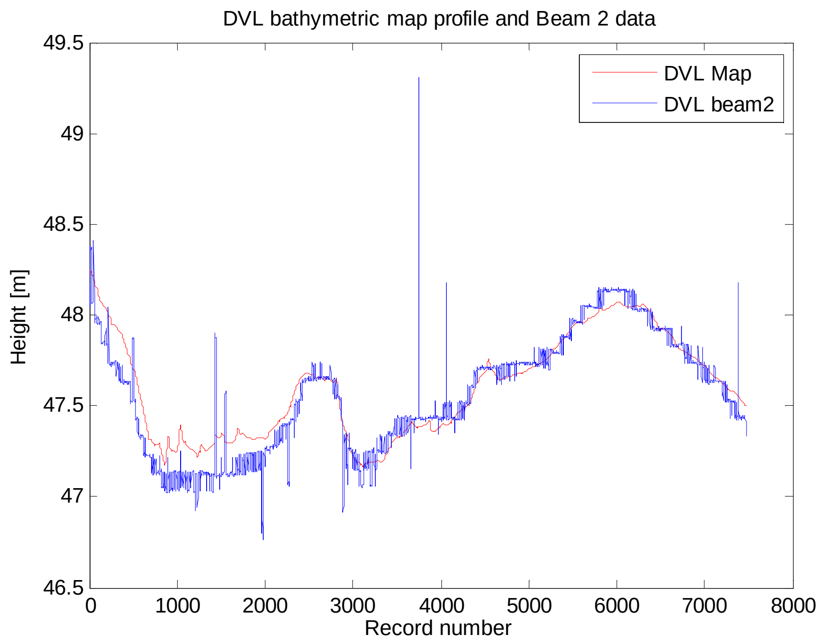

Fig.15-b: Profile of altitudes (expressed in WGS84 datum) measured by DVL beam#2 during the tests with the Medusa ASV along the path shown in Fig.14, superimposed on the corresponding profile of the reference map.

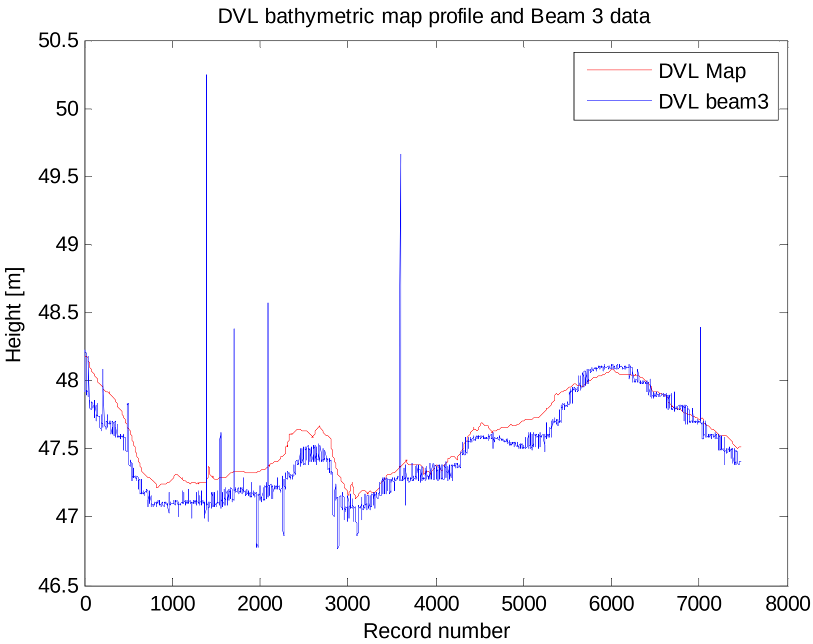

Fig.15-c: Profile of altitudes (expressed in WGS84 datum) measured by DVL beam#3 during the tests with the Medusa ASV along the path shown in Fig.14, superimposed on the corresponding profile of the reference map.

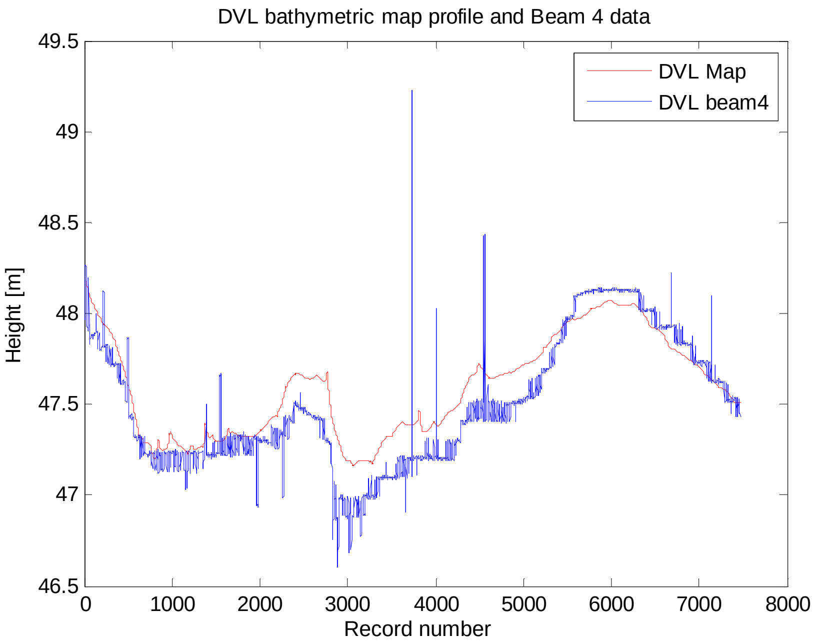

Fig.15-d: Profile of altitudes (expressed in WGS84 datum) measured by DVL beam#4 during the tests with the Medusa ASV along the path shown in Fig.14, superimposed on the corresponding profile of the reference map.

To illustrate the performance achieved in the geophysical navigation trials, we present in the next Figures a graphical representation of the main results. A comparison of the real path followed by the vehicle with the two trajectories estimated by conventional dead-recknoning navigation using the distinct motion sensors can be seen in **Fig.16**. The results illustrated in this figure show clearly the poor performance achieved by the classical navigation methods with standard navigation sensors; these results justify the implementation of more advanced, but equally affordable, navigation solutions such as GN which is experimented in this project.

The trajectory estimated by the GN filter based on the velocity and the noisy attitude data provided by the DVL is plotted in **Fig. 17**. In this figure, the true trajectory and the dead-reckoning estimate can be easily compared. The magnitudes of the GN and dead-reckoning localization errors are plotted in **Fig. 18**. Careful analysis of these plots show that the GN filter diverged in the last leg of the test when the dead-reckoning error attains its maximum value due to a strong bias in the heading measurements provided by the internal attitude sensor of the DVL. In this part of the trajectory, the vehicle navigates over an almost flat terrain which does not provide significant information for terrain navigation. It is worth noting that, despite the large orientation error introduced by the DVL built-in motion sensor, the filter is able to recover and reset the error; this is achieved when the vehicle reaches the area of high slope in the Northeastern part of the lake, converging approximately to the correct position and finishing the maneuver with a negligible error.

The best GN results overall are obtained using the external motion sensor to complement the ground-referenced velocity data provided by the Doppler. As can be observed in **Fig.19**, in this case the GN-estimates follow closely the true trajectory. The larger deviation occurs in the Southern leg where the topography does not convey enough information to enable the correction of the drift accumulated in the previous leg. The accumulated error is due to the limited accuracy of the navigation sensors and the low level of terrain information available in the center of the lake. **Fig.20** shows that GN is able to reduce the localization error in the final part of the trajectory where the filter explores efficiently the large terrain gradient observed in the area of the ramp.

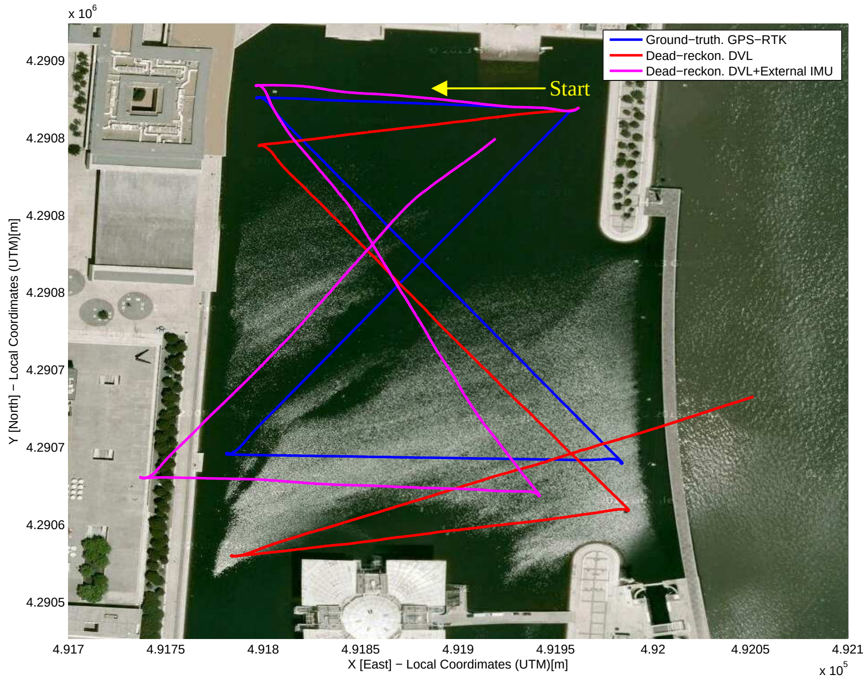

Fig.16: True trajectory (blue) and dead-reckoning estimates obtained with different motion sensor units; the yellow arrow indicates the direction of vehicle motion at the point of departure.

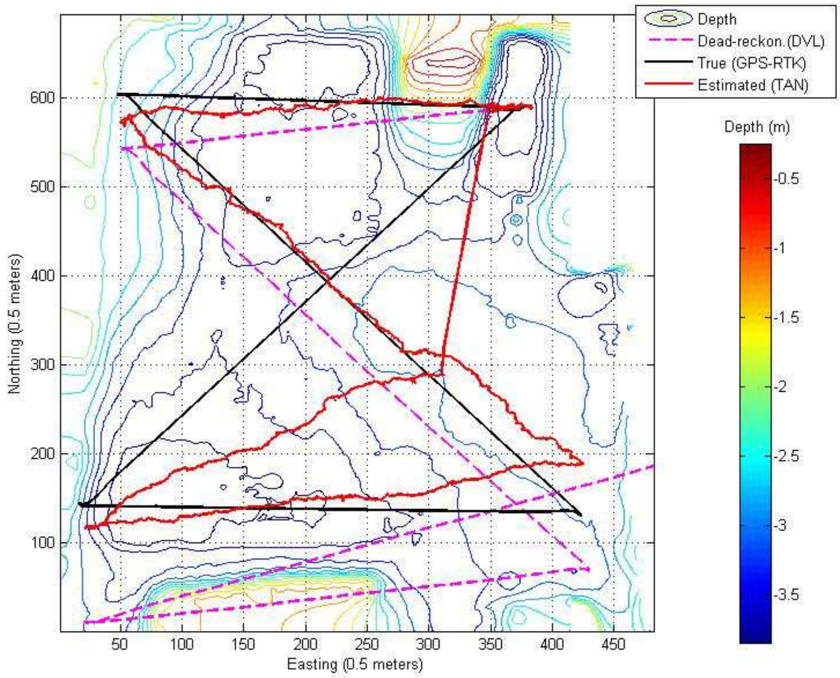

Fig.17: True trajectory, dead-reckoning (DVL), and TAN estimated trajectory.

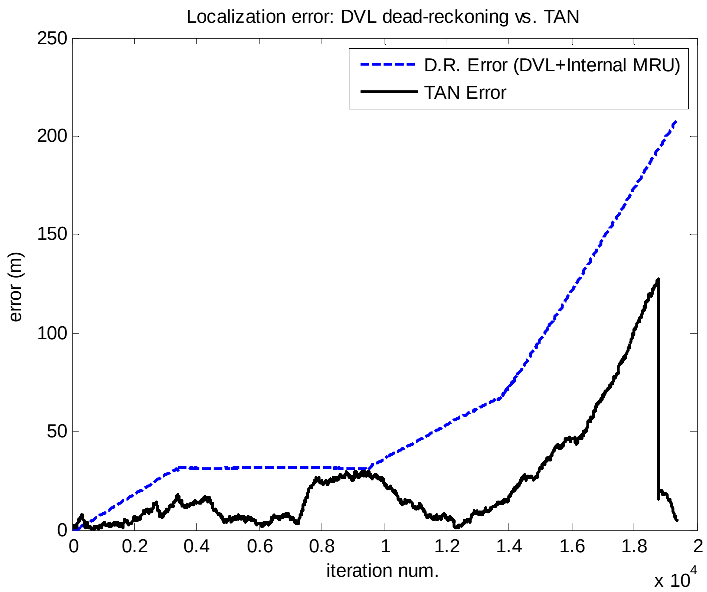

Fig.18: Absolute value of the localization error obtained with TAN and Dead-reckoning performed with the DVL data.

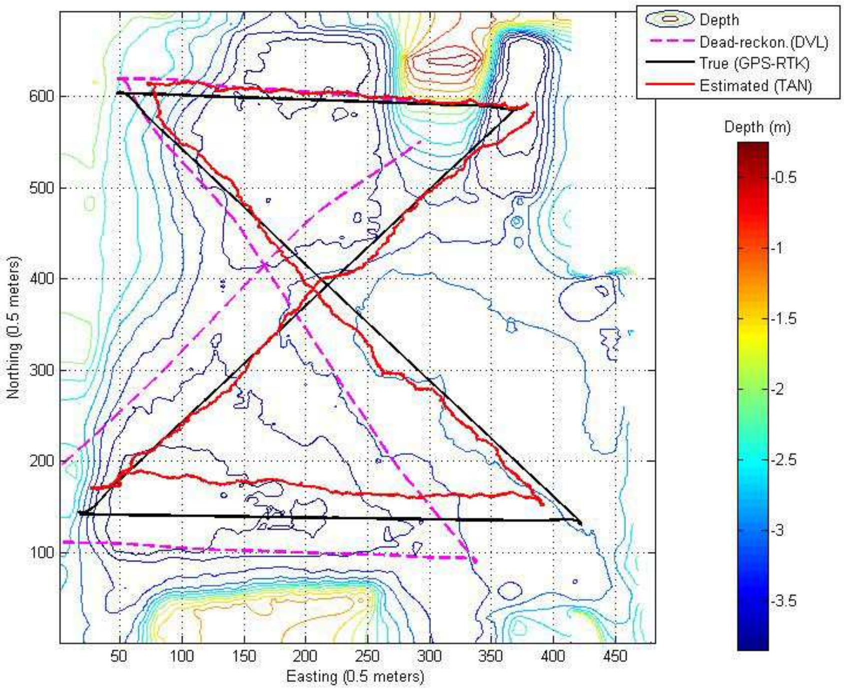

Fig.19: True trajectory, dead-reckoning (DVL + External IMU), and TAN estimated trajectory.

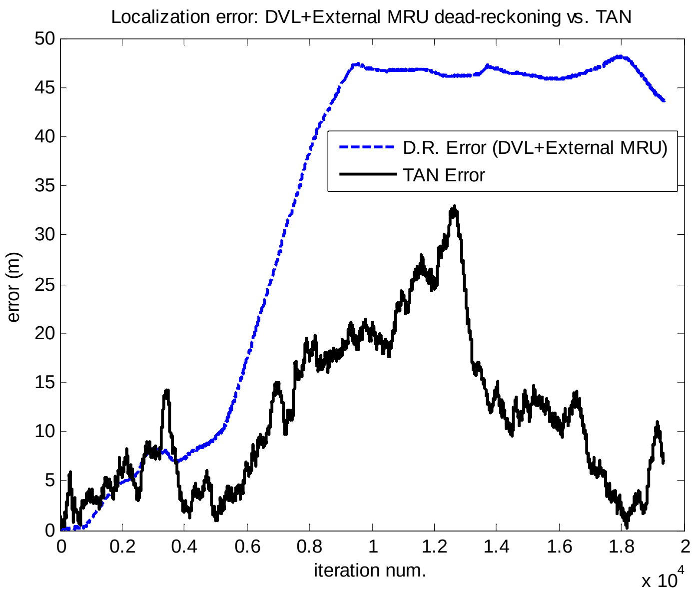

Fig.20: Absolute value of the localization error obtained with TAN and Dead-reckoning performed with the DVL and the external MRU data.

During the experiments the DVL built-in motion sensor introduced large orientation errors which are highly detrimental to the execution of TAN algorithms. It was also was observed that one of the DVL beams failed frequently and introduced large errors in the altitude measurements. For this reason, the utilization of this beam was inhibited in the TAN filter. Despite these limitations, the TAN algorithms were able to accurately localize the vehicle, closing the trajectory loop with an error of a few meters.

A common deficiency of the output of terrain navigation algorithms is the short-term variability of position estimates. As can be noticed in the plots of **Figs**. **18** and **20**, this characteristic is also observed in the present results. To mitigate this problem a complementary filter (CF) was designed and applied to implement data-fusion of the TAN and DVL navigation outputs as described in [7]; the filter structure is represented in the figure below. As a result of its application, it was possible to obtain position estimates which are characterized by smaller estimation errors and reduced short-term variability. These characteristics of the filter outputs are shown in detail in Fig.**??**. This result demonstrates the importance of incorporating conveniently designed data fusion filters in TAN applications.

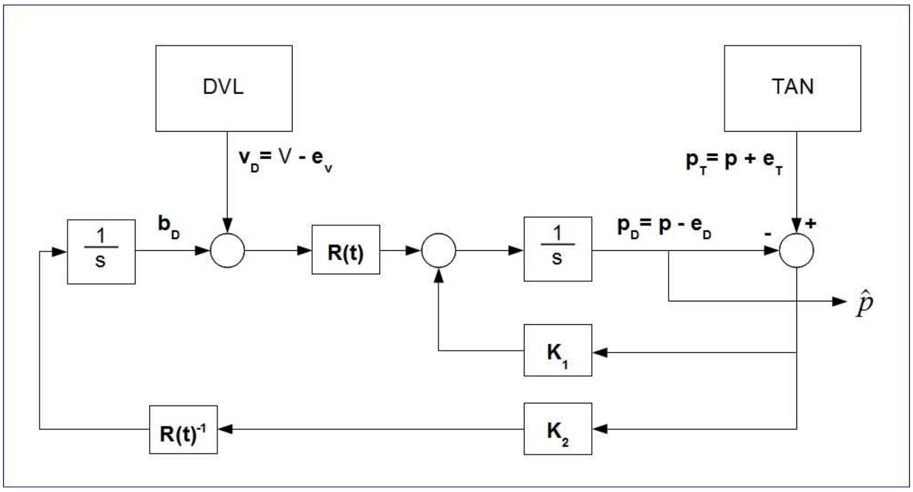

Fig.21: Structure of the complementary filter used to integrate the TAN output with DVL dead-reckoning.

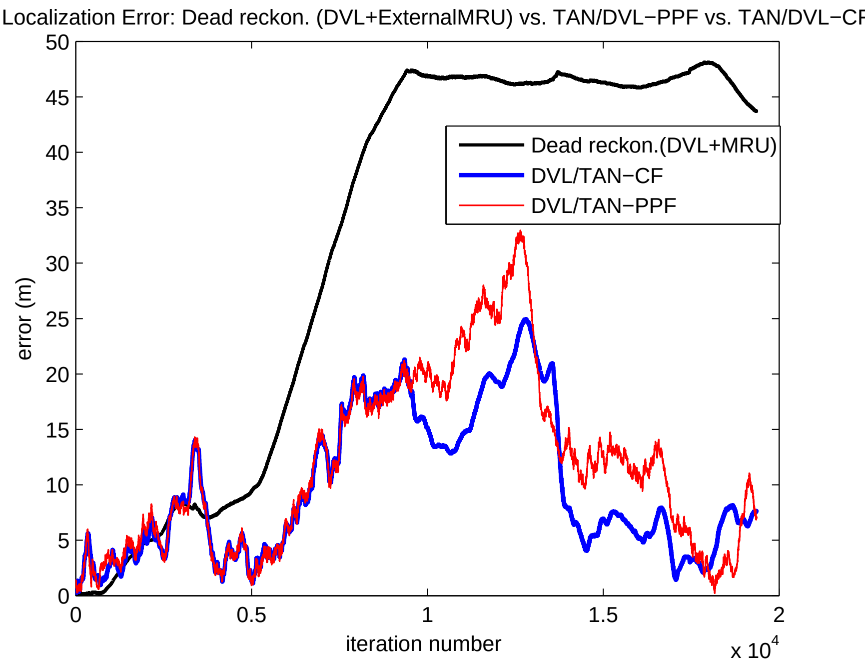

Fig.22: Absolute value of the localization errors obtained by conventional DVL dead-reckoning compared with those obtained with the new geophysical navigation methods.

The above presented results demonstrate in practice the ability of geophysical navigation based on bathymetric information to achieve bounded localization errors even in poorly informative terrain and in the presence of faulty navigation sensors.

6. Research on novel methods in Geophysical Navigation

6.1. Task objectives and expected results

The objective of the task was to investigate and develop new techniques that complement the methods already implemented and expand the capabilities of geophysical navigation of AUVs. The results of the research were planned to be validated through computer simulations using real data. The main results expected consisted of new navigation methods or the optimization of existent algorithms; these results were expected to be assessed through quantitative measures of the efficiency of the methods in computer simulations or real experiments.

6.2. Work developed, results obtained, and publications

The work developed here addressed two main topics:

- Cooperative terrain-based navigation
- Geophysical navigation using complementary sources of terrain information

The objectives achieved and the resulting publications are:

- The theoretical development of a novel method of cooperative Terrain-Aided Navigation of AUVs was the subject of the work developed by the post-doc researcher Luca Baglivo under a research grant of the project; see the Technical Report [10].
- A new approach to terrain-based navigation using side-scan-sonar data was explored at the UA in the context of a Master thesis in Electronic Engineering, [11]. This work exploited a non-conventional source of terrain information in GN. The side-scan-sonar (SSS) data has the advantage of acquiring a large amount of information which in principle can be correlated with a prior map to achieve precise localization. Since SSS is a geophysical instrument used in many scientific, commercial, and military surveys, there are currently large data-sets of this type of data that can be used by robotic vehicles as prior maps for navigation. The present work benefitted from the availability of one these data-sets to assess the performance of this type of navigation methods and explored signal processing techniques that are normally applied in computer vision to process the acoustic images of the sea-floor supplied by the SSS.
- The development of a new magnetic navigation approach with high potential of application in navigation and tracking of underwater vehicles; see [4].

7. Magnetic sensors' setup

7.1. Task objectives and expected results

The objective of the task was to assemble a magnetic gradiometer from a set of two total field magnetometers and prepare the gradiometer array for deep tow surveying. The expected result of this task consisted of a system that could be towed underwater to acquire gradient measurements of the magnetic field. Although the initial objective of acquiring gradient measurements of the magnetic field for GN has been maintained, the implementation envisioned was modified to use vector magnetometers instead of total field sensors.

7.2. Work developed and results obtained

To implement the projected system, a set of two high-sensitivity fluxgate tree-axial magnetic gradiometers (Bartington Grad-03-500M) has been acquired; see **Fig.23**. These two sensors can be configured as an array of 4 vectorial magnetometers to mount a bi-dimensional gradiometer which allows for the acquisition of the local magnetic gradient tensor; see schematic arrangement of the sensors in **Fig.24**. The sensor assembly, including its towing device, **Fig.25**, was projected but is not yet fully operational due mainly to difficulties in sensor calibration and alignment. These very high sensitivity sensors require a complex and time-consuming calibration procedure with an external analog calibration unit (ACU) supplied by the same manufacturer; see **Fig.26**. This calibration unit could not be acquired due to the budget cuts imposed to the project and had to be borrowed from the manufacturer. This fact resulted in a long delay in the preparation of the sensors. The calibration process was concluded only recently. However, in the meanwhile, our team developed software algorithms that can be used in the future to calibrate the sensors dispensing with the need of the ACU. The expertise obtained in this process is of great value for the future utilization of these sensors. The potential of the 3-axis gradiometer for utilization in navigation and tracking has been studied from a theoretical perspective and shown in computer simulations [4]. Besides the work with the gradiometers, this task included the test of two scalar magnetometers owned by IST that were used to acquire a prior magnetic map.

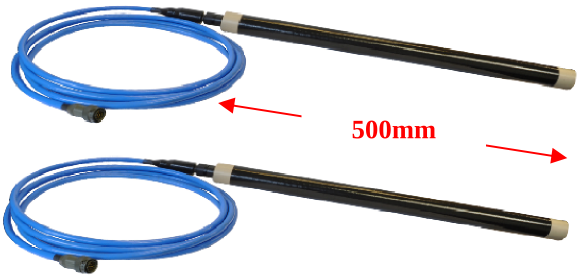

Fig.23: The two Bartington Grad-03-500M marine gradiometers used to build a bi-dimensional magnetic gradiometer.

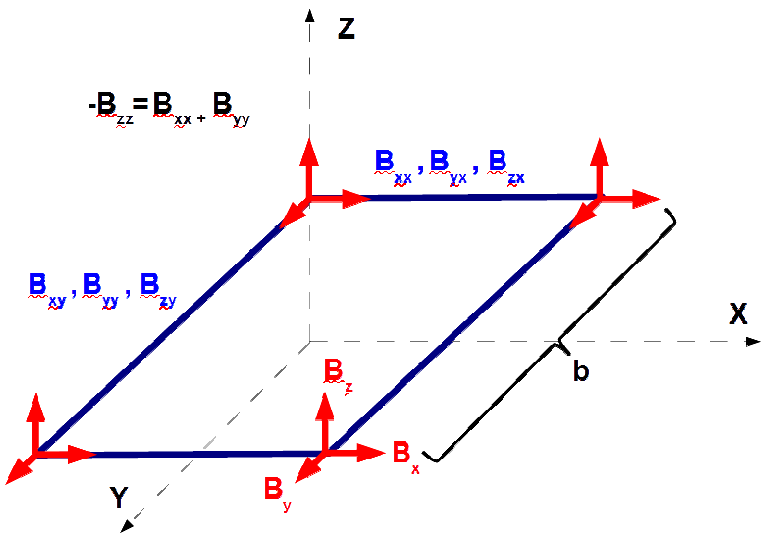

Fig.24: Schematic arrangement of the 3-axial magnetic sensors in the bi-dimensional magnetic gradiometer. The variables Bi denote the components of the magnetic field vector and Bij denote their spatial derivatives corresponding to the components of the magnetic gradient tensor. Bi and Bij are measured directly by the gradiometer but some components are computed from the measured quantities; b is the gradiometer baseline.

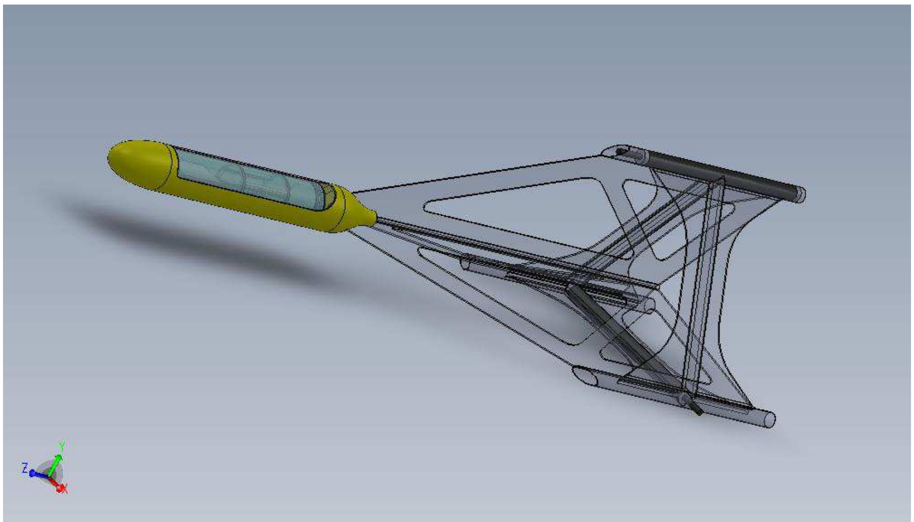

Fig.25: Mechanical support for the magnetic sensors and housing for the electronics of the 2D gradiometer designed to be towed by an AUV. Notice that the geometry of the gradiometer can be adapted provided that the arrangement of the individual vector sensors allows for the acquisition of the magnetic gradient tensor.

Fig.26: The Analog Correction Unit (ACU) supplied by Bartington Instruments, Ltd. This unit was used to acquire the gradient measurements during system calibration.

8. Magnetic signal processing and mapping

8.1. Task objectives and expected results

This task was projected to investigate and test new mapping techniques to derive accurate 3-D representations of geopotential fields with application to AUV navigation. As results, it was expected to obtain:

- 3D models of geomagnetic field variables in the test area, in a representation scheme suitable for geophysical navigation.
- Efficient mapping techniques for 3D representation of geopotential fields, suitable for application in GN.
- Software for 3D magnetic modeling with application to GN.

8.2. Work developed and results obtained

The work addressed the above mentioned topics and the expected results were achieved although they have not been yet applied to GN in real experiments. A software package (MagNav) was developed to model 3D vector magnetic fields used in computer simulations of GN. The software can be used to represent complex magnetic fields as shown in **Fig.27**. The method implements an approximated representation of vector magnetic fields by superposition of dipole fields. It presents the advantage of representing arbitrarily complex magnetic fields in 3 dimensions by a limited set of dipole parameters. As such, the method does not require large amounts of memory to represent three-dimensional fields and allows for very efficient implementation of field simulations, including the effects of scaling with distance. Additionally to the parametric 3D map representations, the software developed relies on 3D analytic models of dipole magnetic fields that can be used in real-time to simulate the effects of moving objects on the environmental magnetic field. These models which are used in a Monte Carlo estimation procedure to track the position of moving vehicles have been presented and published recently; see e.g. [4-5].

Due to difficulties associated to the utilization of the magnetic gradiometers, the work of this task was pursued using two new high-precision, Marine Magnetics Sea-Spy total field magnetometers acquired by IST; see **Figs.28** and **29**. These magnetic sensors permitted the acquisition of prior magnetic maps of very high spatial resolution and high accuracy that support the current work on magnetic-based GN; see details of the magnetic survey executed at the trial site in **Fig.5** and the final magnetic map of the area in **Fig.6**. With the magnetic data already acquired it is possible to compute the spatial gradients of the local geomagnetic anomaly which can be used as prior maps for magnetic-based geophysical navigation. These reference maps are currently being used to assess the efficacy of geomagnetic navigation in computer simulations prior to the execution of experimental tests in the water that are scheduled to be performed in 2015.

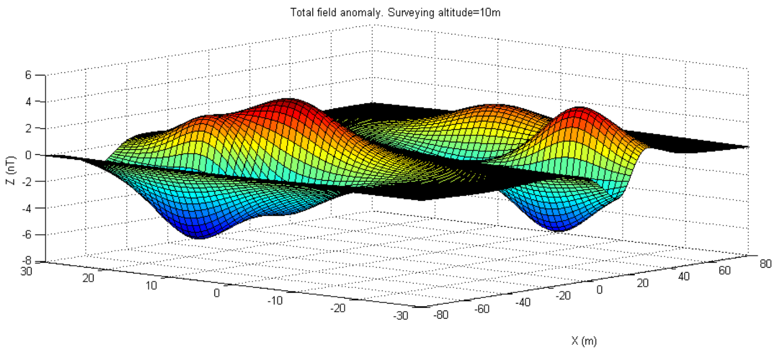

Fig.27: Multi-pole magnetic anomaly modeled by the software package developed in Matlab for magnetic-based geophysical navigation.

Fig.28: Marine Magnetics Sea-Spy total field magnetometer.

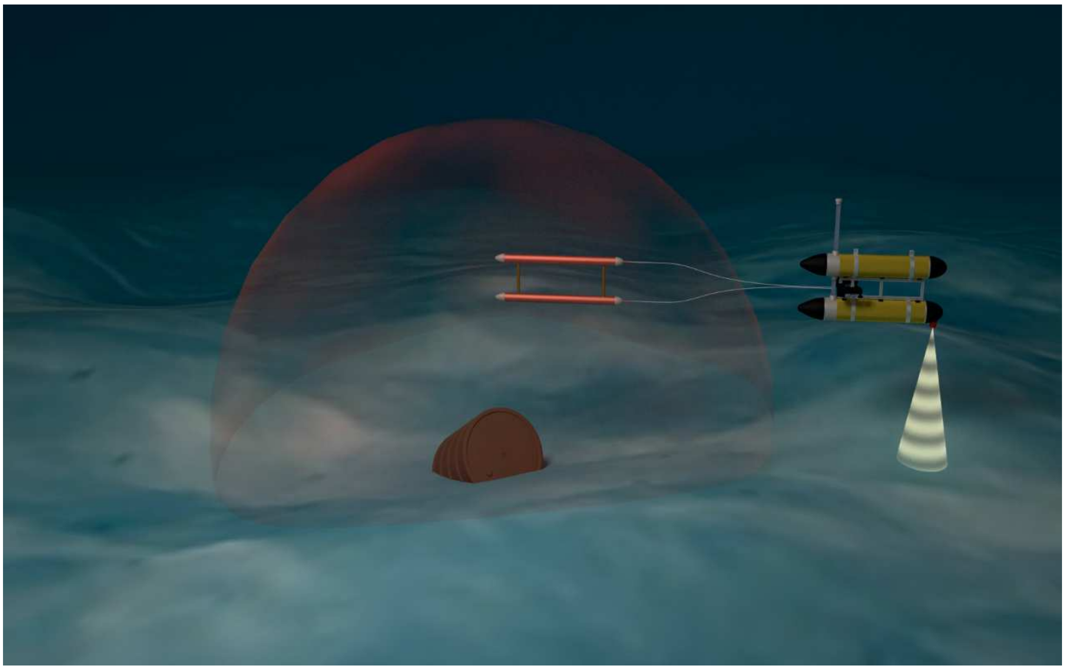

Fig.29: Geophysical Navigation using a magnetic gradiometer built from two scalar magnetometers, complemented with a sonar altimeter.

9. Conclusions and future work

The TAN methods developed showed their efficacy when using low-resolution range measurements and proved to be robust in the presence of faulty navigation sensors. These results illustrate clearly the ability of bathymetric-based GN to achieve bounded localization errors even in poorly informative terrain and using standard, relatively inexpensive navigation sensors.

Magnetic navigation is currently being tested in simulations using the total magnetic field data acquired at the test site and will be followed soon by the execution of experimental tests in the water using a vertical gradiometer towed by a *Medusa* ASV.

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