

Outfall Monitoring using Autonomous Underwater Vehicles

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Abstract

An Autonomous Underwater Vehicle (AUV) is being used by the University of Porto (Portugal) to study fluvial, oceanographic and environmental problems. Its equipment has been progressively upgraded as a result of a research plan, and several missions were already performed. This paper describes the vehicle, its equipment and two of those missions. One was performed in the Minho River for the physical characterisation of its estuary. The other one refers to the monitoring of a sub-fluvial outfall which is part of a thermal power plant cooling system located in the vicinity of Porto. This technology has also a great potential to study wastewater discharges, including the design, construction and monitoring of sea outfalls.

I. Introduction

Traditional sampling techniques for underwater observation are generally expensive and do not offer a comprehensive coverage, specially as the requirements for oceanographic and environmental field studies become more and more demanding⁽¹⁾. In fact, recent progresses in ocean sciences and technologies have been stressing the importance of efficient observation methods in order to fulfil the requirements of the so-called *real-time oceanography*⁽²⁾.

AUVs (Autonomous Underwater Vehicles) can be efficiently used in a wide range of applications. They were first developed with military applications in mind, namely for mine hunting missions. Later on, scientists realised their true potential and started to use them as mobile sensors, taking samples in difficult scenarios at a reasonable cost.

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As a result of the pragmatic co-operation between R&D groups, the Systems and Underwater Technology Laboratory at the University of Porto, in Portugal, acquired, in 1997, a REMUS (*Remote Environment Measuring UnitS*) class AUV to the Woods Hole Oceanographic Institution, MA, USA. Since then, the vehicle (named Isurus) has been undergoing major improvements in Porto, in order to fulfil the requirements of the potential end-users, and has been operated in a wide range of scenarios.

The first operational missions took place in 1998, in the estuary of the river Minho, in the northern border between Portugal and Spain. These missions demonstrated the reliability and the operational effectiveness of this vehicle. During autonomous missions, typically longer than one hour, the vehicle continuously collected CTD and bathymetric data, while navigating on a LBL transponder network. More recently, the Isurus AUV was used for monitoring the disposal of hot water from the cooling system of a Portuguese Combined Cycle Power Plant in Douro river. The results obtained so far demonstrated an excellent performance for executing missions to support hydrothermal and hydraulic studies.

This paper is organized as follows. In Section II, we give a short presentation of the Isurus AUV focussing on the monitoring operation aspects. In Section III we describe a mission performed in the estuarine environment of Minho river and present a Matlab visualization of the oceanographic data collected. Then in Section IV we present the experimental results from a recent outfall monitoring operation using the AUV Isurus. Finally, in Section V we discuss the conclusions and future work.

II. The *Isurus* AUV

The REMUS class AUV Isurus (figure 1) has a torpedo shaped hull, about 1,5 meters long and with a diameter of 20 cm, weighting about 30 kg in air (³). The reduced weight and dimensions, specially designed for coastal waters monitoring (up to a maximum depth of 200m), makes it extremely easy to handle, not requiring any specific equipment for launching and recovering.



Figure 1 – The *Isurus* AUV

During operation, Isurus has no physical connection with the operator, and it can cruise at a maximum forward speed of 4 knots (2 m/s or 7.2 km/h). However, the best energy efficiency achieved at about 2 knots. At this velocity, the energy provided by the low cost rechargeable lead acid batteries lasts for over 10 hours (i.e., over 20 nautical miles).

A. Physical configuration

Physically, the vehicle can be divided in 3 distinct parts. The bow section is flooded and contains the acoustic transducer for navigation and all the sensors that interact with the aquatic environment. The middle section is water sealed and integrates the on-board computer, the electronic components and the batteries. Finally, the tail section (also dry) contains the propulsion system.

The main thrust of the vehicle is provided by a rear placed propeller. The vehicle has also horizontal and vertical control surfaces to change its position both in the vertical and in the horizontal planes.

The vehicle is equipped with the following set of sensors for navigation: a pressure sensor to measure the vehicle depth, a digital magnetic compass to determine its heading, two tilt sensors to measure the vehicle roll and pitch angles, a shaft encoder to measure the propeller rotation speed, and position encoders to determine the angular position of the control surfaces.

The navigation system is one of the most important parts of the vehicle, as it provides spatial location for the oceanographic data and also for corrections in the trajectories. As the electromagnetic signals do not penetrate seawater, it is not possible to use a global positioning system underwater, such as GPS. Instead, Isurus continuously fuses information such as propeller velocity, magnetic heading, position of the fins, inclination, depth (pressure), together with ranges to a set of acoustic beacons (named transponders), in order to produce an estimate of its current location. The acoustic beacons are installed in the operation area and their precise location is transmitted to the vehicle before the mission starts. During the mission, the vehicle emits acoustic signals in specific frequencies, depending on which beacon it is trying to reach. Each beacon replies with another unique frequency, allowing the vehicle to measure the range by multiplying the elapsed time by the sound-speed in water. Triangulating at least two of these ranges allows the vehicle to determine its horizontal position (the vertical coordinate is directly given by the pressure sensor) ⁽⁴⁾.

B. Sensors

Although small in size, it is possible to accommodate in these vehicles a wide range of oceanographic sensors, according to mission objectives. Successful tests have been performed in the past with, for example, sidescan sonars, ADCP (*Acoustic Doppler Current Profiler*) and Optical BackScatters.

For the missions described in this paper, two specific sensors were integrated: a CTD (*Conductivity, Temperature, Depth*), OS200 model from Ocean Sensors, CA, USA, and an

altimeter, from Imagenex, Canada, in a specially designed nose extension. Besides temperature and conductivity measurements, taken at 1,4 Hz, salinity and density values were also obtained from the CTD sensor. The height of the water column could be determined by adding the depth (measure with a pressure sensor) to the distance to the seafloor (measured by the altimeter).

Currently, an underwater video camera and a digital video recording system are being installed in the vehicle.

C. Typical mission

Typically, an AUV mission starts with the vehicle programming, by editing a mission file in the laptop computer, with the objectives that need to be successively accomplished and the exact field location of the navigation transponders, given by a GPS receiver.

After the final diagnostic, where the status of the various subsystems are checked, the mission file is transferred to the vehicle and the cable is disconnected. The vehicle is then launched in the water, from the coast or from a small boat. At this stage, the navigation and control programs are running and dictate the vehicle maneuvers throughout the mission.

The mission ends with the recovery of the vehicle in the expected final position. The connection with the laptop is then reestablished and all the stored information is downloaded.

There are two data sets collected during a typical mission. The first set is related to the vehicle internal data, which is only analysed in the lab. This allows the performance evaluation of the various subsystems (navigation, control, power consumption, etc.) and provides useful information for potential improvements. The other data set comprise all the information from the oceanographic sensors. Adding the two sets together, the vehicle logs an average of 5 Mbytes of information per hour.

III. The Mission in Minho River

A long term cooperation with oceanographers and marine biologists from Porto University has been instrumental to produce a set of application scenarios in which AUV based systems are clearly advantageous when compared with existing alternative methods ⁽⁵⁾, ⁽⁶⁾. One of these scenarios, chosen for the first operational missions, consists in the use of AUVs for the identification of relevant factors affecting the eel recruitment process in estuarine environments ⁽⁷⁾. Aspects of the dynamics of the coastal ocean and the estuary, such as horizontal and vertical circulation are believed to play an important role.

In order to address this scenario, the estuary of river Minho, in the northern border between Portugal and Spain (Figure 2) was chosen, for three main reasons:

- **Logistics:** A marine station situated in this estuary provided the facilities required for field testing and development, including a small boat to support the missions.

A.2 Bathymetry

The availability of an onboard altimeter allowed for testing another type of mission: autonomous bathymetry.

The idea was to evaluate the possibility of using the AUV to map the bottom of the river and construct a 3D map. If viable, the vehicle could be deployed in consecutive sections of the river, in order to build an updated the map of the bottom.

Besides demonstrating the vehicle as a tool for underwater mapping, these charts would also allow for a safer navigation. In the longer term, they may also be used to detect changes in the topography, map the ferry-boat channel, help in the construction of oceanographic circulation models and the construction of 3D virtual environments for mission simulation.

B. Mission Execution

Due to logistic facilities, a section of the river in front of Seixas village was chosen as the place to perform the first mission (see Figure 2).

The vehicle was programmed to perform 5 consecutive rows spaced by 50 meters. Each row is 500 meters long and its orientation is perpendicular to the river current direction.

The final diagnostics were performed close to the launch point, which included the reset of the pressure sensor to compensate for changes in the atmospheric pressure and the calibration of the magnetic compass to compensate for local variation in the magnetic field.

The vehicle performed the mission in ca 1 hour with approximately constant velocity of 1 m/s and depth of 1 m. The CTD and altimeter were programmed to continuously collect temperature, salinity and bathymetry (obtained joining depth from the pressure sensor with distance to the riverbed from altimeter) data.

C. Mission Data Processing

Oceanographic data can be delivered to the end-users as raw data or it can be processed to allow for a rapid validation.

As far as data processing is concerned, some routines were developed in Matlab, mainly for filtering and 2D or 3D maps visualization. Figure 3 shows the result of filtering bathymetry data and interpolating where there was no data available.

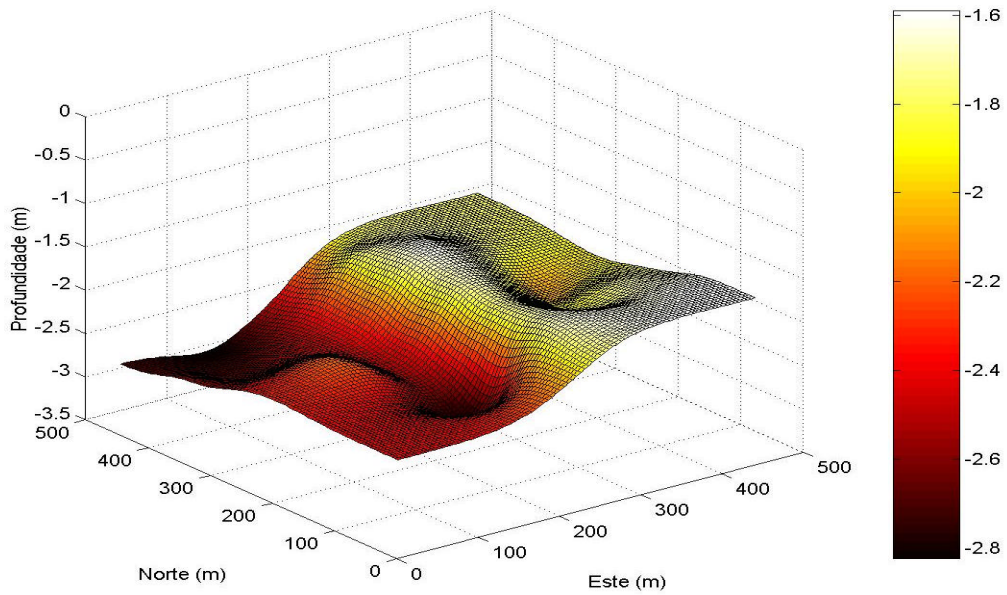


Figure 3 - Bathymetry of the sampled area

It should be pointed out that in this particular mission, the row spacing was 50 meters, which only allows for a low-pass interpolation. This is the reason why the shape of the bottom appears smoother than it actually is. In order to obtain a more accurate description of the bottom, we would need to process data from a mission with closer rows.

In Figures 4 and 5, we can see respectively the distribution plots of the temperature and salinity values for the same region as above, at 1-meter depth. In both figures, the plot reference (0,0) corresponds to coordinates (N 41°53'33"; W 8°49'53").

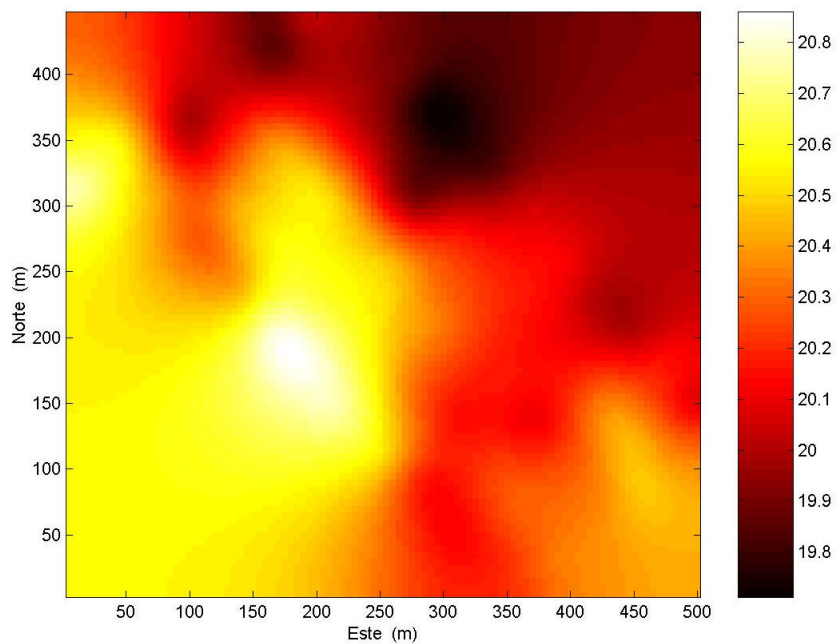


Figure 4 – Temperature Distribution map

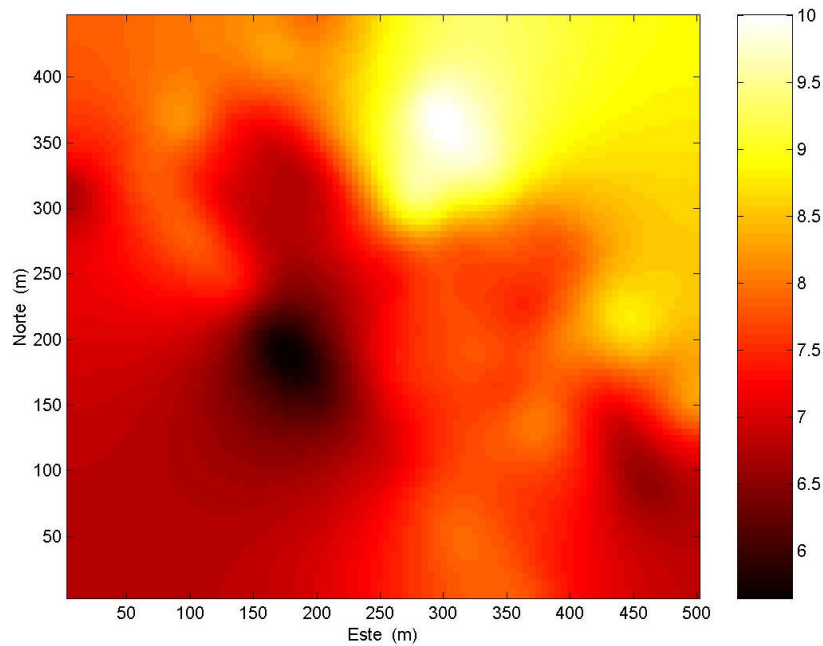


Figure 5 – Salinity Distribution map

In order to have three-dimensional plots of these oceanographic data the vehicle would have to perform a trajectory in Yo-Yo mode by changing depth while navigating.

IV. The Mission in *Tapada do Outeiro* Power Plant

Tapada do Outeiro, a small village in Northern Portugal, 40 km upstream from Porto (see Figure 6), gave the name to the first Portuguese Combined Cycle Power Plant, built in 1998 on the right steep bank of the Douro River. Close to an older coal/oil fired power station (in Figure 6 designated as *Central Termoeléctrica*) whose operation was halted because of environmental reasons, the Tapada do Outeiro CCPP is believed to be one of the most efficient and environmentally-friendly power plants of this class in the world.

The power station uses natural gas (from Algeria via the Maghreb-Europe pipeline) in its three single shaft turbosets, providing approximately 990 MW to the national public network, roughly 20 % of the electricity produced in Portugal.

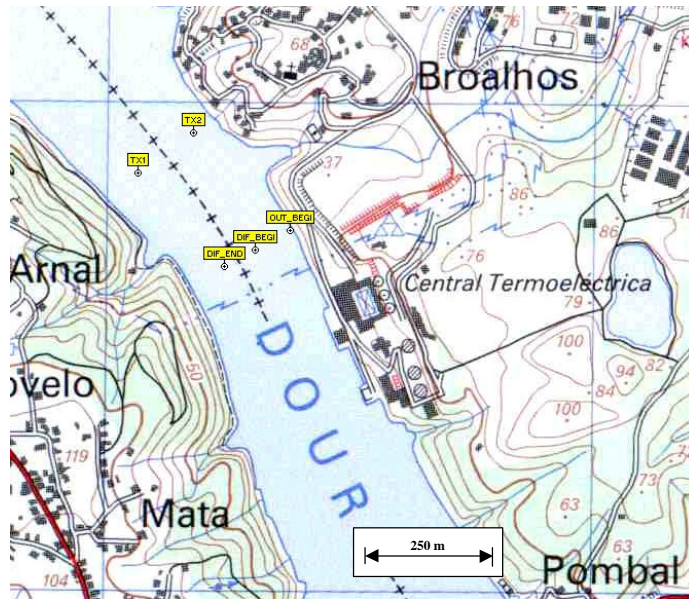


Figure 6 – Tapada do Outeiro CCPP overview

The water cooling system is supported by the river intake and outfall structures. The cool water of the river coming from the intake at 6 m depth is used for cooling the three turbines of the power station. The water generated heated by the turbines in operation is then discharged in the river at 14 m depth using a sub-fluvial outfall.

This outfall (identified in Figure 6 with the three straight-line bullets and flags) is 165 meters long and oriented perpendicularly to the riverbank. It discharges at a distance of 1,5 m from the riverbed and terminates by a multiport diffuser 80 m long, provided with 20 ports spaced 4,14 m apart with a diameter of 0,5 m. The discharge flowrate is about 15 m³/s (5 m³/s for each turbine) in the direction of the river flow. When leaving the turbines, the temperature of the water is around 38 °C and decreases considerably at the discharge points.

Figure 7 shows a picture of the turbulence at the surface generated by the plume in the mixing process.



Figure 7 – Plume at the surface

As usual, the main objectives of this discharge system are to minimise re-circulation and environmental problems.

An optimized trade-off between full operation and an healthy environment can be achieved by developing prediction studies of the thermal plume behaviour and dilution under the conditions of a particular discharge, analysing water re-circulation of the intake/outfall structures during summer days and determining the influence in the mixing process of the river bed and free-surface boundaries, bank interaction and shallowness.

The extensive environmental data gathering capacity of Isurus, which includes horizontal sampling at different depths can be of great value for these studies, namely identifying measures to prevent re-circulation even under extreme low flow conditions.

A. Operation Scenario

In the discharge zone, the width of the river is approximately 230 m and the average depth is 13 m.

During the summer, the temperature in the water column can vary between 18 °C and 25 °C. However, stratification is weak, since the differences in the water column are generally below 1 °C and 2 °C at maximum.

In the year 2000, the average flows from January to May were respectively 442, 321, 245, 751 and 813 m³/s; in August its value was 160 m³/s.

Wind speed is variable during the year being expected significantly lower values in the hot summer days.

B. Mission Execution

Figure 6 shows the setting of the two transponders (identified with flags Tx1 and Tx2) used for navigation in the mission of 16 May 2000. Its GPS positions in the field were respectively 41° 04,1860' N, 8° 27,8960' W and 41° 04,2300' N, 8° 27,8130' W.

Figure 8 shows the launching of the AUV Isurus.

Isurus performed the mission in the area of the discharge between the transponders and the outfall. It was programmed to perform rows of 133 meters long perpendicular to the riverbank and the objective would be completed after 5 consecutive rows, spaced by 50 meters.

The navigation was kept in a constant velocity of approximately 1,6 m/s and depth of 1 m. CTD and altimeter were also used in this mission.

In the day of the mission the maximum value of the discharge flowrate was ca 15 m³/s.



Figure 8 - Launching the vehicle in the water

C. Mission Data Processing

Data shown in Figure 9 refer to three measurements whose duration is indicated. They were obtained in the discharge area with the CTD sensor, during the mission execution.

Besides the calculation of average values, the analysis of the rapid fluctuations may even provide an insight of the turbulent structure of the flow.

A comprehensive analysis of data can be very useful to monitor the outfall performance.

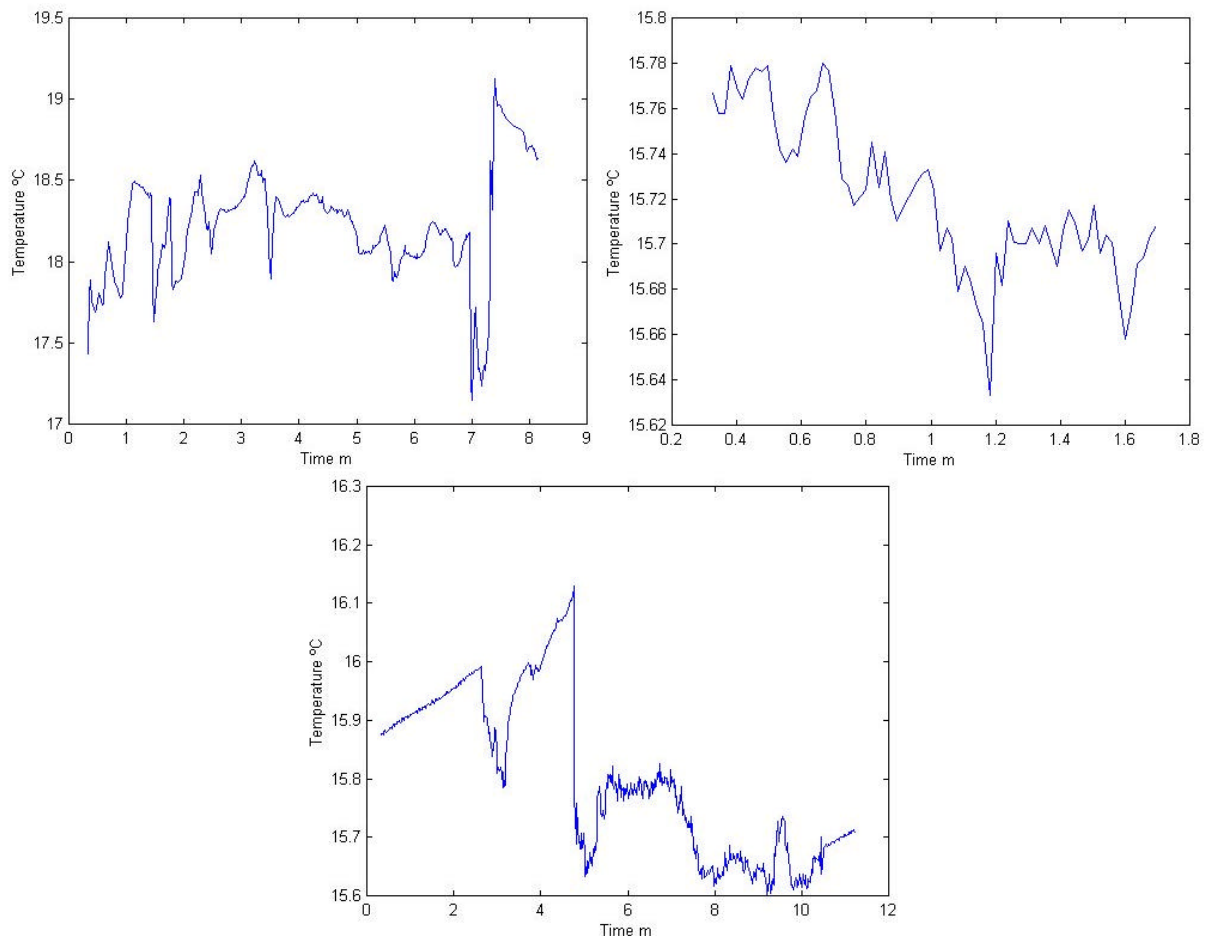


Figure 9 – Temperature plots of the plume at the surface

V. Conclusions

AUVs have been successfully used as mobile sensor platforms to gather large amounts of data in more severe conditions than those permitted by alternative solutions.

The Systems and Underwater Technology Laboratory from the University of Porto has been developing navigation, control and sensing systems for Isurus, a REMUS class AUV, since 1997. These highly operational and low cost vehicles of reduced weight and small dimensions are specially designed for coastal waters, rivers and estuaries monitoring. An example of a mission performed in the Minho River estuary was described.

Isurus has revealed to be an excellent device for a wide range of different applications and is expected to become as well a very useful tool to improve the design, construction and monitoring of outfalls for effluent discharges (⁸), (⁹). One of such applications is being currently studied: the disposal of hot water from the cooling system of Tapada do Outeiro thermal power plant.

Other missions are being planned for the near future in order to study two existing sea outfalls in the neighbourhoods of Porto. These cases refer to waste water discharges which take place at ca 2500 meters from the beach. We expect that, besides hydraulic studies, the video camera, being installed in the vehicle, will be helpful for visual inspection of the outfall diffusers. One of the focus of the research plan is the type of sensors that should be used to monitor this kind of effluents.

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