

MAPPING THE AVEIRO SEA OUTFALL PLUME: SAMPLING STRATEGY FOR AN AUTONOMOUS UNDERWATER VEHICLE

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KEYWORDS

mapping, plumes, sampling, strategies, autonomous, vehicles

ABSTRACT

Near field model predictions can be used to reduce the uncertainty about outfall sewage plume location during a monitoring mission.

In this paper we present an innovative methodology that uses these models to predict the plume location, establishing a sensing strategy applicable to a monitoring mission using an AUV.

The paper describes two applications that implement this methodology, accomplishing the automatic mission definition using real-time oceanographic data.

An AUV mission was conducted to detect and map the Aveiro outfall plume, making use of these applications to specify an efficient sampling strategy.

INTRODUCTION

Outfall sewage plumes show to be very difficult to observe in detail. The several field studies already conducted exhibit very complex and patchy structures both in vertical and horizontal sections. It is not clear yet if this plume patchiness is due to physical processes or measurement limitations. Although all this difficulties, these studies are very important since, besides giving a better understanding of the plume behaviour under certain conditions, can be used to be checked against prediction models.

Rapid tow-yo sampling is expected to reduce the time variability during and between transects. Autonomous Underwater Vehicles (AUVs) may be a useful instrument for outfall sewage plumes detection but its efficient use depends crucially on a sampling strategy.

Efficient sampling strategies, using oceanographic data obtained in real time to simulate the plume behaviour, may play an important role in the success of an AUV outfall monitoring mission.

The Systems and Underwater Technology Lab (LSTS) have been involved in the quality monitoring program of the Aveiro sea outfall, introducing the AUV technology to detect and map sewage plumes.

In this paper we start with brief descriptions of the Aveiro outfall specifications and the Isurus AUV, focusing on its setup operation and mission specification. Next a methodology for plume detection using near field model predictions and applicable for AUVs monitoring missions is described. Then in the following two sections we present two applications that implement the plume detection methodology, enabling the real-time AUV mission definition during a campaign. Results from a monitoring mission to the Aveiro outfall performed with the Isurus AUV on last July 2002 are also presented and discussed. We finalize with some conclusions.

AVEIRO SEA OUTFALL

The bathymetry of the Aveiro coast and the mouth of its estuary, the oceanographic instrumentation sites and the S. Jacinto outfall are shown in Figure 1.

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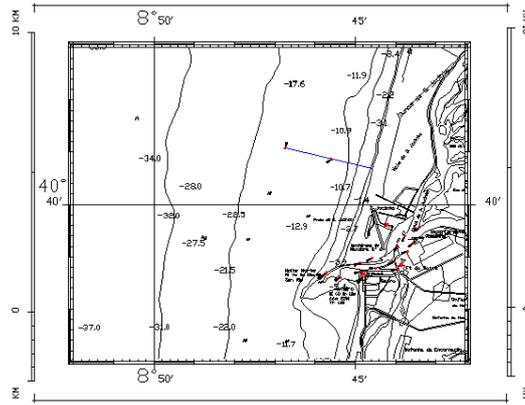


Figure 1: Bathymetry, outfall and oceanographic instrumentation sites in the Aveiro coast.

This Portuguese outfall, in operation since May 2000, is presently discharging about $0.7 \text{ m}^3/\text{s}$ of mainly industrial wastewater. Its total length, including the diffuser, is 3378 m (first 3135 m with a diameter of 1600 m and last 243 m with a diameter of 1200m). The diffuser, consisting of 72 ports alternating in each side, 0.175 m diameter, is 332 m long. Presently only 20 of the 72 ports are working. These are discharging upwards at an angle of 30° above the horizontal axis. The outfall has a bearing direction of 290° and is discharging at a depth of about 15 m.

A seawater quality monitoring program for this outfall has already started in September 2000. Its main purposes are to evaluate the background seawater quality both in the offshore and nearshore locations around the vicinity of the sea outfall and to follow the impacts of wastewater discharge in the area. In this monitoring program, measurement and sampling sessions are organized four times a year, being once per season.

ISURUS AUV SETUP OPERATION

Isurus is a REMUS (Remote Environment Measuring UnitS) class AUV (Figure 2), built by the Woods Hole Oceanographic Institution, MA, USA, in 1997. The Systems and Underwater Technology Lab at the University of Porto has been operating and customizing it for the past 5 years. Several missions were already performed with great success namely in the estuary of Minho River in the border between Portugal and Spain, and also in the Douro River.



Figure 2: Isurus AUV

Isurus has a diameter of 20 cm and is about 1.5 meters long, weighting about 30 kg in air. Although small in size, this vehicle can accommodate a wide range of oceanographic sensors, according to mission objectives.

Isurus uses acoustic technology to estimate its position in the field. Acoustic transponders, placed in a known location in the field, give references to the vehicle navigation.

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

After the final diagnostic, where the status of the various subsystems is 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 manoeuvres 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, with oceanographic data included.

MONITORING METHODOLOGY

Several field studies using different types of techniques were already performed in order to detect and map sewage plumes [1][2]. The results obtained showed very complex structures difficult to identify with the classic picture of the buoyant plume [3][4]. None of these studies could prove if the patchiness of these structures is real and due to physical processes or measurement limitations.

Autonomous Underwater Vehicles show to be a very useful instrument in this case [5], since they enable an efficient data collection required to detect and map the plume, but its successful use, like any other technique, depends crucially on the efficiency of a sampling strategy.

In order to reduce the uncertainty about plume location and concentrate the vehicle mission only in the wastefield area, we decided to use the outputs of a near field prediction model to specify the mission transects.

The model that showed to be appropriate was RSB. This model is based on the experimental measurements of Roberts, Snyder and Baumgartner of multiport line diffusers in density-stratified currents of arbitrary direction [6]. It is a length scale model that uses semi-empirical formulations based on the relative magnitudes of the dominant length scales of the problem. The model predictions are the plume characteristics at the end of near field, which include dilution, rise height, thickness and length of the initial mixing zone.

A latter version of RSB model was used to support integration of a current profile that can be obtained from an ADCP instrument. The other inputs needed to run the model are density stratification of the water column that can be obtained from a CTD (conductivity, temperature, depth) profile and effluent density that can be calculated using temperature and salinity data. The model outputs used to define the mission area were maximum and minimum rise height and initial mixing zone. Additional improvements to the model were done to calculate the wastefield width, also necessary to restrict the mission transects. These calculations are based on the RSB model equations.

The sensing strategy specially designed to be used in the field for outfall plume detection using AUV's follows the methodology illustrated in Figure 3.

The figure first layer, represents the plume behaviour simulation using RSB model, giving the necessary outputs for the inspection area definition, represented by the right box of the second layer. The inspection area includes the locations used to specify the AUV mission and the CTD profiles location out of the plume downstream area and in the wastefield. The CTD stations out of the plume downstream area are to be performed simultaneously with the AUV mission in order to be checked against the vehicle mapping plot results, for plume recognition. The CTD stations in the wastefield are to be performed just after the end of the vehicle mission for sensors calibration.

The mission points are then used to define the other settings necessary for the mission specification. They include the mission tasks and the transponders location. All this information is then passed to the AUV mission file box (figure third layer), where the mission settings can be edited and the mission file generated. This file can then be transferred to the vehicle.

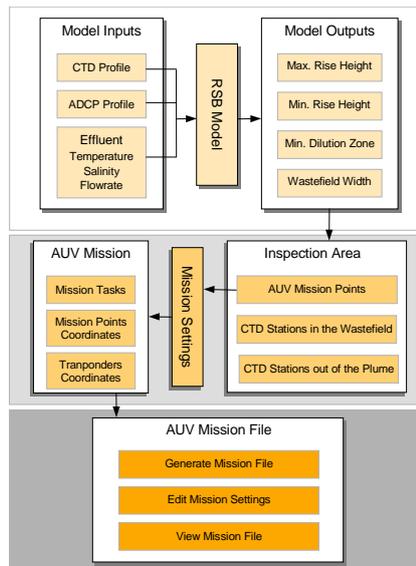


Figure 3: Sensing strategy.

The following two sections describe two applications that implement this methodology. These applications were specially developed to be used in the field.

MONITORING AREA DEFINITION APPLICATION

Due to environment conditions, the field application of the sensing strategy described above would be very difficult unless it would be implemented in an easy to use application.

Figure 4 presents the layout of the application that was developed for the S. Jacinto outfall plume near field detection with the Isurus AUV.

The upper zone of the application performs the operations related with the first layer of the methodology illustrated in Figure 3 while the operations of lower zone correspond to the second layer of the same figure.

The application can be divided in five distinct parts. In the upper zone, from the left the right, following that order we can perform:

- ADCP profile selection;
- CTD profile selection;
- Plume behaviour characterization;

In the lower zone, from the left the right, following that order, we can perform:

- Inspection area definition;
- Locations coordinates specification.

Each of these parts will be described in the following subsections.

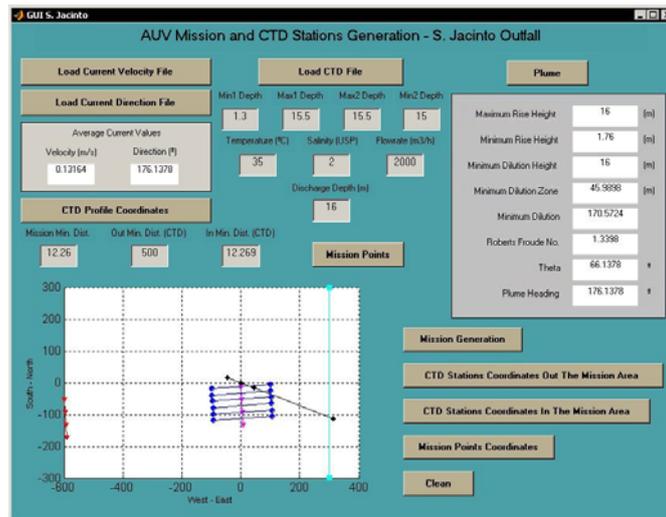


Figure 4: Monitoring area definition application layout.

ADCP Profile Selection

After the ADCP profile acquisition, the velocity and direction current files can be loaded. An internal process will then read the files information, select the relevant data and calculate an average velocity and direction current profile that will be used in the following processes. Average values of current velocity and direction are then calculated, based on the average profile, and printed in the screen in "Average Current Values" box for user information. Afterwards, the geodesic coordinates of the CTD station that has to be performed for background waters characterization can be determinate by clicking on the "CTD Profile Coordinates" button. For S. Jacinto outfall, this geodesic position is specified to be at 500 m distance from the middle point of the diffuser, in the current opposite direction.

CTD Profile Selection

Following the CTD acquisition profile, the text file produced can be loaded from the application using the "Load CTD File" button. A similar process to the one used for ADCP profile generation selects the sensor relevant data, which includes pressure, temperature, salinity, turbidity and pH. A close look to the instability of the profile generated has to be performed in order to validate the gathered data and to select the limits of the downcast and the upcast profiles. A plot of the profile's depth (Figure 5) gives help to determinate these limits that have then to be input in the maximum and minimum depth boxes.

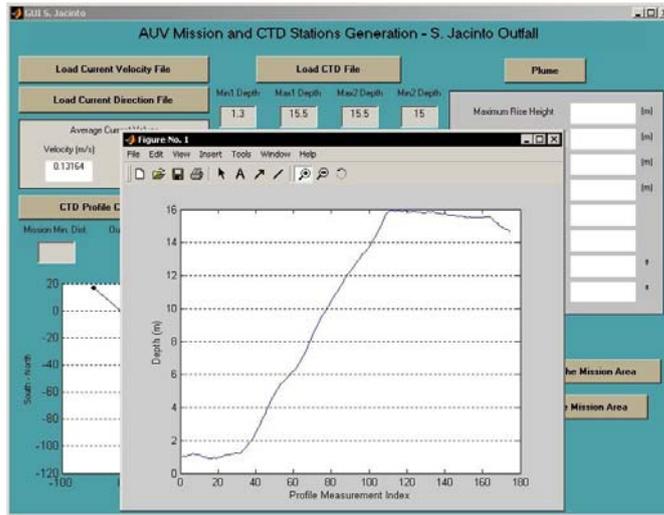


Figure 5: Depth profile plot for downcast limits selection.

Afterwards a multiple plot of the sensor data available, together with density, internally calculated, is showed for user information control (Figure 6).

After effluent temperature, salinity and flow-rate be specified in the application, all inputs can be integrated in the RSB model to produce the plume behaviour characterization.

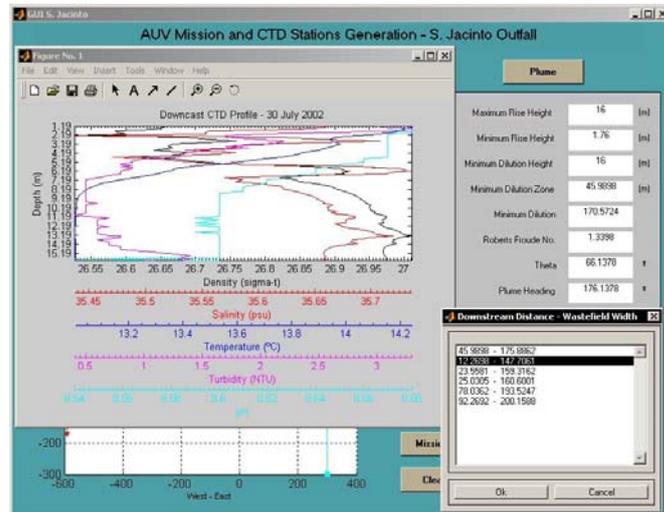


Figure 6: Profile parameters data plot and plume downstream measurement distances.

Plume Behaviour Simulation

A mouse click on "Plume" button generates and prints in the screen the plume characteristics in the end of near field. They include the maximum and minimum rise heights, height to the level of minimum dilution, initial mixing zone length and minimum dilution value. Given the importance of the Robert's Froude number and theta (the angle between current and diffuser axis) for the plume behaviour simulation, they are also printed for user control. The average current direction value effectively used in the RSB simulation is also printed.

Since RSB model integrates only a stable density profile (increasing with depth), this should be created before it can be used in the model. An internally application process creates the density profile assuring that the density parameter increases with the increase of depth.

Inspection Area Definition

An exhaustive previous study to the S. Jacinto outfall plume behaviour for the all seasons [vii] [viii], showed that, even in the Summer time, the initial mixing zone length is, usually, not longer than 100 m and the wastefield width not larger than 200 m. This study also demonstrated that, due to the low discharge depth and low effluent flowrate, the plume is always located in the whole water column a few meters from the sea bed.

These length scales associated with the vehicle batteries power conditions and the navigation requirements established that it would be reasonable to specify the mission transects width 200 meters large, perpendicular to the current direction, covering an area downstream of 100 meters long and 12 meters depth. For a two hours mission this conditions specify 6 horizontal layers with 20 meters spacing between adjacent transects, equally distributed from the 2 to the 12 meters depth, with 2m vertical resolution.

In order to adjust the AUV mission area to the downstream measurement distances used in the RSB model laboratory experiments [5], a list dialog box allows to choose the distance measured in the current direction, from the middle point of the diffuser to the first mission transect.

Besides giving an idea of the plume dispersion in the downstream area, since the wastefield width for the several distances is also calculated, that process also enables to compare more precisely the mapping results with the model equations and consequently evaluates its performance.

The extreme points global position of the parallel transects is then determined for the AUV mission file specification. These points are then displayed with bullets in the application inspection area plot, for user control information (Figure 7).

The transponders global and geodesic position is also calculated for the AUV mission file specification according to the mission area and taking into account the navigation requirements. The transponders geodesic position is then displayed in the screen for its deployment in the sea.

Locations Coordinates Specification

After the specification of the safe distance between the ship navigation and the mission areas, the location coordinates of the four CTD stations are calculated. These CTD stations should be out of the plume downstream area, parallel to the mission transects, spaced of 40 m.

Following a similar process, but in this time taking into account the safe distance between the ship navigation area and the vicinity of the outfall, the four CTD stations located in the interception of the mission area centerline with the transects are calculated. These CTD stations are also spaced of 40 m.

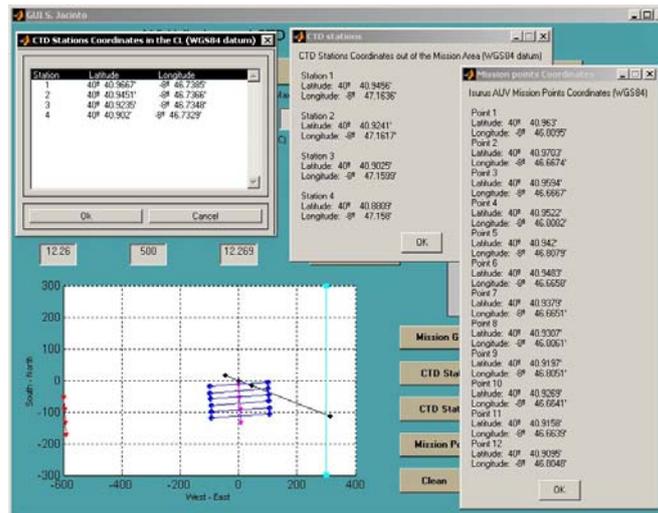


Figure 7: Monitoring area locations geodesic coordinates.

The global positions are then plotted with triangles in the inspection area for user control information (Figure 7) and the correspondent geodesic coordinates are displayed in separate information boxes to be performed during and after the end of the mission.

Geodesic coordinates of the AUV mission file locations are also displayed for help the user to locate the vehicle during the mission.

AUV MISSION DEFINITION APPLICATION

Given the great amount of parameters required to be specified in the vehicle mission file, the real-time generation of the AUV mission demands an automatic process for the creation of this file during the campaign execution.

To cover this need, an application that automatically generates the mission file was developed. This application starts always with a minimal specification common to all missions. Then the user can choose to:

- Define a plume monitoring mission, loading all the relevant data from the application described in the previous section to generate a file for the specific mission, or
- Define an ordinary mission, from the scratch, specifying manually all the mission details. This option can be used, for instance, for test purposes.

The mission transects are displayed in a 3D plot to produce a clear picture of the mission configuration (Figure 8). The user can rotate the 3D figure axes or edit any figure property such as the axes limits or the tick size.

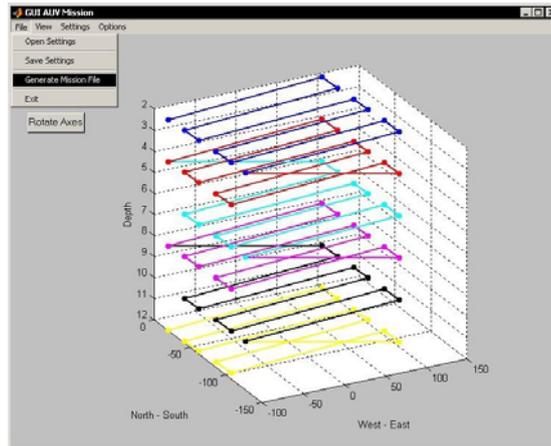


Figure 8: AUV mission definition application layout.

The application is divided in four menus:

- File;
- View;
- Settings;
- Options.

The functionalities of each of these menus will be described in the following subsections.

File Menu

Besides usual options such as open, save or exit, the file menu offers two different functionalities:

- 'Generate Mission File', to create a text file in the format understand by the vehicle and save it;
- 'Save Settings', to save all the relevant data related with the mission definition. The data can then be used for another mission or to look for any information from a previous one.

View Menu

This functionality enables to open the just created mission file to visually verify if there is any problem with the parameters specification (Figure 9).

Settings Menu

This menu permits to define in a friendly way all the data necessary for the AUV mission specification, which are:

- Locations, correspondent to the points necessary to define the mission transects;
- Transponders;
- Reactions;
- Tasks.

The application enables the user to insert, edit or remove locations, transponders and tasks.

Concerning reactions, a vehicle event can only be selected for edition. 'Too Deep' is one of the events that can be edited. Among its fields is the threshold value for the abort event. When the vehicle navigates further than this threshold it will end the mission and surfaces.

Regarding tasks, besides the common tasks, such as the details of the starting position or the sensors calibration time, the transects shape that will be performed during the mission can be defined. The transects shape is specified by, among other fields, the destinations location and the depth mode, as can be seen in Figure 10.

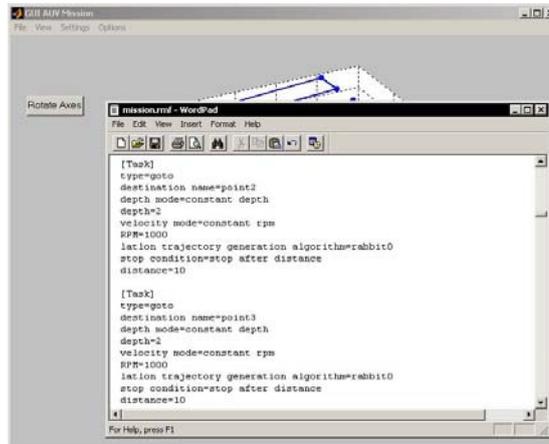


Figure 9: View and edition of the mission file generated.

Options Menu

This menu enables the user to choose the automatic file generation mode for plume detection, launching the Monitoring Area Definition Application, described in the previous section. Besides that, options related with the graphic properties of the 3D-plot can be configured.

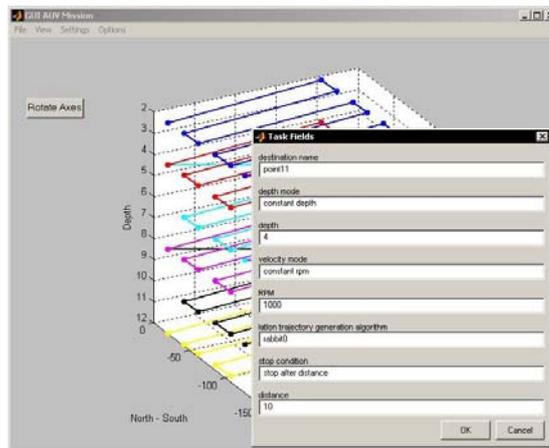


Figure 10: Transects fields edition.

RESULTS

A monitoring mission to detect and map the Aveiro outfall plume using the Isurus AUV was performed in July 2002. This campaign used the two applications described before to specify the plume detection sampling strategy. The data that fill these applications boxes, from Figure 4 to Figure 10, were used in this campaign.

Isurus AUV performed a 2 hours mission with transects shaped as illustrated in Figure 8. Each one of the layers performed at the same depth (horizontal way) is represented in this figure with a different color.

We present the data collected by the Isurus AUV during the mission using two types of plots:

- Vertical sections and,
- Horizontal sections.

The six vertical sections, approximately in the West-East direction, were obtained interpolating data of the longest straight transects perpendicular to the current direction, picking one of each layer (depth). The first section is considered here to be the closest transect to the diffuser. From Figure 4 it can be seen that this first section is distant from the diffuser approximately 12 meters (Mission Minimum Distance) and the following consecutive parallel sections are distanced of 20 meters. Thus, one vertical section is approximately 200 meters width (West-East direction) and covers 12 meters depth.

The six horizontal sections, illustrated in Figure 8 by colored layers, were obtained interpolating data of the six parallel transects at the same depth, covering approximately an area of 100 meters long, approximately North-South direction and 200 meters width, approximately West-East direction. The first horizontal section is considered here to be the closest to the surface and is at 2 meters depth. The following consecutive parallel sections are distanced of 2 meters depth.

Vertical Sections

Figure 11, Figure 12 and Figure 13 present respectively the temperature, salinity and density plots of the six vertical sections. The left plot of first line represents the first section and enumeration increases from left to right and up to down.

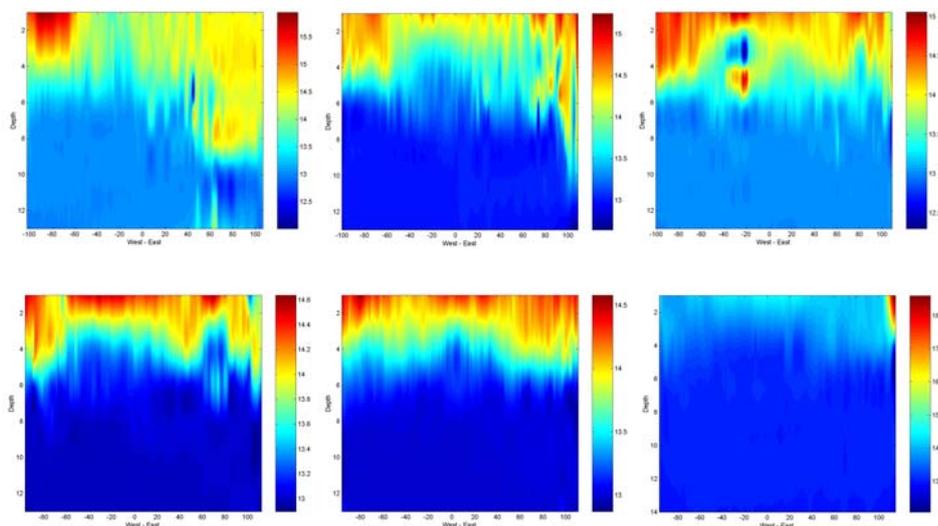


Figure 11: Temperature vertical sections plot.

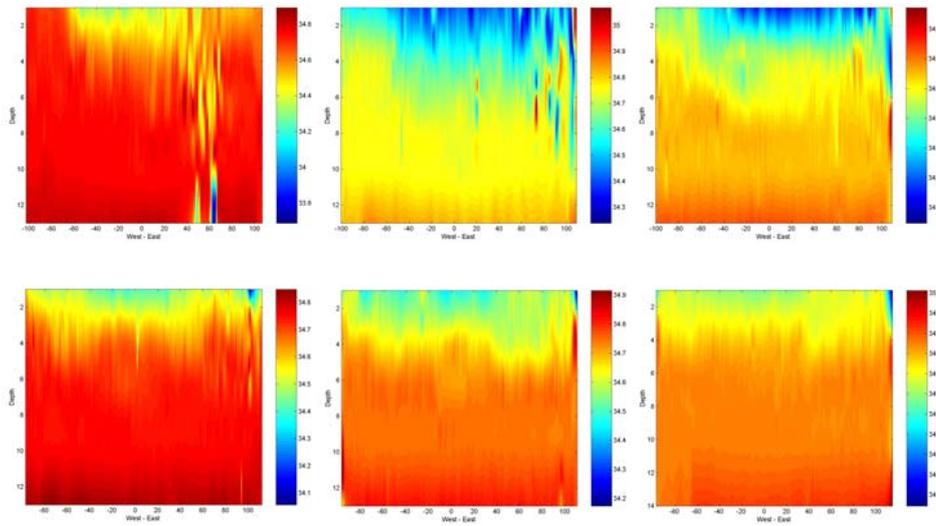


Figure 12: Salinity vertical sections plot.

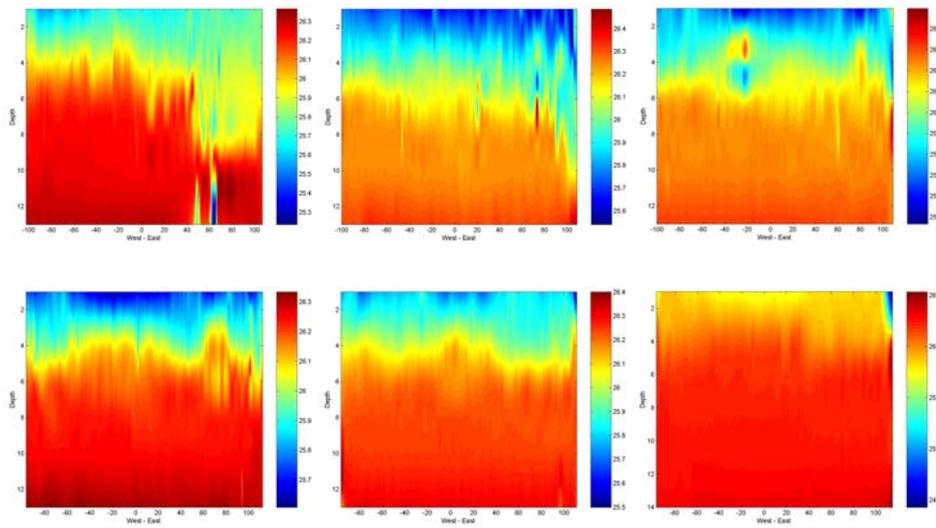


Figure 13: Density vertical sections plot.

Horizontal Sections

Figure 14, Figure 15 and Figure 16 present respectively the temperature, salinity and density plots of the six horizontal sections. As for the vertical sections, the left plot of first line represents the first section and enumeration increases from left to right and up to down.

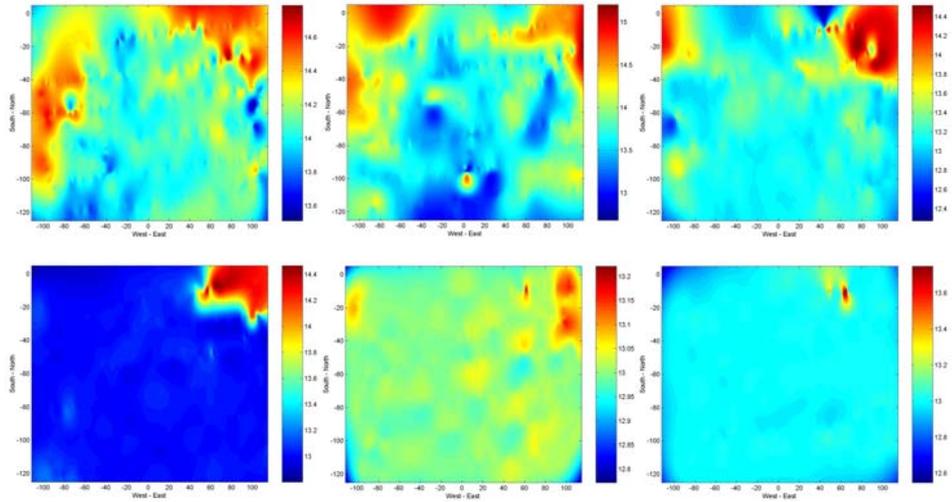


Figure 14: Temperature horizontal sections plot.

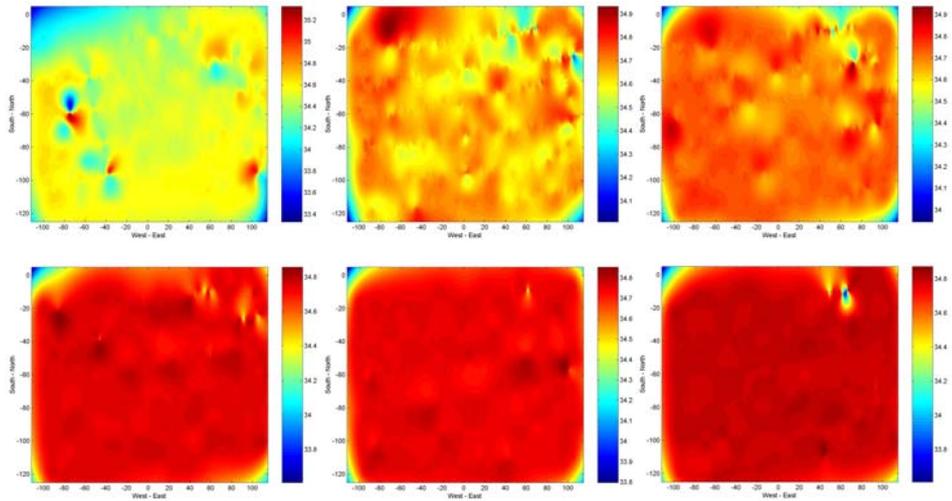


Figure 15: Salinity horizontal sections plot.

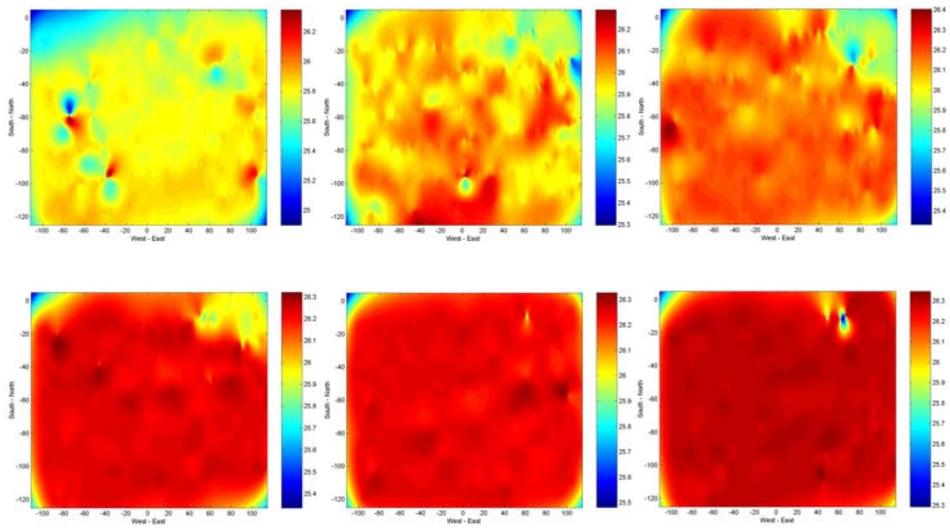


Figure 16: Density horizontal sections plot.

As was mentioned in the Monitoring Methodology section, four CTD stations out of the plume downstream area were performed simultaneously with the AUV mission in order to be checked against the vehicle mapping plot results, for plume recognition.

Figure 18 and Figure 18 present temperature, salinity, sigma-t and turbidity plots for these four stations out of the AUV mission area, and illustrated in Figure 7 with triangles pointing in the direction that were performed. Geodesic coordinates of these stations can also be found in the same figure.

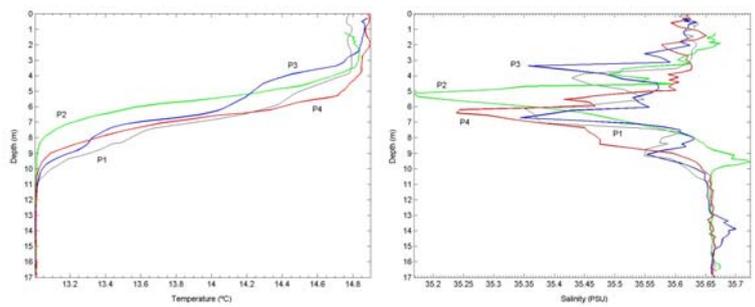


Figure 17: Temperature and salinity profiles of the stations out of the plume downstream area.

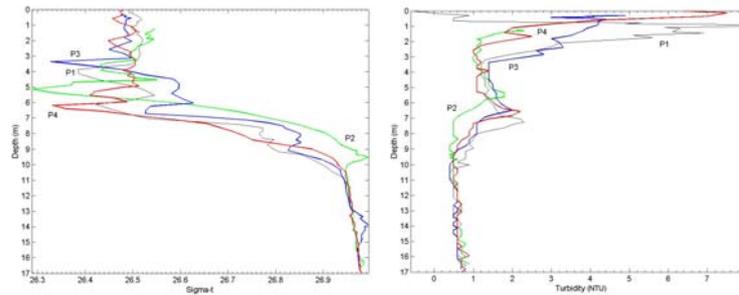


Figure 18: Sigma-t and turbidity profiles of the stations out of the plume downstream area.

DISCUSSION

As expected, the complexity and variability of the environment conditions associated with the uncontrollable parameters involved turn plume mapping a difficult problem to solve.

Several field studies showed that plume mapping with natural tracers is a difficult task. This problem becomes worse if the effluent flowrate is very low, which is the case of S. Jacinto outfall.

The presented data have associated some scale problems that can be caused by two possible factors: the measurement resolution or the interpolation algorithms used.

We can observe from the temperature plots of the vertical sections that no instability in this parameter occurs after the third section. It can be said that the same situation happens for the salinity vertical section plots. Second and third vertical sections of this parameter show an effective signature of lower values in the first 3 meters depth. These sections occur respectively at 32 and 52 meters distance from the diffuser.

These results are in accordance with the predicted results obtained from the RSB model, since the initial mixing length was predicted to be 45 meters.

In the horizontal sections it is not possible to identify any particular signature in one of the parameters studied but it can be observed some instability in the first two layers that it is not clearly present in the lower layers.

CONCLUSIONS

Near field model predictions can be used to reduce the uncertainty about outfall sewage plume location during a monitoring mission.

The successful use of these models is greatly dependent on the integration of real-time inputs. We took this approach, developing two applications, ease to use even in the adverse campaign conditions, which accomplish real-time oceanographic data to automatically define an AUV mission.

Positive results on plume detection using these applications will enable a clear mapping between gathered data and model predictions, allowing model performance evaluation.

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