THE USE OF MATHEMATICAL MODELS AND AUTONOMOUS UNDERWATER VEHICLES TO MONITOR EFFLUENT DISCHARGES

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KEYWORDS
monitoring, autonomous underwater vehicles, wastewater discharges, sea outfalls

ABSTRACT
Near field model predictions can be used to reduce the uncertainty about the location of an outfall sewage plume 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 of this methodology, accomplishing the automatic mission definition using real-time oceanographic data.
An AUV monitoring 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 are difficult to observe in detail. Several field studies exhibit very complex and patchy structures both in vertical and horizontal sections Washburn (1992), Petrenko (1998), Jones (2001), Carvalho (2002). It is not clear yet if this plume patchiness is due to physical processes or measurement limitations. Autonomous Underwater Vehicles (AUVs) are very useful instrument in this case, since they enable an efficient data collection required to detect and map the plume. However their successful use, as any other technique, depends crucially on a sampling strategy. Efficient sampling strategies, defined 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) has been involved in the monitoring program of the Aveiro sea outfall, introducing the AUV technology to detect and map sewage plumes.
In this paper we start with a brief description of a methodology for plume detection using near field model predictions, applicable for AUVs monitoring missions. Then we present two applications that use this 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. Finally, some conclusions are presented.

MONITORING METHODOLOGY
In order to reduce the uncertainty about plume location and concentrate the vehicle mission 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, Roberts (1989), is based on the experimental measurements of Roberts, Snyder and Baumgartner of multiport with diffusers in density-stratified currents of arbitrary direction. It is a length scale model that uses semi-empirical formulations based on the relative magnitudes of the dominant length scales of the diffusion 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 the effluent density. The model outputs used to define the mission area were the maximum and minimum rise height and the length of the 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 1.

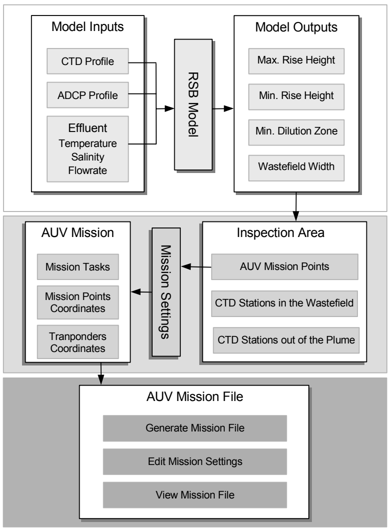

Figure 1: Sensing strategy.

The first layer of the figure 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 (third layer of the figure), where the mission settings can be edited and the mission file generated. This file can then be transferred to the vehicle.
The following two sections describe two applications that implement this methodology. These applications were specially developed to be used in the field.

AUV MONITORING MISSION APPLICATIONS
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. First picture of Figure 2 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 1 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: the ADCP profile selection, the CTD profile selection and the plume behaviour characterization. In the lower zone, from the left the right, following that order, we can perform: the inspection area definition and the locations coordinates specification. Each of these parts will be described in the following subsections.

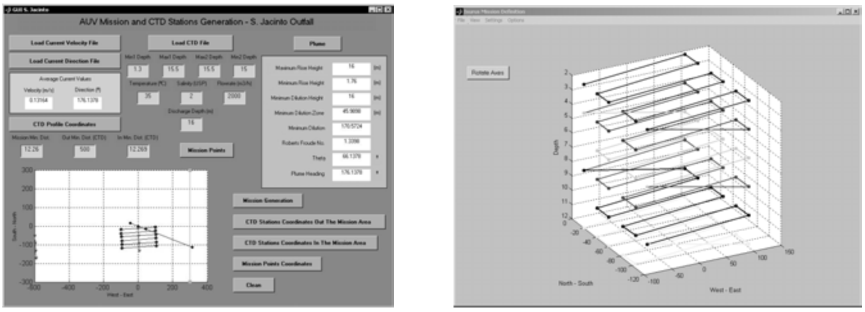

Figure 2: Layouts of the AUV monitoring missions applications.

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.
Following the CTD profile acquisition, 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 gives help to determinate these limits that have then to be input in the maximum and minimum depth boxes. Afterwards a multiple plot of the sensor data available, together with density, internally calculated, is showed for user information control. 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.
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.
An exhaustive previous study to the S. Jacinto outfall plume behaviour for the all seasons 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 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. 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.

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.

The global positions are then plotted with triangles in the inspection area for user control information 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.

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 (second picture of Figure 3). The user can rotate the 3D figure axes or edit any figure property such as the axes limits or the tick size.

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 and plot of the application boxes in Figure 2 were used in this campaign. Isurus AUV performed a 2 hour mission with transects shaped as illustrated in second picture of Figure 2 and first plot of Figure 3. According to the model predictions the plume was established at the surface with a near field length of 45 m, see second plot of Figure 3.

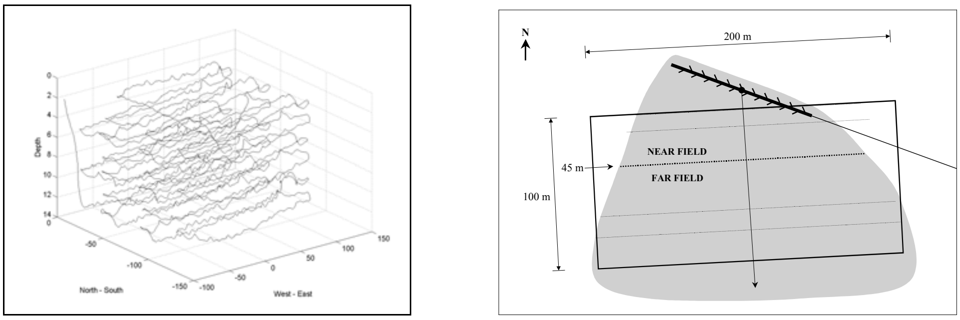

Figure 3: 3D trajectory of Isurus monitoring mission and expected plume position in the inspection area.

As expected during mission performance was obtained continuous measurements of temperature, conductivity and depth. After mission conclusion, using these three measurements were estimated salinity and then density, Fofonoff (1983).

For a better visualization an interpretation of the data obtained were interpolated horizontal and vertical sections. In the Figure 3 are presented the 2D plots of temperature salinity and density of the horizontal sections respectively from top-down at 2 and 4 m depth. In the Figure 4 are presented the 2D plots of temperature salinity and density of the vertical sections distanced from top-down 32 and 112 m from the diffuser.

Relatively to the horizontal sections we can observe clearly the presence of the plume in the centre of the plots, especially in the salinity and density ones were there is a clear reduction. Note that this is in accordance with the results predicted by the model (second plot of Figure 3). The results of the vertical sections denote the plume established at the surface, as expected, with a clear reduction of salinity and density and an increase of temperature in this area. Note that this effect is reduced with the increase of distance to the diffuser, which corresponds to the natural reduction of the plume thickness along the far field.

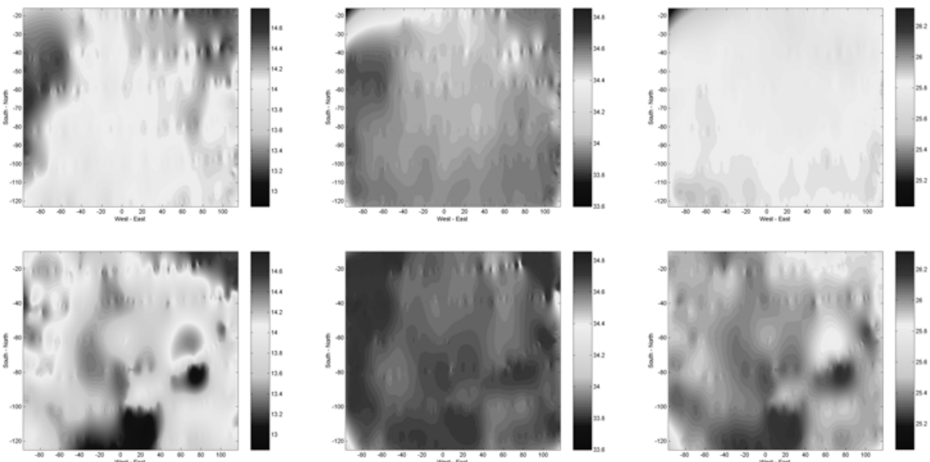

Figure 3 – Temperature, salinity and density of the horizontal sections at 2 and 4 m depth.

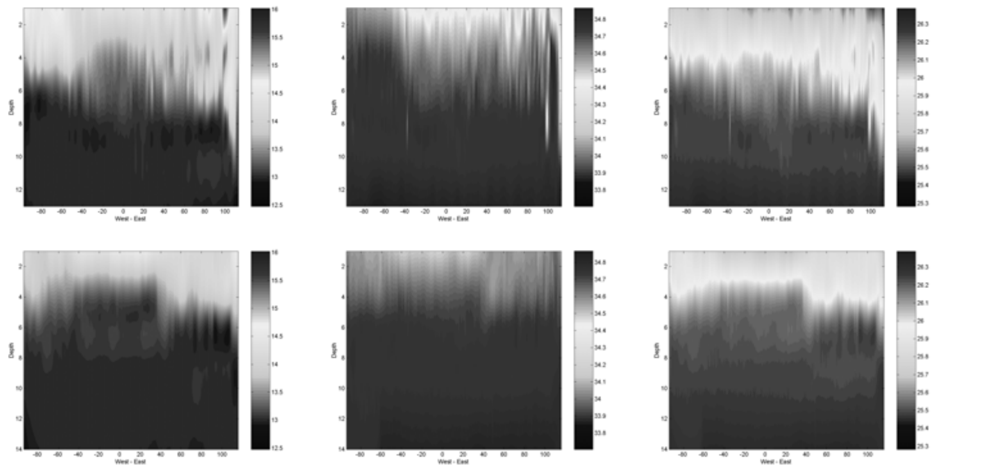

Figure 4 – Temperature, salinity and density of vertical sections distanced 32 and 112 m from the diffuser.

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.

ACKNOWLEDGMENTS

The authors would like to thank the following Portuguese institutions for their collaboration, financial and logistic support: FCT-Fundação para a Ciência e Tecnologia, SIMRIA-Saneamento Integrado dos Municípios da Ria, ISR-Instituto de Sistemas e Robótica, IH-Instituto Hidrográfico and INETI-Instituto Nacional de Engenharia e Tecnologia Industrial.

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