Mapping Ocean Outfall Plumes and their Mixing using Autonomous Underwater Vehicles

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Abstract

This paper reports on our experiences developing methods to survey an ocean outfall discharge plume using an Autonomous Underwater Vehicle (AUV). . The mobility of an AUV provides a significant advantage in surveying discharge plumes over traditional boat-based methods, and when combined with optical and oceanographic sensors, provides a capability for both detecting plumes and assessing their mixing in both the near and far-fields. Unique to this study is the optical sensing of of the presence of Colored Dissolved Organic Matter (CDOM) in the discharge plume for quantitatively assessing the dilution ratio of the plume water. This capability is demonstrated for two Publicly Operated Treatment Works (POTWs) located offshore San Diego, California that have significantly different environmental settings and operating parameters. The first is the South Bay Ocean Outfall (SBOO) operated by the International Boundary Water Commission (IBWC) whose discharge is located in approximately 30m deep water at a flow rate of 28 million gallons per day (MGD). The second discharge is the Point Loma Ocean Outfall (PLOO) which discharges at approximately 90m with a nominal volume flow rate of 250 MGD. The methodologies for planning the AUV missions to sample the discharge plume, characterizing the plume using the signals measured by the onboard oceanographic and optical sensors, and use of those data in predictive models is outline. The results suggest that even in variable oceanic conditions, properly planned missions for AUVs equipped with appropriate sensors can accurately characterize and track ocean outfall plumes with high spatial resolution more effectively than traditional methods.

Keywords
Ocean outfall monitoring, plume mixing, colored dissolved organic matter (CDOM), autonomous underwater vehicle (AUV)

INTRODUCTION

Routine ocean outfall plume detection and mapping remains an elusive task for operators of Publicly Operated Treatment Works (POTWs), yet is often a requirement for permits which require monitoring the receiving waters to assess environmental impacts and exceedances of regulatory standards. A principal challenge in tracking a plume is spatial variability of the ocean currents and density structure in coastal waters, resulting in uncertainty in assessing plume direction when sampling at discrete time intervals – all too often the plume is missed. For example, Terrill et al (2009) show that monthly sampling of a discharge offshore San Diego using traditional Conductivity, Temperature, Depth (CTD) grids were only able to detect the discharge plume twice out of 16 monthly surveys. The density stratification and primary current direction are typically used in the design phase of siting a POTW discharge and estimating bulk plume properties such as rise height, width, and thickness, but the environmental information is often not available to guide the sampling of the plume on a routine basis. Likewise, sensors for clear, unambiguous detection of the wastewater plume are not routinely used within a discharger's monitoring plan to characterize the location of the plume.

Evolving technology in the field of oceanographic instrumentation continues to enhance survey methods for detecting and mapping ocean outfall plumes. Traditional methods of plume detection include using natural tracers associated with the effluent (Jones et al., 1990, 1991, 1993; Washburn et al., 1992; Wu et al., 1994), acoustic backscatter methods (Dammann et al., 1991; Besiktepe et al., 1995; Petrenko et al., 1998) and introduced tracer techniques (Proni et al., 1994; Carvalho et al., 2002; Hunt et al., 2010). Since these methods are traditionally employed from boats operating in a survey mode or involve capturing water samples at a limited number of stations, the analysis of the data is often difficult due to poor spatial sampling that may not represent the full extent of the plume making it difficult to accurately measure its characteristics (Ramos et al., 2007). Modern techniques using the methods listed above on a mobile platform, an autonomous underwater vehicle (AUV), have proven to be a more effective approach for mapping ocean outfall plumes (Wu et al., 1994; Fletcher, 2001; Ramos, et al., 2000, 2002, 2007). AUVs increased spatial resolution, adaptive sampling options, and reduced spatial aliasing effects, decreasing operational costs. This has made them an appealing approach when compared to traditional monitoring techniques.

This paper presents a plume mapping method utilizing as natural tracer colored dissolved organic matter (CDOM) measured by a Remote Environmental Measuring UnitS (REMUS) class AUV. Near real-time in situ current and temperature profiles were measured by an Acoustic Doppler Current Profiler (ADCP) and thermistor chain at the outfall. The support mission planning included particle trajectory estimates and prediction modelling of near-field behaviour of the buoyant discharge jet. These data served as decision aids for adaptively planning AUV missions. In this paper we present successful measurements of plume rise height, width, mixing zone length, thickness and dilution ratios, under highly variable ocean conditions, using the Scripps REMUS on the South Bay Ocean Outfall (SBOO) and the Point Loma Ocean Outfall (PLOO). Specifications for each outfall are shown in Table 1.

Ocean Outfall Specifications

Table 1. South Bay Ocean Outfall (SBOO) and Point Loma Ocean Outfall (PLOO) specifications.

	Depth of Discharge (m)	Average Flow (m^3/s)	Study Period	Diffuser Type	Operators
SBOO	27	1.05	July 2007 – October 2008	Y-shaped (Only 1/3 of lower leg operational)	International Boundary Water Commission
PLOO	95	7.36	April 2010 – April 2011	Y-shaped	City of San Diego

Figure 1. Location map of South Bay (SBOO) and Point Loma (PLOO) Ocean Outfalls.

SBOO/PLOO Moorings

Oceanographic buoys designed by Scripps Institution of Oceanography for realtime monitoring of ocean conditions at a POTW discharge were used for this study and were similar in configuration at the SBOO and PLOO. The mechanics of the mooring consists of a surface buoy that contained an Acoustic Doppler Current Profiler (ADCP TRDI Instruments, San Diego, CA)[1], a temperature chain (Precision Measurement Engineering, Encinitas, CA)[2], a self-contained temperature and salinity sensor (Seabird Electronics, Seattle WA)[3], and Scripps-built data logger, satellite telemetry unit, Global Positioning System (GPS) receiver, and a battery pack. All mechanical aspects of the buoys', mooring, and anchoring system were designed and fabricated by technical staff within the research group. The system was designed for a nominal 6-month servicing interval to replace sensor batteries and offload data from the internal memory recorders. Due to mechanical wear and fatigue on the mooring components, major components of the mooring (swivels, chain, and shackles) were also replaced at this time. Ocean currents were measured using a downward looking ADCP that provided profiles of ocean currents from 4.3 m to the sea floor.

Measurements of water column stratification were made using temperature sensors located at different depths. For each buoy, a temperature chain was employed, which consisted of 10 nodes spaced across the

[1] Manufactured by Teledyne RD Instruments
[2] Manufactured by Precision Measurement Engineering
[3] Manufactured by Seabird Electronics

water column, each measuring ocean temperature with accuracy of 0.01°C. Measurements at each depth were time-synchronized to provide a water column profile of stratification at 5-minute intervals. Both data from the ADCP and temperature chain were transmitted hourly via Iridium satellite message, and posted to a website for data access within minutes of transmission. The near real-time data, and graphical products of trends in stratification and currents are generated hourly in an automated fashion

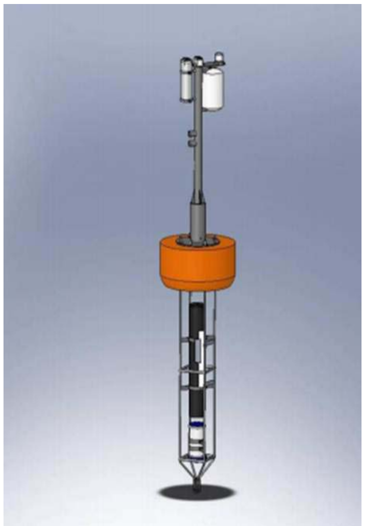


Figure 2. Drawing and a photograph of the Scripps-designed coastal buoy system for measuring stratification and currents at the South Bay and Point Loma Ocean Outfalls.

REMUS AUV

The Remote Environmental Measuring UnitS (REMUS)[4] (Figure 3) vehicle is an autonomous underwater vehicle with a 100m depth rating and 22 hour battery capacity when transiting at 3 knots. Mission life is a function of speed, and decreases to 8 hours at maximum speeds of approximately 5 knots. The system uses both onboard navigation sensors (compass for heading, Doppler Velocity Log (DVL) for speed and altitude over seafloor, and pressure sensor for vehicle depth) and external sensors (GPS, transponders) for navigation. Survey missions are developed and uploaded to the vehicle before deployment using a Wi-Fi connection. The vehicle is typically launched by two persons from the boat at a pre-set location to begin its mission. Upon mission start, a GPS fix is obtained before the vehicle dives below the surface to initialize its navigation. During the mission, the vehicle relays its position, status, and engineering data using an underwater acoustic modem system to a receiver on the ship. Typically messages are transmitted every 2-3 minutes. In addition, the shipboard system can range the vehicle as well as send low level commands (start, stop, abort). Upon completion of the mission, the vehicle is again recovered by two personnel.

[4] Manufactured by Hydroid LLC

Figure 3. The Remote Environmental Measuring UnitS (REMUS) vehicle on board prior to deployment uses GPS, an acoustic doppler current profiler (ADCP), conductivity, temperature, depth (CTD), optical backscatter, and colored dissolved organic matter sensor (CDOM).

The vehicle also includes an array of instrumentation for environmental monitoring. The combination of the conductivity, temperature, depth (CTD) and optical sensors (the standard tools used in boat-based National Pollutant Discharge Elimination System (NPDES) monitoring programs) placed onto a flexible platform such as REMUS, lends itself well to the plume mapping through surveying changes in ocean properties. The REMUS has four main sections—a nose section, with a 1200 kHz ADCP, a mid-body, and tail section. The nose section contained both the Ultra-Short BaseLine (USBL) and Long BaseLine (LBL) acoustic navigation transducers. Initial instrumentation also included the following sensors: YSI CTD, WETLabs BB2F (optical backscatter and chlorophyll-a). During initial surveys at the SBOO, boat based sampling of the plume water indicated it had an elevated CDOM signature. Thus, to optimize plume tracking the AUV payload was augmented with a higher resolution CTDand a WETLabs ECO triplet capable of measuring optical backscatter and CDOM. The higher resolution CTD (Neil Brown Instruments, Falmouth, MA) samples data at 1 Hzand allows for accurate data collection across temperature and salinity gradients.

The three dimensional track of the REMUS is available after each outfall survey and is the first step in data assessment to verify the region sampled is consistent with survey objectives. Figure 4 shows examples of a a) plan view of a near-field SBOO mission on March 3rd, 2008 and b) a three dimensional view of an undulating survey and PLOO tracks on August 3rd, 2010. The 'mow the lawn' pattern for SBOO sampled at1 Hz at three nominal depths centered at 20 m, 15 m, and 10 m with a speed of 3.5 knots with a resulting horizontal resolution of 1.5 m. In addition, an oval track measured around the effluent source using a 6 m vertical saw tooth pattern for depth ranges 3 – 9 m, 10 – 16 m, and 17 – 23 m, yielding a horizontal resolution of approximately 57 m (defined as distance between same depth measurements). Similarly, the far-field PLOO mission shown in Figure 4 utilized a saw tooth patterns typically between 30-90 m to increase spatial sampling of the study area. For far-field missions, it was not feasible to map the plume at successive depths similar to near-field missions due to mission length and battery life limitations. The pattern shown was found to be a good balance between spatial coverage and mission length for far-field missions.

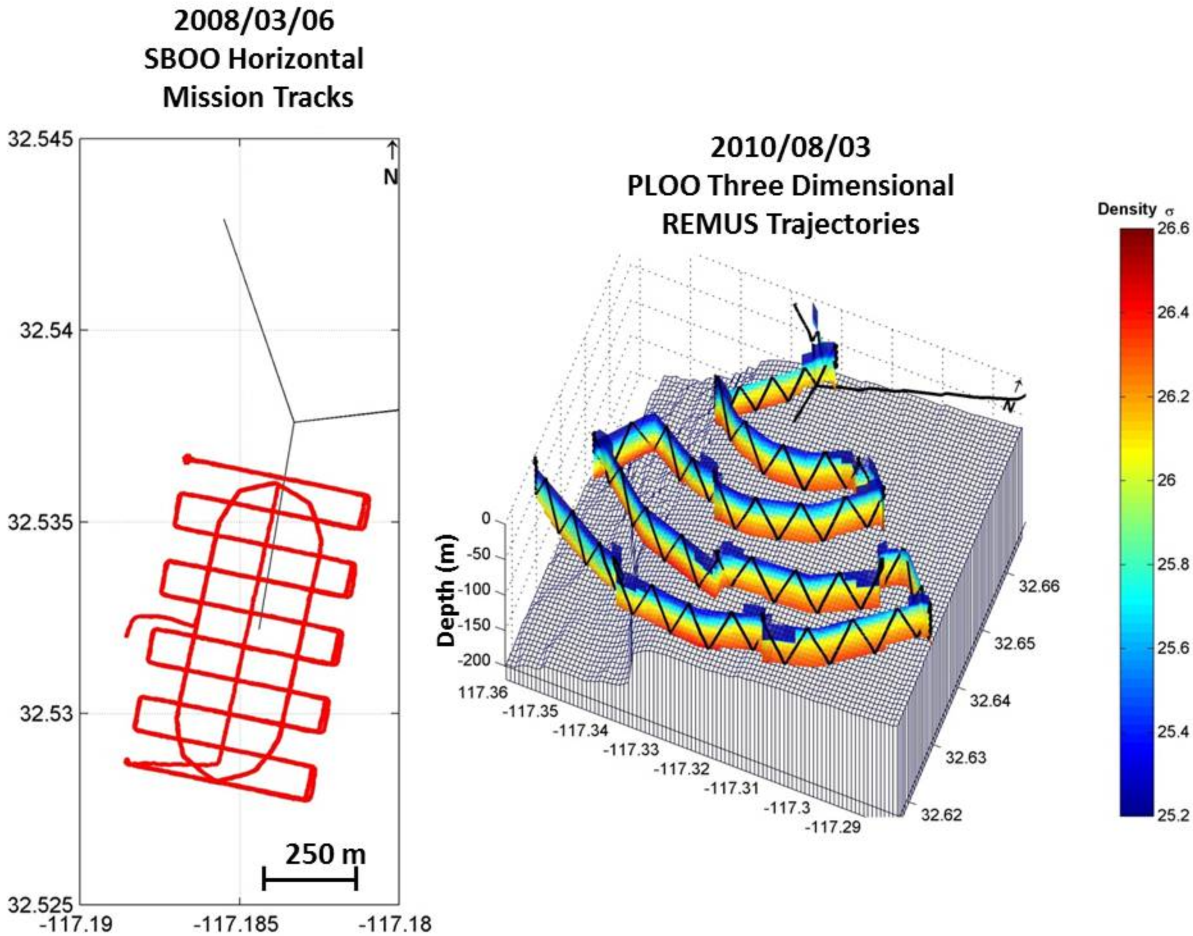


Figure 4. Examples of 2D SBOO and 3D PLOO mission tracks for March 6th, 2008 and August 3rd, 2010 respectively. a) *SBOO:* The lawnmower-like pattern was measured at approximately 20 m, 15 m, and 10 m while the oval was measured using 6 m saw tooth pattern for depth ranges 3 – 9 m, 10 – 16 m, and 17 – 23 m. b) *PLOO*: Saw tooth trajectory pattern typical for far-field missions. Horizontal resolution between saw tooth measurements is approximately 450 m.

MISSION PLANNING

The area around an ocean outfall can be separated into two distinct regions in which different mixing processes dominate. After leaving the diffuser, the buoyant plume quickly mixes as a turbulent jet in a region local to the discharge(Roberts, 1989). The majority of the mixing occurs during the plume rise in the near-field and has a characterisitic dilution ratio dependent on the engineering parameters of the discharge and the receiving water density structure. In the far-field, dilution increases at a much slower rate due to background oceanic turbulence driven by winds, tides, along-shore pressure gradients, and internal waves.

To estimate the near-field plume height pre-mission, the U.S. EPA Roberts-Snyder-Baumgartner (RSB) plume model was applied to the buoy mooring data (Roberts et al. 1989, Roberts 1999a, Roberts 1999b, B.Jones, personal communication). The RSB model is based on piece-wise linear stratification assumptions between mooring buoy observations and uniform currents, for straight diffusers, assuming Gaussian distribution of the concentration of waste field at the end of near-field (Roberts 1999a, Roberts 1999b, Frick et al. 2001).

An ongoing problem in accurately tracking the plume is the design of an effective sampling plan (Ramos et al., 2002). Variable oceanographic conditions require a flexible mission plan that can be changed to adapt to the current ocean conditions at the time of sampling. For SBOO and PLOO missions, multiple missions would be planned and developed prior to sampling using near real-time oceanographic conditions at the outfall as monitored by the buoy coupled with near-field plume model predictions.

In the days preceding a monitoring mission, RSB model outputs and telemetered time series from the moored buoy instrumentation were utilized for PLOO REMUS path planning. Figure 5 shows the RSB output of predicted plume rise height and thickness (black lines) overlaid on plume density for November 2010. The observed plume rise height and mid-point are shown for monitoring missions on November 16th and 30th. In the days leading up to each mission, these types of analysis were conducted to serve as mission planning aids for optimal mission depths of the vehicle. For each mission shown in Figure 5, 30 – 90 m was the depth range selected for the REMUS which was based on the predicted rise height and thickness of the plume.

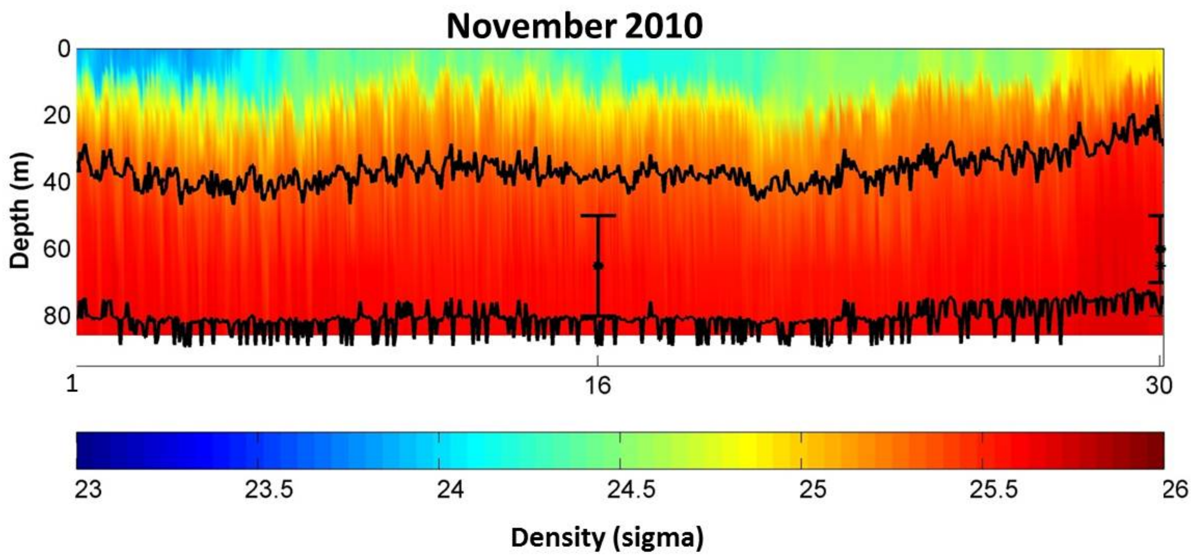


Figure 5. RSB model output illustrating predicted plume rise height and thickness based on plume density data input. Such outputs were generated before each mission to plan mission depth ranges. Observed mid-point, thickness, and rise height are shown for November 16th and 30th missions. The depth range chosen for each mission based on this output was 30 -90 m.

Mission planning for sampling the far-field plume rely upon time series analysis of data from the buoy's current profiler. These data are used to generate automated hourly spatial plots of estimated plume trajectories and plume age (Figure 6). The web-accessible information served as a key decision aid for horizontal path planning of each plume survey. When used in conjunction with the adjacent 25-hour averaged current profile plot, REMUS mission paths (dotted line) were chosen to spatially optimize plume measurements within the constraints of the vehicle life. Hourly current velocity profiles were also monitored in the hours leading up to the mission. If conditions had changed significantly from the time of mission planning, adjustments to the track could be made to increase the chances of successful plume detection.

An example of this planning tool, for plume trajectories at depths 60, 65, 70, 80, 85, and 90 m is shown in Figure 6. Hourly ADCP data is used to generate estimated positions of a particle (water parcel) discharged at the outfall (0 hour) for a two day period. Figure 6 and current profile data were the key decision aids used to design a PLOO far-field mission. Due to the discharge depth (95 m), typical stratification conditions, we found through the RSB model output that the likelihood of the PLOO plume surfacing was low. In contrast the SBOO discharge is at a depth of 27 m and has been found to surface during weak stratification conditions (Terrill et al 2009). Thus, in addition to the methods described above, near real time high frequency (HF) - radar-derived surface currents were reviewed daily to assist in mission planning as the surface current data could be used to track the plume location (Kim, Terrill, Cornuelle 2009).

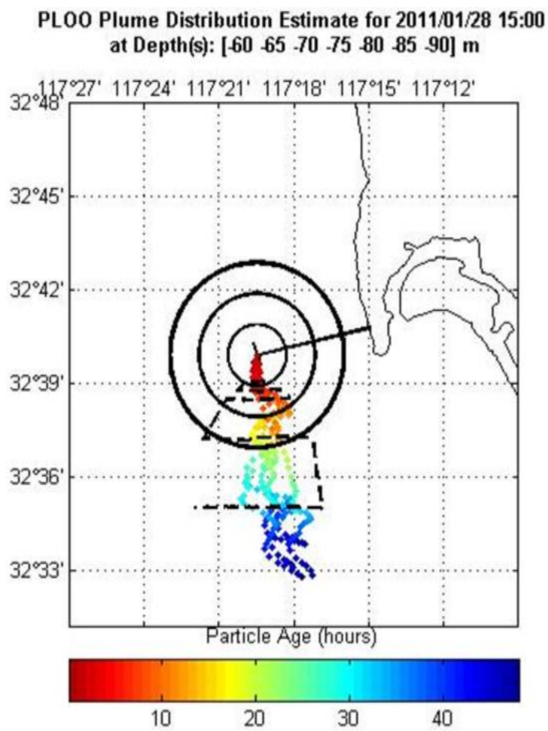


Figure 6. Near real-time PLOO plume trajectory estimate for depths of 60, 65, 70, 75, 80, 85, and 90 m from the PLOO mooring buoy. The 2D monitoring mission (dotted line) was designed to optimally sample the plume location within the constraints of the vehicle's operating parameters. Circles at 1 km, 2 km, and 3 km radius give approximate distance from the outfall.

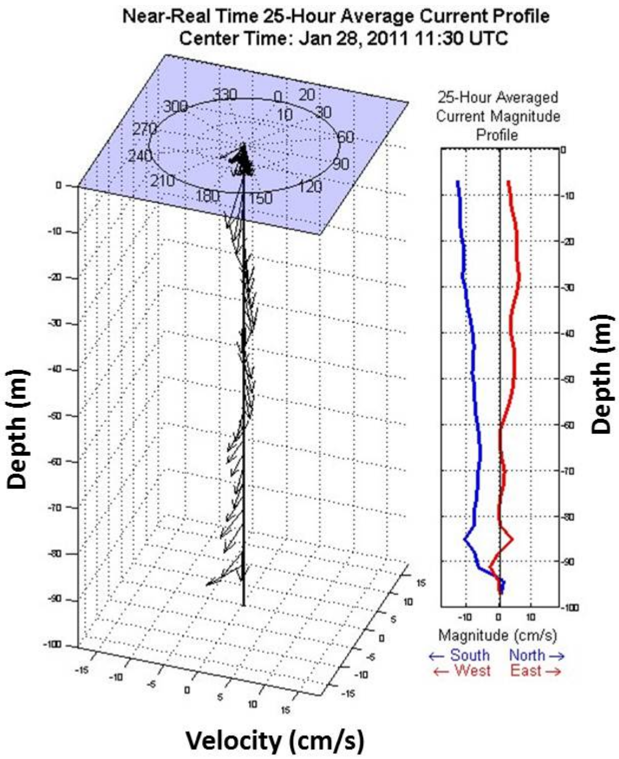


Figure 7. A 25-hour averaged ADCP profile plot for January 28, 2011 used to plan a PLOO monitoring missions. The profile shows a southerly current direction (blue line) with little east/west current in the bottom half of the water column (expected plume depths).

RESULTS AND DISCUSSION

SBOO Plume Surveys

A total of 18 plume sampling missions were conducted between July 2007 and October 2008 using the REMUS and boat-based CTD’s. The SBOO plume was sampled during dry weather when both high and low stratification conditions were present, as well as when the plume was being advected to the north and to the south. Wet weather sampling typically occurred during low levels of stratification.

At the SBOO, our initial tools for plume detection were optical backscatter measured at 660nm and salinity signatures caused by the mixing of fresh plume water with the seawater. The plume can be consistently detected by an elevated optical backscatter signal and low salinity in the near-field while the low salinity signature often persisted in the far-field (up to 3.7 km). Seawater salinity in the vicinity of the outfall ranges from 33.7 psu in winter months to 34.2 psu during summer and the outfall plume has a signature of 0.07 to 0.2 psu below ambient seawater. However, use of optical backscatter and salinity alone did not always provide a robust method for far-field detection because of other sources of variability for those scalars. Large variations in the vertical salinity profile relative to the plume signature can obscure plume detection while other sources of suspended particles, such as the bottom nepheloid layer (a layer of sediment suspended near the seafloor by current scouring) and organics from the kelp beds, introduce optical backscatter signals similar to those found in the discharge plume.. Despite these limitations, the plume was identified in all but one mission (17 out of 18) by using the spatial pattern of the plume emanating from the known discharge location and supporting velocity data from the SBOO buoy regarding the most probable plume trajectory.

In light of varied results in distinguishing plume water using only optical backscatter, a CDOM fluorometer and high resolution CTD were integrated into the REMUS. CDOM exists naturally in seawater and freshwater environments and can consist of decaying organics and is typically a good indicator of fresh water land inputs.

An example mission for resolving the near-field characteristics of the discharge was conducted on March 6, 2008. Velocity measurements from the SBOO buoy show that flow is toward the south-southeast, and temperature measurements show that stratification is relatively weak with a 3 degrees Celsius (°C) temperature difference between bottom and surface waters. Plume signatures of elevated CDOM in the south-southeast are consistent with the estimated plume distribution based on SBOO buoy velocity measurements because the core of the plume is aligned with the estimated distribution (Figure 8). The core of the plume has CDOM values as high as 10 ppb.

Dilution Estimation

Plume dilution in the near-field can be estimated using natural tracers associated with a sewage plume. For the SBOO, dilution is estimated using the natural tracers temperature (*T*) and salinity (*S*) and their graphical representation on a *T*-*S* diagram, with initial mixing lines between wastewater and ambient waters similar to the methods presented by Washburn et al., 1992, Petrenko et al., 1998, and Ramos et al., 2007. Once discharged from the diffuser, wastewater (with temperature T_e and salinity S_e) mixes with the surrounding ambient waters (T_a and S_a) at the depth of the diffuser. The mixed water mass (T_m and S_m) correspond to an intermediate point on the initial mixing lines linking the effluent and ambient T-S points. T_m and S_m vary according to the dilution factor between effluent and the ambient water characteristics near the diffuser. For a given dilution D, T_m and S_m are equal to (Fischer et al., 1979):

$$T_m = T_a + \frac{1}{D}(T_e - T_a) \qquad (1)$$

$$S_m = S_a + \frac{1}{D}(S_e - S_a) \qquad (2)$$

Observations presented as a function of CDOM on the *T*-*S* diagram show that the SBOO plume has a distinct water mass with a relatively fresh signature (approximately -0.7 parts per thousand [ppt] lower than ambient waters) and elevated CDOM values (Figure 9).

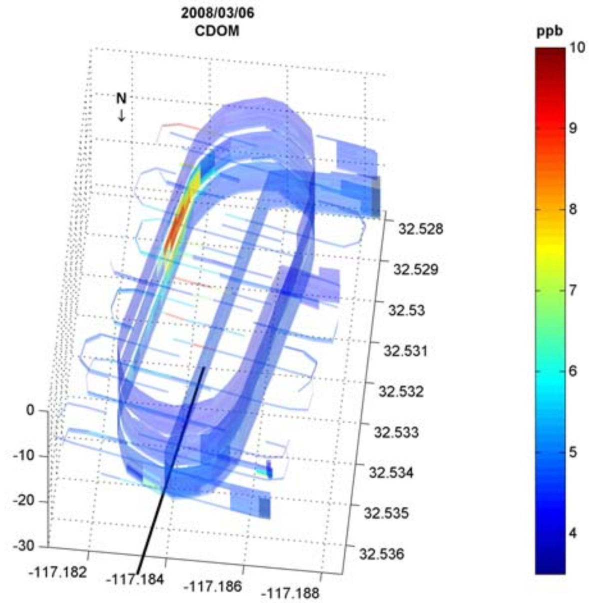


Figure 8. SBOO Plume Organic Matter Concentrations. Elevated values of CDOM (>7 ppb) indicate high concentrations of organic matter in the SBOO plume. The SBOO is shown in black with the observed plume toward the south-southeast. The observed plume is coincident with the plume trajectory (colored lines) estimated from the SBOO buoy velocity profiles.

Once discharged from the diffusers, wastewater, which has lower density than the surrounding ambient waters, rises until an equilibrium depth is reached or it surfaces. Most of the mixing is considered to take place during the plume rise in this zone and is often referred to as the initial mixing zone. Initial effluent characteristics for the SBOO are used as the wastewater endpoint on the initial mixing lines and are defined as $T_e = 21^o$ C and $S_e = 0$ ppt (Wayne Belzer, SBOO manager, personal communication, April 1, 2011). Data from the March 6, 2008 mission indicated that some of this initial mixing was occurring between 25 m and 23 m depth. Two ambient *T-S* points unaffected by wastewater were used as end points for the initial mixing lines at these depths. The range of T_a and S_a account for the natural variability in ambient conditions. Given these characteristics, two initial mixing lines were drawn between the effluent *T-S* point and the two ambient *T-S* points (Figure 9). Each point on the initial mixing line is separated by a dilution interval of 1:50. According to this plot, the core of the plume (which is easily distinguishable based on CDOM values) is located above the mixing lines indicating that the plume water has mixed with water shallower than the defined initial dilution zone. However, several T-S points fall between the initial mixing lines with initial dilutions ranging from just below 100 to 200.

This mission did not observe the plume surfacing, however, given the relatively weak stratification; it is probable that the plume rose to shallower depths at a location outside the scope of sampling. Observations were likely made in a still rising plume, meaning minimum dilution estimations cannot be made from these data.

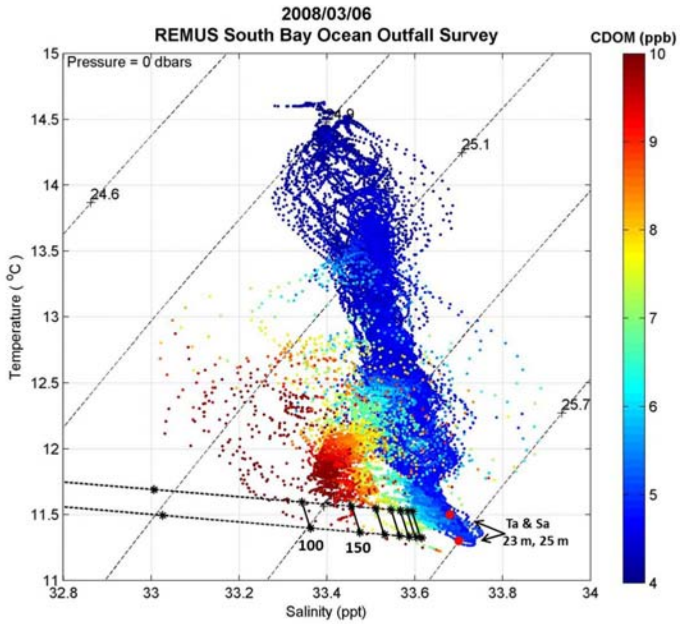


Figure 9. A Temperature-Salinity (*T-S*) Diagram colored by CDOM concentrations for sampling conducted on March 6, 2008, shows the plume as a distinct water mass with a low salinity (approximately 33.4 ppt), high CDOM (>6 ppb) signature. Lines of constant density are shown with dashed lines. Initial mixing lines show a range of initial dilutions between 100 – 400 ppb.

PLOO Plume Surveys

A total of 19 REMUS plume sampling missions were conducted between April 2010 and April 2011 on the PLOO. The study area did not have the same constraints as the SBOO study area. The mission ranges varied between less than 1 km and 9 km depending on mission objectives. The plume was sampled during high stratification conditions which persisted throughout the year, as well as when the plume was being advected to the north and to the south.

Dilution calculations from previous work have traditionally relied on the natural tracers temperature and salinity and their graphical representation on a *T-S* diagram as presented by Washburn, 1992 or dye tracer techniques (e.g. Proni et al., 1994; Carvalho et al., 2002; Hunt et al., 2010). The use of *T-S* diagrams is only effective at estimating initial dilutions near the diffuser, while using artificial tracers are not practical for routine monitoring. A method was developed to use CDOM as measure of the plume dilution in both the near and far-field.

Source Effluent CDOM Dilution Calibration: January 25th, 2011

A WETlabs ECO Fluorometer calibrated to measure CDOM at fluorescence excitation/emission (Ex/Em) = 370/460 nm proved to be an effective technique in plume mapping during the SBOO missions. Similar conclusions were found by Petrenko et al., 1997 while using a fluorometer at Ex/Em 228/340. They concluded that lower wavelengths are unaffected by phytoplankton layers and in contrast with salinity; do not decrease with shallower depths. Thus, it may be a more promising technique than traditional natural tracer methods (salinity, backscatter).

A calibration using source effluent from the Point Loma Wastewater Treatment Plant (PLWTP) was conducted to determine the relationship between the source effluent CDOM signature and the dilution ratios as calculated from CDOM. A black 100 gallon tank was utilized for high dilutions (1:50 to 1:600) while a black 5 gallon tank was used for lower dilutions values (1:1 to 1:25). Both containers were tested to ensure no bias was created by the sampling setup and the dark tanks were used to remove stray light. Seawater with background CDOM concentration of 3.96 ppb, was used to dilute the effluent to achieve the desired ratios (Figure 10). The calibration curve shows a linear trend with an R^2 value of 0.9876 and a maximum dilution of 1:600. Dilutions above this ratio did not exhibit a measurable difference from background CDOM signatures. The CDOM signature of the source effluent measured 117 ppb and had a consistent value in separate calibrations. Assuming that CDOM is a conservative tracer, dilutions of plume water are calculated in both the near and far-field regions by manipulating the equation:

$$C_2 = \frac{C_1 V_1}{V_2} \quad (3)$$

where C_1 and V_1 are the initial concentration and initial volume, and C_2 and V_2 are the new concentration and new volume. Substituting variables yields:

$$C_{sw} = \frac{C_{ww} V_{ww}}{V_{ww} + V_{sw}} \quad (4)$$

where:

C_{sw} = CDOM concentration of plume water (minus background concentrations);
C_{ww} = CDOM concentration of effluent;
V_{sw} = Volume of seawater;
V_{ww} = Volume of wastewater.

Let V_{ww} = 1 and solve for the parts of seawater (V_{sw}) required to reach the measured seawater concentration:

$$V_{sw} = \frac{C_{ww} - C_{sw}}{C_{sw}} \quad (5)$$

Equation 5 allows for calculation of the entire dilution field based off of the CDOM *T-S* diagrams of each PLOO mission. Figure 11 show the *T-S* diagram (top image) from the February 28th, 2011 PLOO mission used to calculate the subsequent dilution field (bottom image). The CDOM signature of the plume clearly distinguishes the plume from the surrounding ambient water allowing for estimates of the dilution of plume water. For each CDOM measurement within the plume, C_{sw} is calculated by subtracting the background CDOM value from the measured value. Knowing C_{ww} = 117 ppb, the dilution field is calculated using equation 5. A dilution of 1:100 is shown in the core of the plume decreasing to 1:250 at the areas of the plume adjacent to ambient waters.

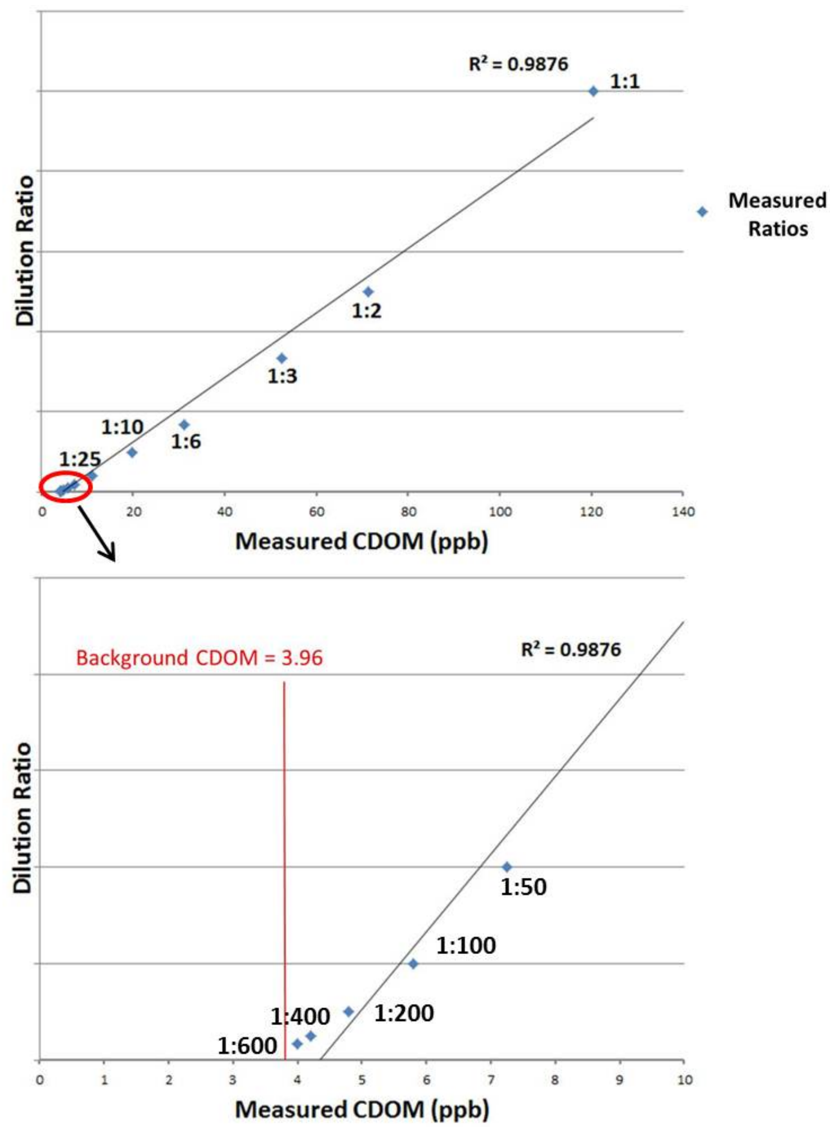
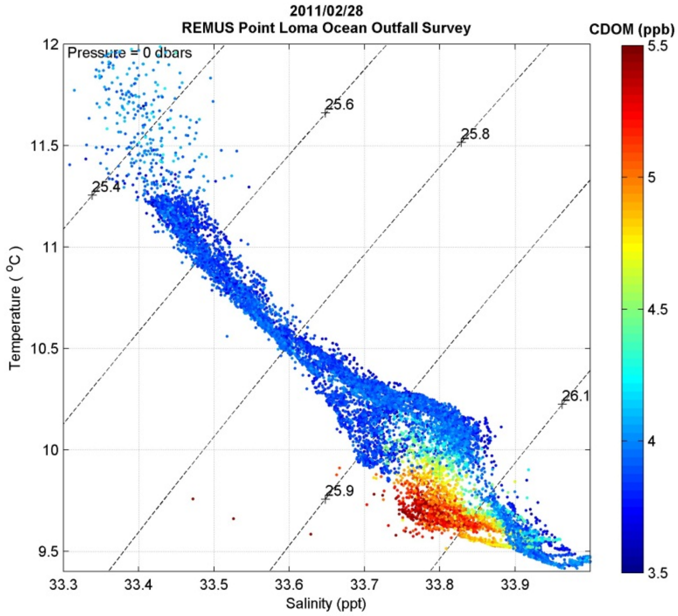


Figure 10. A CDOM calibration curve of source effluent from the Point Loma Wastewater Facility. The effluent was mixed with seawater (background CDOM = 3.96) to create a range of dilutions from 1:1 to 1:600. The WETlabs ECO triplet used on the REMUS was used to measure CDOM concentrations at each dilution ratio. The graph shows a linear trend with successful measurement of CDOM signatures up to a dilution of 1:600 before background contamination.



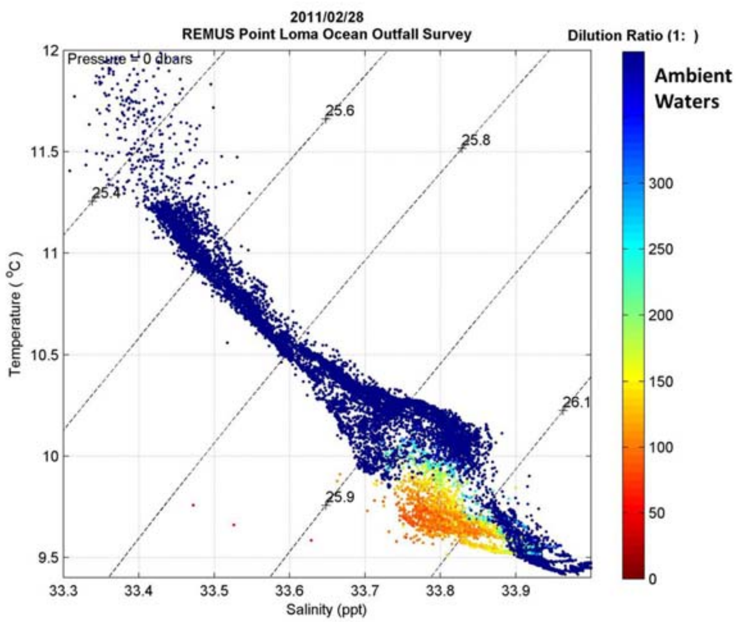


Figure 11. A CDOM T-S diagram (top) for the February 28th, 2011 PLOO mission. The CDOM signature of the plume clearly separates it from surrounding ambient water. These data are used to calculate the dilution field seen in the bottom plot. According to the plot, the core of the plume has dilutions around 1:100.

The spatial extent of the plume is shown in Figure 12 along with the vertical distribution of the number of measurements of plume water (n). For this mission, current measurements in the hours preceding deployment were highly variable, adding to the difficultly of mission planning. The mission path shown in Figure 12 was selected based on current readings minutes before deployment. Due to the variability of the currents, the eastern edge of the plume was not captured, thus making accurate estimates of plume width difficult. However, the vertical distribution figure shows a plume rise height of approximately 35 m and a thickness of 55 m.

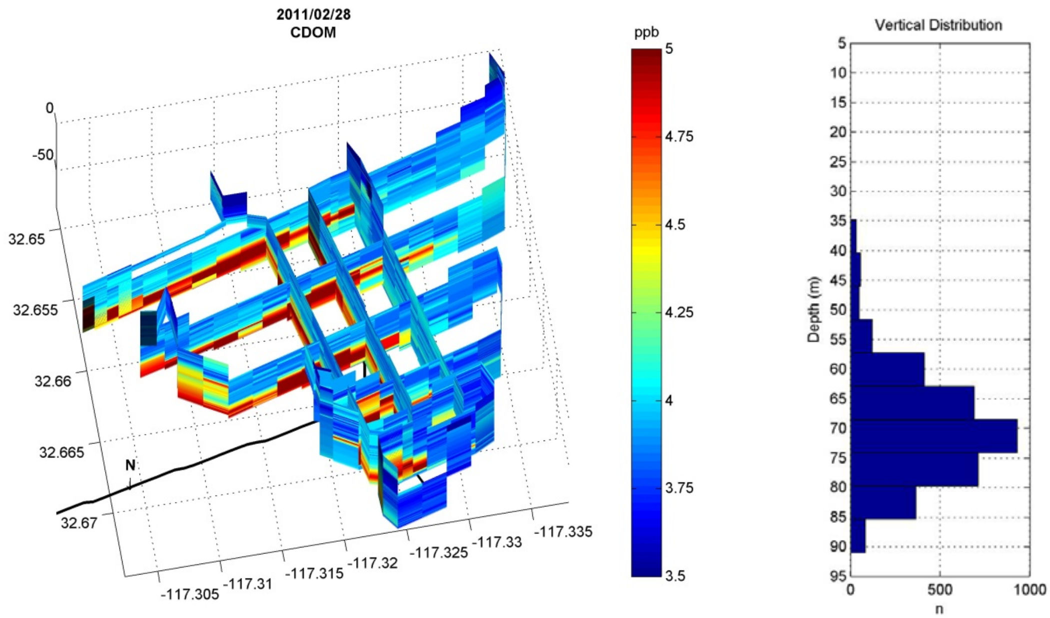


Figure 12. CDOM concentrations for a mission on February 28th, 2011. The PLOO is shown in black with the observed plume toward the south-southeast. The adjacent figure denotes the vertical distribution of plume measurements (n) that fall into thresholds designating plume water (CDOM > 4.25). These figures allow for estimates of the plume width, thickness and rise height.

Long range PLOO missions were performed when current directions were consistent in one direction for more than a day. These conditions typically form a stable plume moving downstream consistent with current trajectories allowing for easier path planning. An example of a mission under these conditions is shown in Figure 13. Current trajectories for a 24 hour period predict a southerly direction for plume advection. The observed plume is toward the south-southeast. The difference between the predicted and observed directions may be due to spatial variations in the currents that are not considered in our trajectory computation based upon data from a single location. Despite these offsets, the REMUS path clearly captures the plume advected 5 km from the discharge. The cross-section of the plume appears to remain relatively stable as distance increases from the source in the far-field. Figure 13 provides a mapping of the plume dilution.

Figure 14 presents the median of the dilution ratios as measured by CDOM as a function of time from the source for two missions under similar environmental conditions; August 3, 2010 and February 28, 2011. The median of the dilution ratio is based upon all the data sampled by the AUV at a particular range pass (eg – Figure 13), while the time estimates are based upon the advection time scale as computed using the current meter data. Similar plume Froude numbers, direction, rise height, and thickness allowed direct comparisons between the two datasets to determine dilution trends in the entire mixing field. The trend for the dilution ratio is found to vary as $^{t5/3}$ in the nearfield and then quicly transition to a much slower mixing rate of $t^{0.15}$ in the far-field. These results are expected since dilution in the far-field is dominated by lower background ocean turbulence levels vs the near-field jet where buoyancy and momentum exchange processes dominate. Figure 14 illustrates both the dynamic range of discharge plume dilutions over which CDOM can be used as well as the effectiveness of the AUV sampling to characterize both nearfield and far-field mixing.

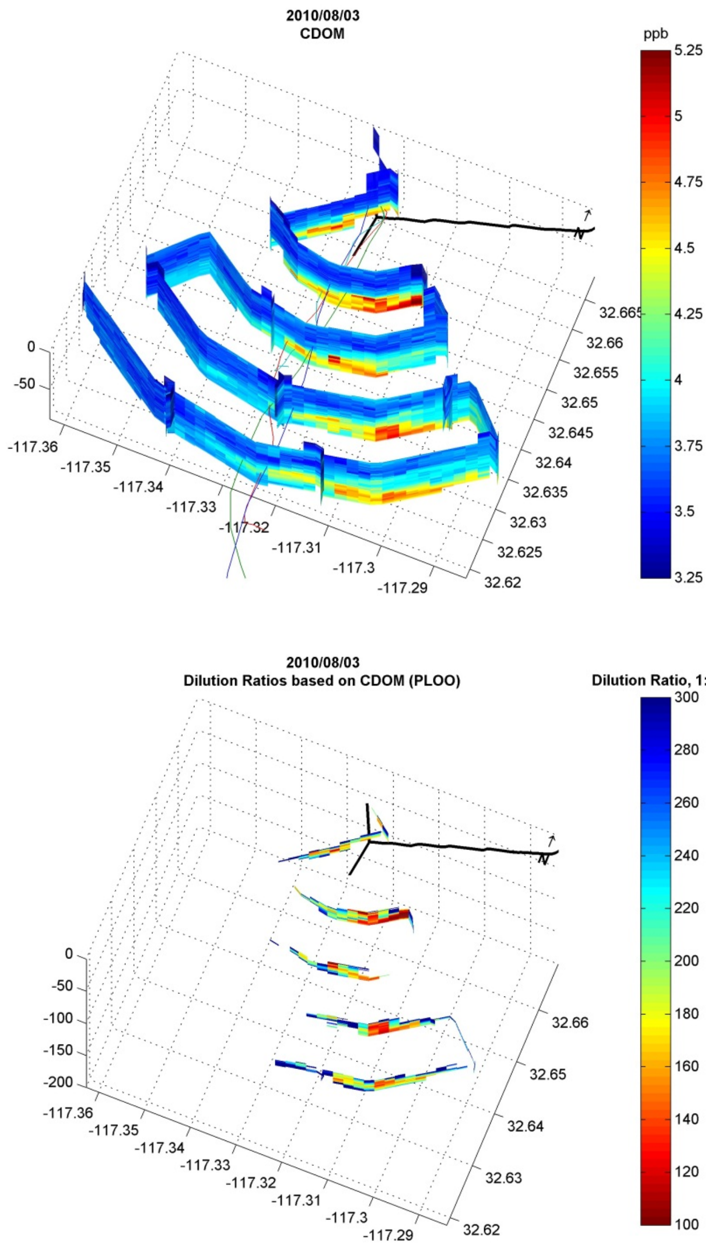


Figure 13. *Top:* CDOM concentrations for a long range mission on August 3rd, 2010. The PLOO is shown in black with predicted particle trajectories (colored lines) heading south from the outfall and the observed plume toward the south-southeast. *Bottom:* Dilution ratios of the measured plume calculated using Equation 5.

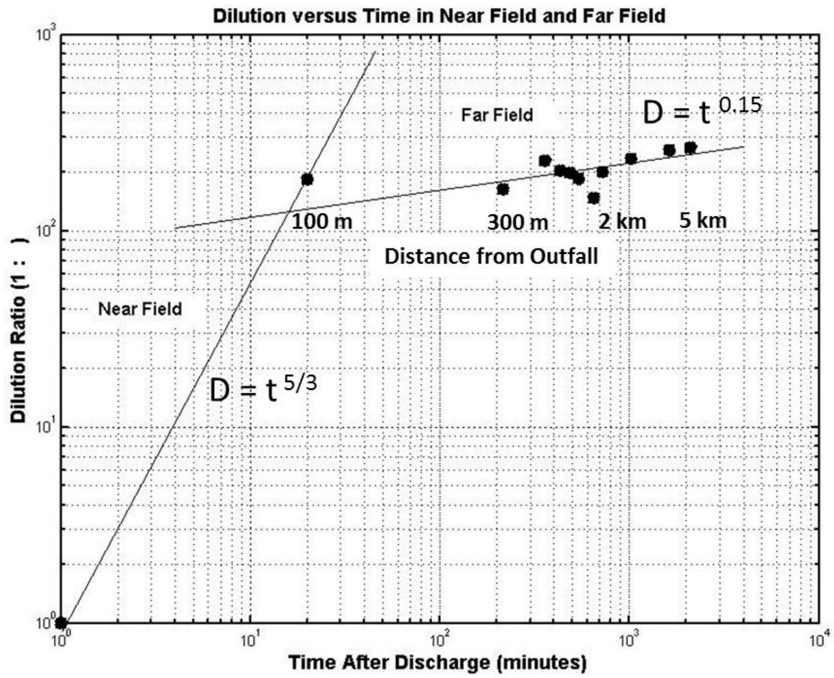


Figure 14. A log-log plot of the median of the measured dilution ratios using the CDOM proxy as a function of time from PLOO. A near-field (February 28, 2011) and far-field (August 3, 2010) mission were combined to show the trend in dilution as a function of time from the outfall. Both missions had similar plume direction and Froude number. .The AUV samples both the near and far-field effectively.

CONCLUSIONS

In this paper, we report the results of developing methodologies for using AUVs for surveying discharge plumes at two different ocean outfalls located off the coast of San Diego, California. The methodologies have evolved, and are based upon over 50 different plume surveys in support of special studies to better understand those particular dischargers at resolutions never before measured. A plume mapping technique using CDOM as a tracer was developed to effectively detect and map wastewater plumes as well as estimate their dilution. Our ability to capture the elusive discharge plumes were made possible only through use of modern ocean observation instrumentation that telemetered data in near real-time and allowed for adaptive AUV mission planning. These data were used to both estimate the plume rise height and the trajectory of the plume advection by background currents. While optical backscatter was found to provide a signature for the plume water, onboard CDOM measurements proved more robust at tracking the plume than traditional techniques.

Previous work using natural tracers was typically relegated to the near-field due to the inability of traditional natural tracers (salinity, backscatter) to maintain a plume signature with increased distance from the outfall. Our results show that the CDOM signature of the plume does not share these same limitations allowing for high resolution mapping of plumes in both the near and far-fields. Missions conducted on the PLOO built on the techniques used from the SBOO work to better characterize the plume. A focus of the work was developing a method to calculate the dilution field based on CDOM values. Calibrating the CDOM signal to effluent dilution provides a capability not yet realized for effectively measuring the performance of the discharge mixing in both the near and far-field.

This work shows the feasibility of using the natural plume tracer, CDOM, to effectively map plume water and plume characteristics. Traditional methods using salinity and backscatter signatures were effective in mapping plume water in the near-field; however they were often obscured by other sources of variability, particularly as distance increased from the source. Conversely, elevated CDOM signatures were consistent in both the near and far-fields allowing for direct calculations of plume dilution, width, height and thickness. The results suggest that plume mapping/characterization based on elevated CDOM plume signatures is a viable option for routine monitoring of POTW ocean discharges. We anticipate that continued analysis of the data will allow us to examine how variations in background ocean conditions will influence the far-field mixing.

ACKNOWLEDGEMENTS
We thank the sponsorship of the International Boundary Water Commission (IBWC), City of San Diego, and National Oceans and Atmospheric Administration (NOAA) for the sponsorship of this work. We also recognize the sponsorship of the U.S. Office of Naval Research CODE 32 for their continued sponsorship of the development of AUV technology and application to coastal oceanography. Dr. Burt Jones, University of Southern California, is thanked for his encouragement in the use of AUVs for monitoring ocean outfalls and for assistance in running the RSB plume rise height model.

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