Acoustic Remote Sensing Applications
S.P. Singal (Ed)

22. Acoustic Measurements of Currents and Effluent Plume Dilutions in the Western Edge of the Florida Current

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1. Introduction

The Southeast Florida Outfall Experiment (SEFLOE), which was carried out in the coastal ocean off Southeast Florida, U.S.A., between 1988 and 1993, was the most extensive application of acoustical technologies in wastewater effluent studies so far performed in the U.S.A. The general objective of SEFLOE was to develop a scientific basis for managerial regulation and rules governing effluent discharges. Physical oceanographic, biological, and chemical measurements were made both during establishment of initial effluent plume dilution and subsequent plume dilution. Acoustics played a central role in all three disciplines. In particular, acoustical systems were used to (1) detect and map the three dimensional subocean-surface effluent plume distribution, (2) guide chemical and biological sampling, (3) provide relative plume dilution measurements with space and time, (4) distinguish between effluent plumes and interfering plumes arising from other sources, (5) detect the presence of ambient biota within the water column in the vicinity of the discharge, and (6) measure three dimensional oceanic currents from near-ocean-surface to near-ocean-bottom every ten to fifteen minutes.

A general site map for two of the outfalls studied is shown in Fig. 1. Both outfalls have diffuser systems, which are designated by a solid circle. Note the presence of the offshore dredged material disposal site (ODMDS) and the shipping channel to the Port of Miami; interfering plumes may arise from both these locations.

An outstanding feature of the coastal ocean off sotheast Florida is the Florida

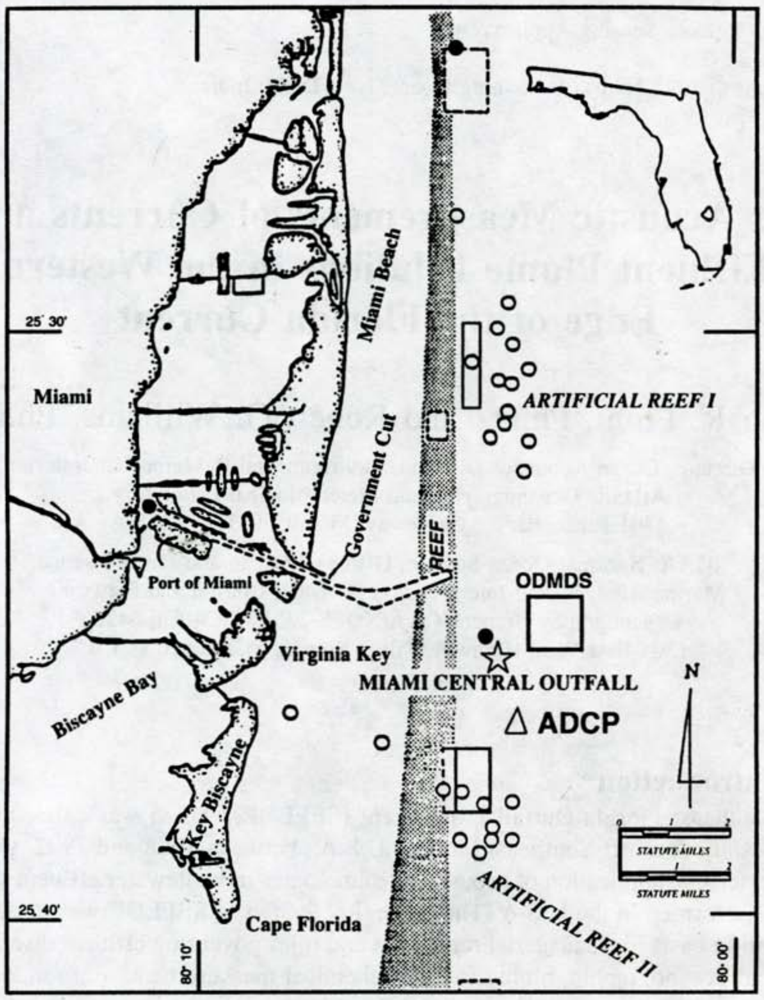

Fig. 1. Location Map showing the diffusers ●, the conventional current meter arrays ☆ and the ADCP Δ.

Current (as the Gulf Stream is named locally). All outfall sites are located in the western boundary region of this current, in water depths of about 30 m. Because of Wandering or meandering of the western boundary of the Florida Current, the outfalls often lay "within" the Florida Current or lay "external to" the Florida Current. Dramatically different ambient current regimes were therefore present at the sites, at different times. In this discussion, results from the measurements in the vicinity of the "Miami Central" outfall, off Virginia Key (Fig. 1) are presented.

2. Measurement Design

The overall measurement scheme for SEFLOE is discussed by Hazen and Sawyer

(1). In general, chemical and biological measurements had low sampling frequencies, e.g., biweekly, while physical oceanographic and acoustic measurements had high sampling frequencies, e.g., every 15–20 minutes. Of particular interest in the present discussion are the following instruments: (1) Savonius rotor current meters, (2) acoustic Doppler current profilers, and (3) towed acoustical backscatter systems.

A current meter mooring was installed near each outfall site. Each mooring had two Savonius rotor current meters, one near-surface and one near-bottom mounted on the mooring. At the Miami Central District, an Acoustic Doppler Current Profiler (ADCP) operating at 1228.8 kHz was installed on the bottom near the outfalls. Research ships were equipped with active acoustical systems operating at 200 kHz and 20 kHz, for the towed backscatter measurements.

In active acoustical systems a pulse of sound is emitted from a source (transducer), propagates through the water, scatters from encountered particles, and returns to the transducer. The received acoustical signal is converted to an electrical signal and recorded. The acoustic system used for SEFLOE utilized two transducers mounted in a hydrodynamically stable towbody towed alongside the research vessel at a speed of about 2 m/s. Sound pulses of 2.00×10^5 Hz frequency and 5.0×10^{-4} s duration were transmitted synchronously with pulses of either 2.0×10^4 Hz or 4.0×10^4 Hz frequency and 1.0×10^{-3} s duration at a repetition period of 2.4×10^{-1} s.

Principal system operating parameters include: frequency = 200 kHz; beamwidth = five degrees with six dB down half-angle; source level = 223.7 dB rel 1 μPa. at 1 m; receiving response of the transducer = – 183 dB re 1 V/μ Pa.

3. Observations

A. Currents

Figures 2 and 3 show current speed and direction measured near the Miami Central District outfall site by a conventional Savonius rotor current meter and an ADCP respectively for the period July 11, 1992 through August 12, 1992. The conventional current meter was at 17 meters below the ocean's surface, so an acoustic range corresponding to the 17-meter depth was selected for the ADCP. The upper panel in each figure shows the current speed and the lower panel shows the current direction. Note the similarity of data between the conventional Savonius rotor current meter and the ADCP. An extended discussion of disparities and similarities between the Savonius rotor data and the ADCP is presented in Hazen and Sawyer [1].

Between July 11–14, July 19–27, and July 31–August 12, 1992, the site was occupied by a Florida Current meander. Between July 14–19, and between July 27–31, 1992, short period, e.g., 3–8 hour current rotations were present. During these rotary current periods the Florida Current was absent from the outfall site.

A powerful capability of the ADCP is to provide nearly full water column current profiles. Figures 4 and 5 show water column horizontal current data at 18

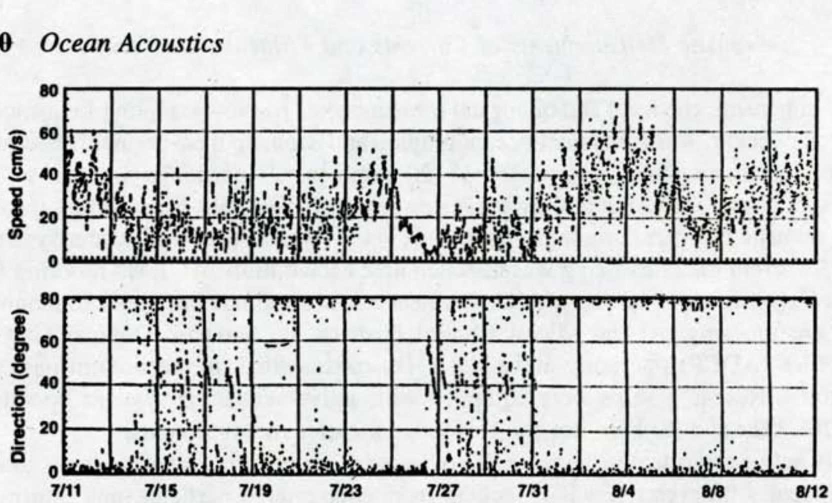

Fig. 2. Current speed and direction measured at the Miami Central outfall site for the period July 11, 1992 through August 12, 1992, at a water depth of approximately 17 meters by a conventional current meter (Savonius rotor).

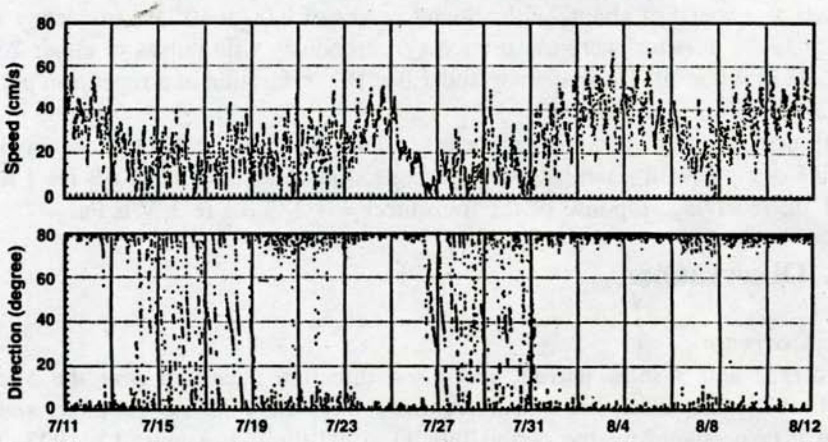

Fig. 3. Current speed and direction measured at the Miami Central outfall site for the period July 11, 1992 through August 12, 1992, at a water depth of approximately 17 meters by an ADCP.

different depths during meander present, August 3–6 and meander absent, July 26–30, 1992, periods respectively. The ambient water column current is seen to be decreasing uniformly from surface to bottom with essentially coherent rotations of ambient current direction during both times. Knowledge of the water column ambient current profile is fundamental to calculation of initial plume dilution, (Proni, Huang, and Dammann [2]). Based on acoustically derived water column current profiles, it is possible to determine the efficacy of using a single conventional current meter to estimate the vertically averaged horizontal ambient current, (Hazen and Sawyer [1]) for the Miami site.

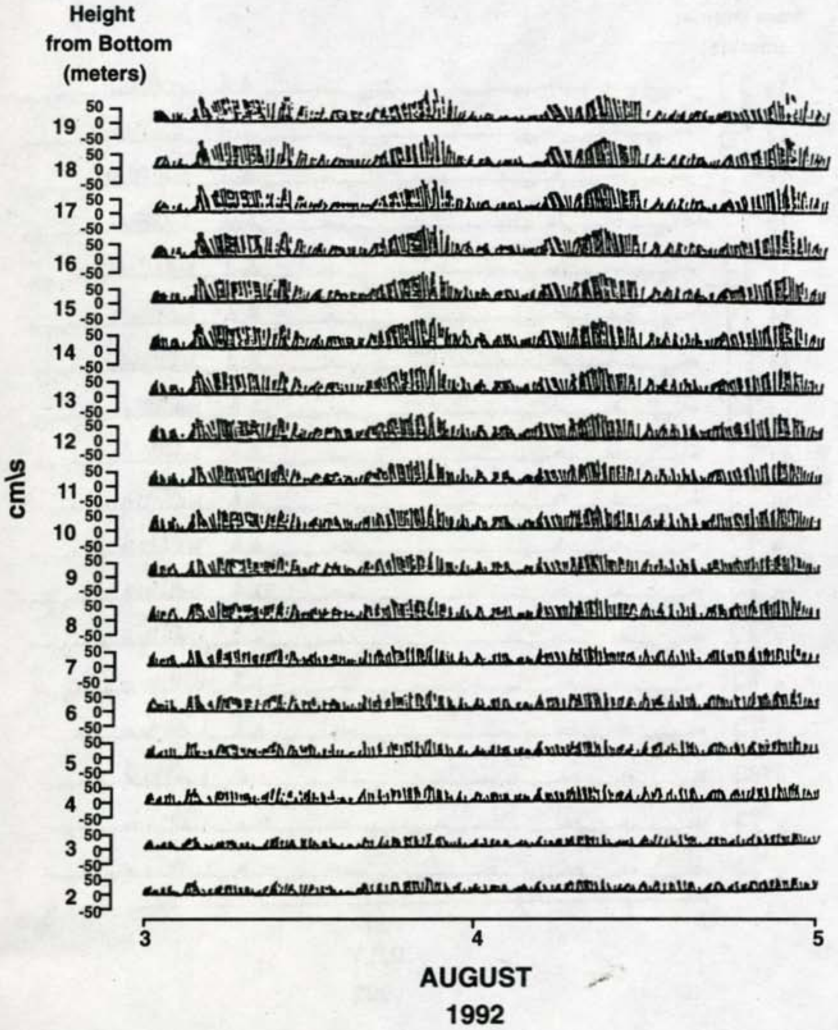

Fig. 4. Horizontal current speeds at different depths for a Florida Current meander present for August 3–5, 1992, at the Miami Central site.

B. Plumes

An example of acoustical data obtained on a near-straight line transect over the wastewater outfall (Miami Central District) is shown in Fig. 6. This transect was obtained on January 24, 1988 on a general North-South course with ships' speed at two m/s (four knots); total transect length shown is approximately 1700 meters. The data are displayed as contours of constant volume scattering strength plotted in decibels; volume scattering strength is defined as ten times the logarithm to the

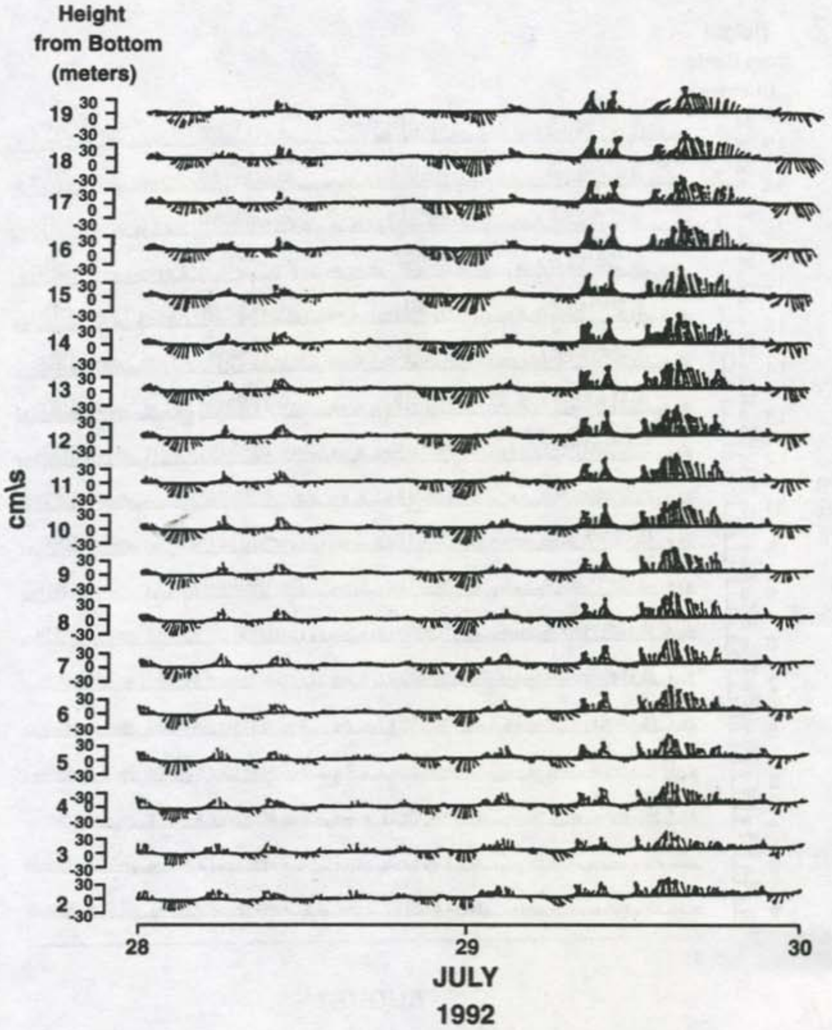

Fig. 5. Horizontal current speeds at different depths for a Florida Current meander absent for July 28–30, 1992, at the Miami Central site.

base ten of the ratio of the reflected sound intensity to the incident sound intensity and is related to equipment operating parameters through the sonar equation.

The values of the contours are actually the backscattered signal received minus a background backscattered signal which is obtained in a region of the coastal ocean close to the plume but into which the plume has not penetrated. In this way, spatially homogeneous background features (e.g., plankton of particulate horizons) are removed from the signal. The origin of the horizontal distance axis is placed

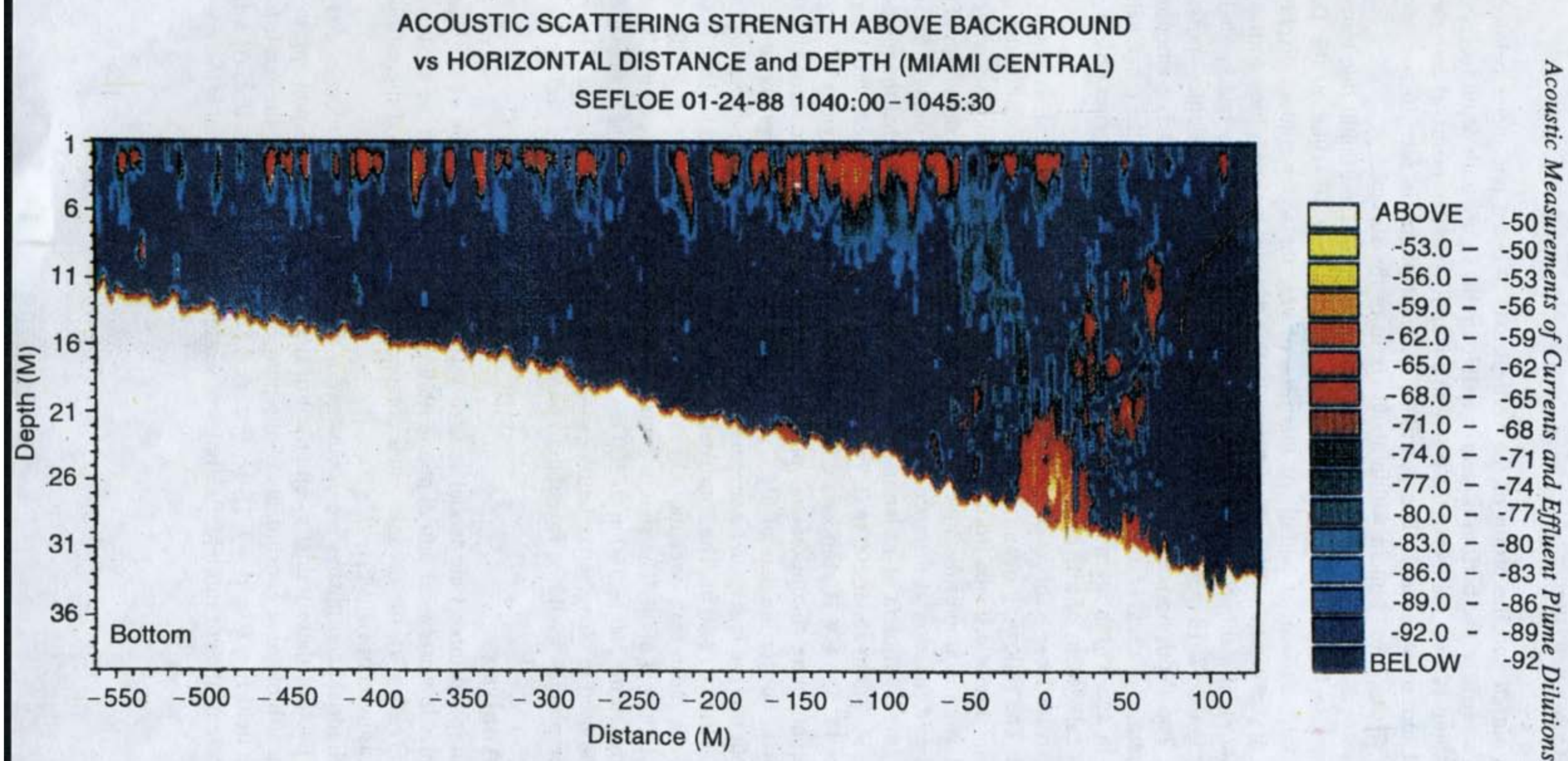

Fig. 6. Acoustical map of Miami Central outfall made using 200 kHz system

at the outfall and the origin of the vertical axis is taken one meter below the ocean's surface. The bottom is clearly visible in this figure with depth increasing from about 12 m at the left of the figure to about 30 m at the (positive) zero meter outfall terminus distance. The positively buoyant plume is seen to rise to the ocean's surace and remain within about six m of the surface.

A second example of acoustical data obtained on a near-straight line transect is shown in Fig. 7. This transect was obtained on June 10, 1988, at the Dade County North District outfall. At this time of year the water column displayed incipient stratification. The effect of stratification upon wastewater plume formation is quite significant. Note that besides a surface plume at least one secondary plume in the 12–18 meter depth interval is visible with weaker "plumes" possible at the 7 m depth horizon and at the 24 m depth horizon. The large amount of (apparently) discrete scatterers located below 21 m and between the range values of 50 m and 450 m are not scatterers, but interference signals generated by the acoustical system of a fishing vessel operating near the outfall.

Statistics from a subset of the data (Fig. 6) were computed and are shown in Fig. 8. The following quantities are displayed: (1) the peak backscattered signal as a function of distance from the outfall, (2) the mean of the peak backscattered signal as a function of distance from the outfall, (3) the standard deviation of the signal as a function of distance and (4) the ratio of the standard deviation to the mean (the coefficient of variation, or CV). The interpretation is that the plume is continous out to about 200 m (CV < 1); beyond 200 m, the plume is breaking up (CV > 1). The CV is seen as a concise measure of plume behaviour.

A contrasting circumstance is presented in Fig. 9, showing the same statistics as above, but for the data of Fig. 7. The width of the "vertical" plume at the 15 m depth horizon is seen to be approximately 60 m (multiple ports) extending from about –20 m to +40 m. The "horizontal" plume at the 15 m depth horizon is seen to have a mean that, over the 300 meters distance shown in Fig. 9, diminishes only slightly if at all. The standard deviation is smaller than the mean (CV < 1) over the entire 260 m, (60 m to 300 m). This result shows that the acoustic data may be used to characterize both near-surface and sub-surface plumes. The subsurface plumes would be invisible to conventional sensors at the surface.

4. Analysis

A conceptual three field model is used to help in the evaluation of the use of acoustics in wastewater outfall plume studies. The three fields are the wastewater field $F(r, \theta, z, t)$, the oceanic water column field $W(r, \theta, z, t)$ and the estimator or measurement field $E(r, \theta, z, t)$.

Cylindrical coordinates are used where r, θ, z are position coordinates and t is time. Each of these fields is comprised of many subfields, corresponding to the chemical-biological constituents of the plume. For example, for the wastewater plume field $F(r, \theta, z, t) = F\{f_1(r, \theta, z, t), ..., f(r, \theta, z, t) ... f_N(r, \theta, z, t)\}$ where f_i represents the i th subfield. Examples of wastewater plume subfields include the

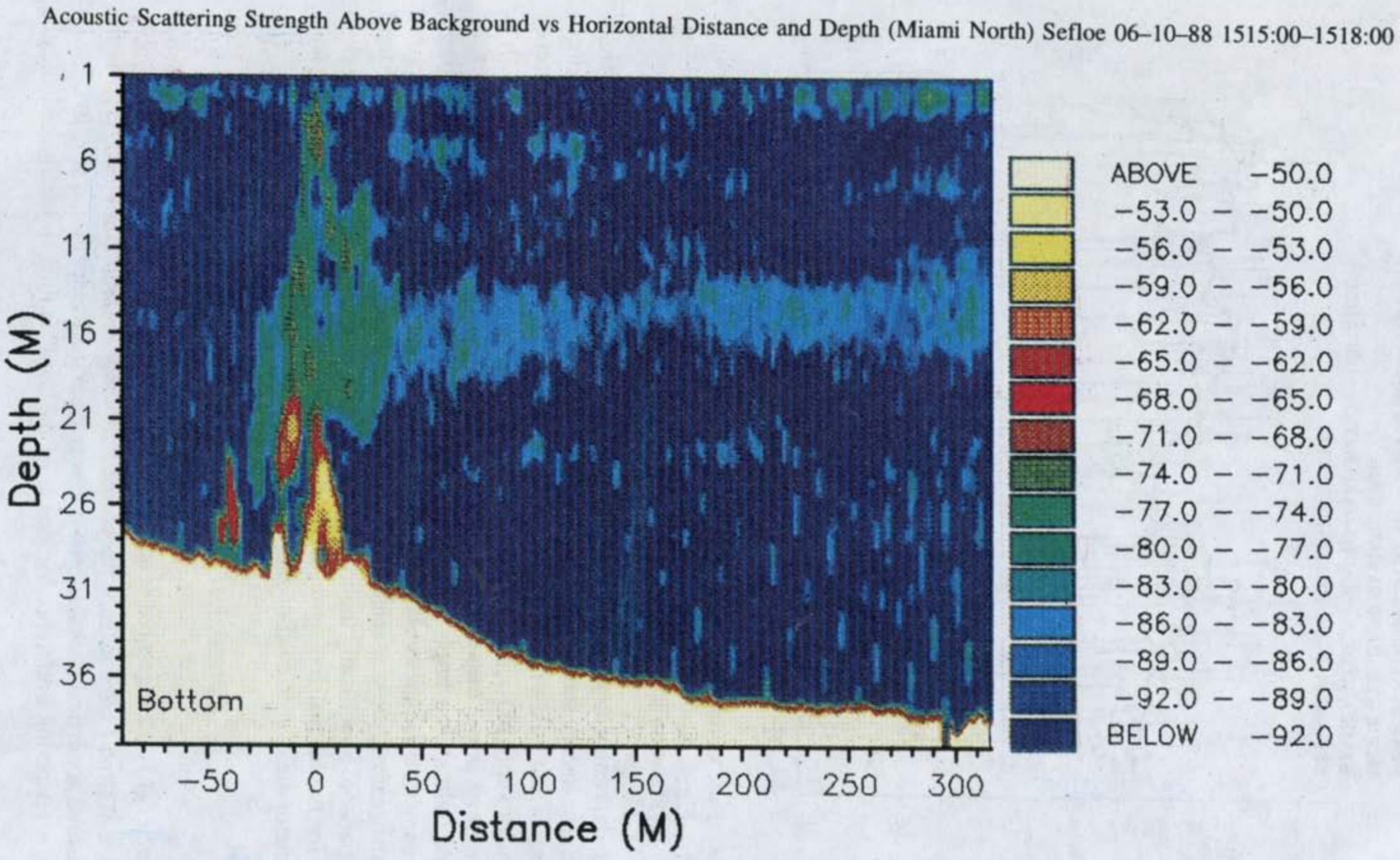
Acoustic Scattering Strength Above Background vs Horizontal Distance and Depth (Miami North) Sefloe 06–10–88 1515:00–1518:00

Fig. 7. Acoustical map of Miami North outfall showing partial plume detrainment

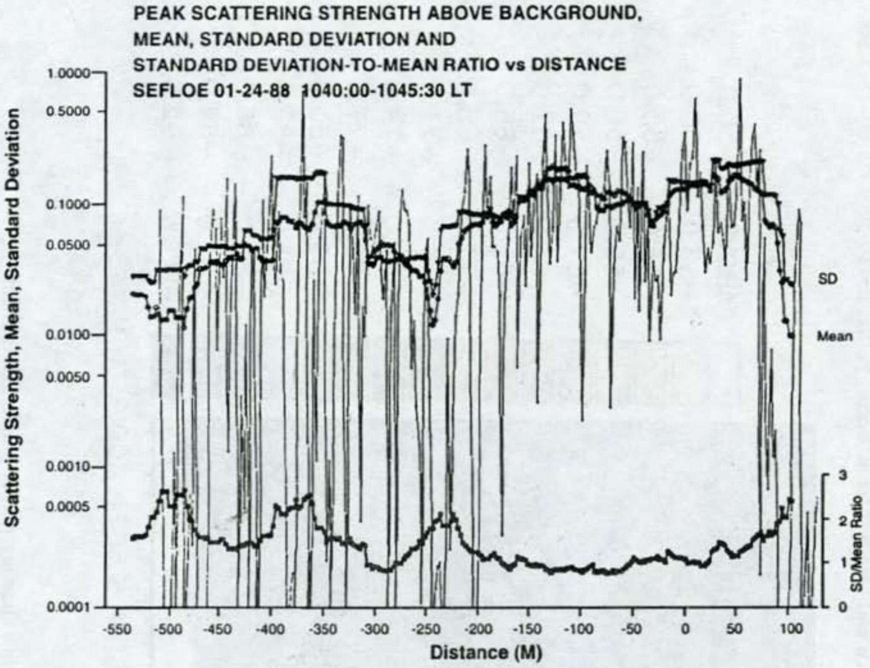

Fig. 8. Peak scattering strength as a function of distance for the acoustical data shown in Fig. 6. Also shown are the mean, standard deviation, and coefficient of variation (SD/Mean Ratio) calculated over 50 m segments.

particulate concentration subfield, the fecal coliform subfield, the nitrogen subfield, the kinetic energy subfield, the freshness subfield and so on. The two most prominent estimator subfields used in the present study are the acoustical backscattered intensity subfield $I(r, \theta, z, t)$ and the dye concentration subfield $C_D(r, \theta, z, t)$. A quantity of prime importance is the spatial rate of dilution with distance of the plume field. Accordingly, despite greatly disparate spatial resolution and sample gathering time requirements of the estimator fields, the slope of the linear regression (least-squares) line was selected as the initial test statistic for inter-estimator field comparison. Specifically the initial test statistic is the slope of the linear regression line for the normalized signal level, δ_E, versus distance from the outfall for each estimator field utilized. For the acoustical estimator field δ_A is

$$\delta_A(r, \theta, z, t) = \frac{\langle I_F\ (r, \theta, z, t)\rangle - \langle I_W\ (r, \theta, z, t)\rangle}{\langle I_F\ (o, o, o, t)\rangle - \langle I_W\ (o, o, o, t)\rangle}$$

where $\langle I_F\rangle$ is the measured acoustical backscattered intensity I at the coordinates, r, θ, z at time t arising from the plume and water column combined, $\langle I_W\rangle$ is the measured acoustical backscattered intensity from the water column at r, θ, z, t, with o, o, o, t denoting a reference location (e.g., the "boil" at time t). Ideally, as indicated

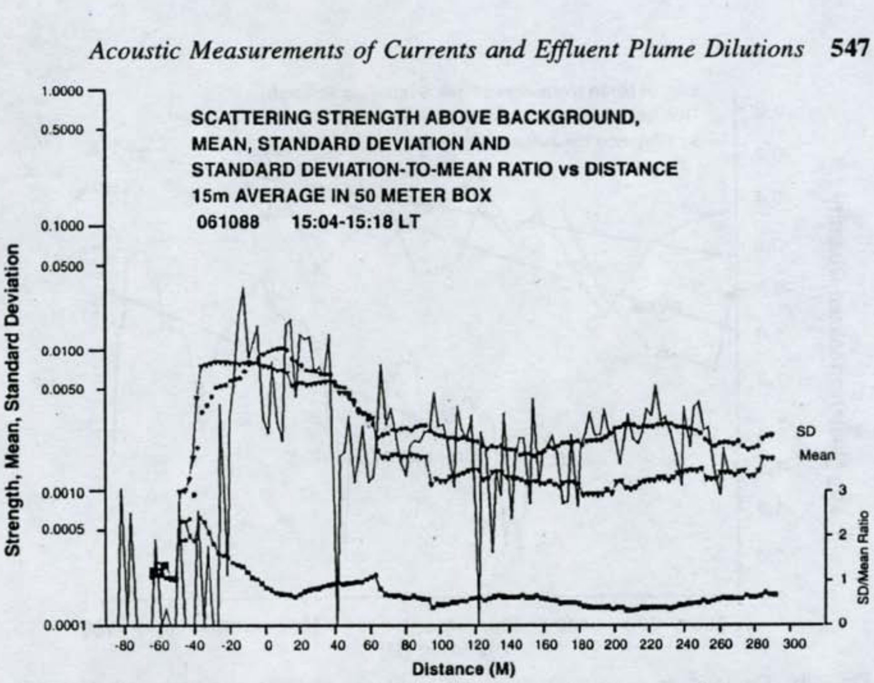

Fig. 9. Peak scattering strength as a function of distance for the acoustical data shown in Fig. 7. Also shown are the mean, standard deviation, and coefficient of variation over (SD/Mean Ratio) 50 m segments.

in the preceding equation, a point-by-point differencing of the backscattered intensity of the plume-plus-background and background alone, i.e., water column without plume, is desired. Thus far, in practice, this ideal circumstance is approximated by differencing a nearby "average" water column backscatter profile. The accuracy of this process depends on the spatial homogeneity (in r) of the water column and is analogous to the taking of a "standard" chemical water bottle sample. The logarithm of the mean normalized peak scattering strength, i.e., $\bar{\delta}_A$ (derived from the data shown in Fig. 6 and 7); the logarithm of the mean normalized dye concentration measurements, i.e., log $\bar{\delta}_D$; and the logarithm of the mean normalized fecal coliform concentration measurements, i.e., log $\bar{\delta}_{F.C.}$, as a function of distance from the surface "boil" location is shown in Fig. 10. The overbar denotes mean, where the mean used is a running mean calculated in 50 m increments of range. The "boil" value of each quantity is taken as the reference for normalization. A typical initial dilution measured for the outfall in the boil and location is 25:1. As can be seen from Fig. 10, the slopes of log $\bar{\delta}_A$, log $\bar{\delta}_D$, log $\bar{\delta}_{F.C.}$, are all on the order of 10^{-3}. The differences among the numbers 0.5, 1.1, and 1.3 are not considered statistically significant.

Figure 11 shows ambient temperature and density profiles corresponding to the data shown in Figs. 6 and 7. From these profiles it may be seen that significant water column stratification is present in June as compared to January. It is noted

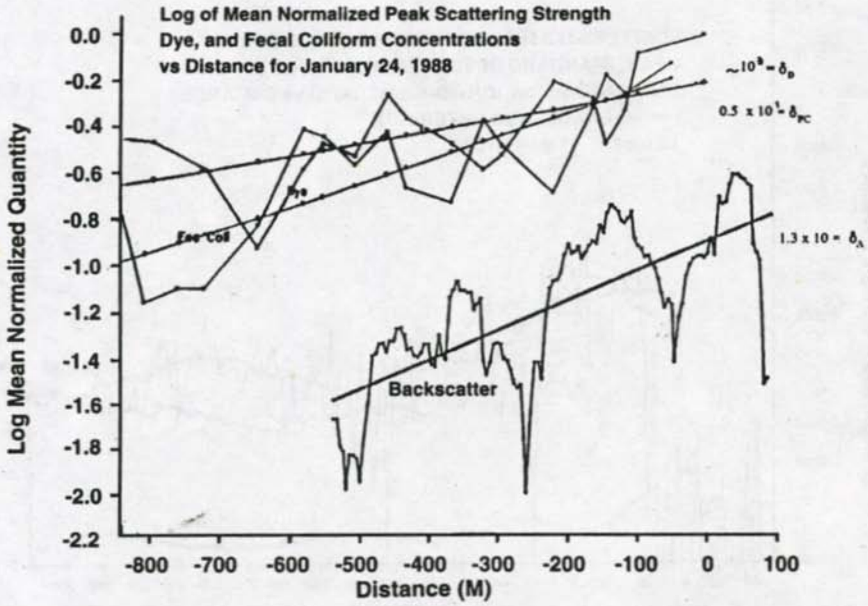

Fig. 10. Comparison of injected dye, fecal coliform, and acoustic backscatter intensity levels with distance from the Miami Central outfall for the transect shown in Fig. 6.

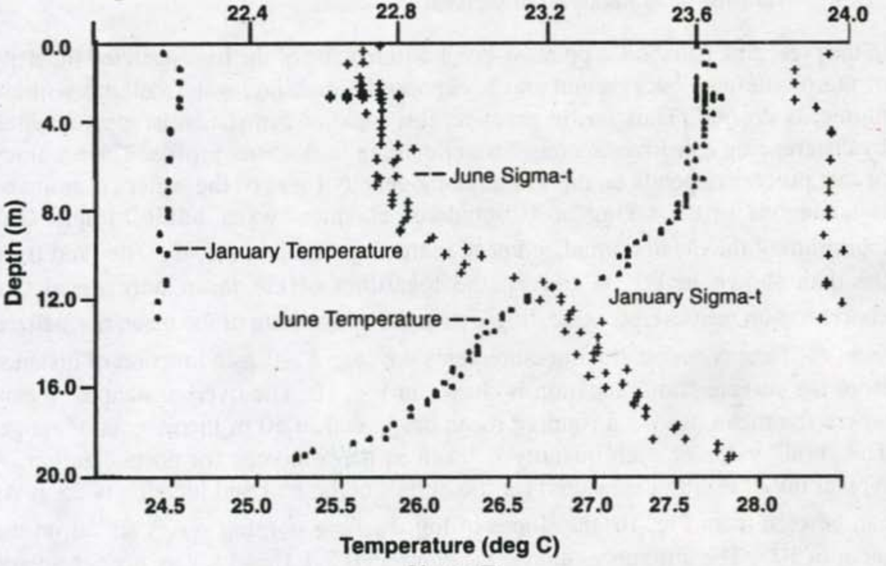

Fig. 11. Temperature and density (sigma-t) as a funtion of depth for January and June, 1992, for the Miami central outfall site.

that the "horizontal" plume portion of Fig. 7 corresponds to a depth just below a depth at which the density gradient undergoes a significant increase as depth diminishes, i.e., from 6×10^{-7} gm/cm^3/cm to 2×10^{-6} gm/cm^3/cm over the depth interval from 12 m to 9 m in the water column. A density reduction of about .0006 gm/cm^3 is seen to occur.

It is speculated that at the edges of the rising plume, entrainment of oceanic water gradually reduces the density deficit of the plume (or, equivalently, gradually increases the density of the edges of the plume) so that the "outer" portion of the vertically rising plume does not have sufficient positive buoyancy to overcome the density decrease onsetting at 12 m depth. Thus the outer portion of the plume is "peeled-off", or detrained, at a "ceiling" within the pycnocline.

5. Summary and Conclusions

The SEFLOE project has demonstrated the utility of acoustical methods for studying effluent plumes arising from wastewater outfalls in the coastal ocean. Before the SEFLOE study, basically two current regimes were expected to be present at the study sites; the first arising from the presence of the Florida Current and the second arising from large, several days in duration, eddies (Lee, [3]). Utilizing the water column ambient current data from the ADCP, a third current regime was discovered (Proni and Williams, [4]; Williams and Proni, [5]); namely, relatively short period, e.g., 3–8 hour rotary currents. The coherence of these rotary currents over the water column was demonstrated by conventional data as well. A full discussion of these rotary currents is given in Proni and Williams [4]. The poorest wastewater effluent dilutions (Hazen and Sawyer, [1]) were observed during rotary currents.

Acoustical backscatter data revealed the existence of a detrainment phenomenon in which part of the rising wastewater plume was trapped near mid-water depth. At that depth the trapped plume dispersed horizontally. In many previous studies (e.g., Proni and Hansen, [6]), it has been noted that naturally occurring organic material accrues in the coastal ocean at certain density horizons. Clearly acoustical systems may serve not only to map the subsurface deffluent plume but also to map the naturally occurring organisms thereby providing an ideal instrument for finding the joint probability of exposure of organisms to contaminants.

We have seen, based on limited case studies, that reduction of acoustical backscatter level with distance can serve as a surrogate for the reduction of effluent constituents such as fecal coliform (if present). Similarly we see that acoustics is ideally suited for guiding biological and chemical sampling both with respect to depth, range, and spatial location.

In summary, acoustical remote sensing of wastewater effluent plumes, particularly when used in combination with non-acoustic measurements, is a valuable tool for assessing the impact of effluent discharge in the marine environment.

6. Acknowledgements

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