Acoustic reflector of opportunity distribution as a surrogate for inferring effluent distribution in a survey of Massachusetts Bay

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Abstract - In 1998 the Massachusetts Water Resources Authority (MWRA) expects to complete the construction of a new oceanic wastewater outfall system which will have the capacity to release as much as 1.2 x 10^9 (gal) of treated wastewater per day. The design of the system is such that during summer months the effluent plume should be trapped beneath the seasonal thermocline. It is proposed that the spatio-temporal distribution of acoustic reflectors (probably biological) present in the seasonal thermocline is a reasonable surrogate for inferring characteristics of the spatio-temporal distribution of acoustic reflectors that will result from the release of wastewater effluent. In September 1995, we conducted a joint U.S. EPA, MWRA, NOAA survey of Massachusetts Bay. The primary data sets gathered were acoustic backscatter profiles at 20kHz and 200kHz made every 0.5(sec) with 0.5(m) vertical resolution. Also, CTD casts and water bottle samples were taken at selected locations. Oceanographic phenomena such as internal waves and tidal surges in conjunction with topographic features cause the surrogate scattering layers to be vertically modulated with possible mixing of materials normally trapped within layer boundaries. Analysis of acoustic backscatter measurements provide visualizations of such events and allow for the estimation of the surrogate scattering layer distributions in the vertical and horizontal planes. Quantitative comparison of acoustic backscatter strength with CTD derived density and transmissometry measurements give an indication of the relationship of the surrogate scattering layers to the water density structure at selected sites in the study (and an indication of the reliability of the surrogate). In addition to its role as a surrogate for wastewater, the relationship of the surrogate scattering material layers with respect to the isopycnal surfaces is also considered.

In an effort to improve water quality in Boston Harbor and Massachusetts Bay and to accommodate the wastewater disposal needs of the Massachusetts area into the foreseeable future, the Massachusetts Water Resource Authority (MWRA) is relocating its oceanic wastewater outfall from its present location adjacent to Deer Island at the mouth of Boston Harbor to a location in Massachusetts Bay 15.3 km (9.5 mi) seaward of Deer Island (Fig. 1a). Effluent material will be transported from the treatment facility at Deer Island to the outfall location via a 7.3m (24ft) tunnel. At the terminus of the tunnel the wastewater will rise into the receiving waters through a series of 55 parallel vertical riser pipes, each of which will be capped with a diffuser turret having 8 horizontal ports. The depth of the water at the diffuser ports is approximately 30.5 m (100ft). The outfall has been designed to provide an effluent plume which has a high initial dilution and which seasonally is substantially trapped beneath the surface of Massachusetts Bay. Fig. 1b is a simplified conceptual illustration of the expected subsurface trapping of the effluent plume and its subsequent horizontal dispersion during periods of stratification. Density gradients in the water column are a primary mechanism by which this trapping occurs. During the late summer and early fall the seasonal thermocline in Massachusetts Bay is at its maximum extent and consequently subsurface effluent plume trapping would be expected to be maximized as well. The data presented here were gathered in September of 1995.

It is important to gain information about what the effluent dispersion characteristics in Massachusetts Bay will be. Studies have been carried out using oceanographic data and transport models [2][3], and hydraulic models [4]. There can of course be no direct measurements of effluent dispersion from the diffuser site until such effluent exists. If however, there exists a set of physical and biological phenomena that can reflect acoustic energy impinged upon it (referred to as backscatter if the direction of reflection is reciprocal to the direction of transmission), and that set of phenomena is known to occupy approximately the same region of the water column as the wastewater effluent, and if the dynamical behavior of the backscattering phenomena with respect to the dynamics of the ocean environment would be expected to be similar to that of

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the effluent (at larger scales), then it is possible to cautiously infer certain characteristics of the wastewater effluent dispersion by observing the acoustic backscatter from these surrogate backscattering phenomena [SBP].

Many mechanisms have been identified as sources of acoustic backscatter in the ocean. Some of the stronger sources are:

1) Scattering from inanimate nonresonate particulate matter. Examples might be sediment particles being transported by currents or particulates suspended in a wastewater effluent plume.

2) Scattering from nonresonate biological objects. Phytoplankton is known to be a good source of nonresonate acoustic backscatter.

3) Scattering from inanimate resonate objects. Examples might be bubbles entrained in the water column due to wave breaking, or air bubbles released by a subsurface vehicle or individual.

4) Scattering from resonate biological organisms. Gas bubbles internal to certain organisms are known to be good sources of backscatter, dependent on the frequency of the acoustic system. Zooplankton is well documented to be a good source of acoustic scatter and is abundant in many oceanic environments. (Scattering from resonating objects can be quite strong as compared to nonresonate objects.) Discussions of the above phenomena may be found in [5].

5) Scattering from isotropic and laminar temperature fluctuations [6]. Examples of this might be internal waves modulating the thermocline [7], or the motions of a subsurface object through the thermocline.

In the environs of Massachusetts Bay it is reasonable to expect that all the above mentioned scattering phenomena might be encountered. It must emphatically be stated however, that without extensive non-acoustical measurements the exact nature of the scattering phenomena must remain unspecified. Also separating the contributions from multiple scattering phenomena present within an acoustic profile is generally difficult. Assuming the existence of SBP in Massachusetts Bay, this survey addressed whether the SBP occupy the same space in the water column as the effluent will, and whether time dependent oceanic processes affect the SBP in a manner similar to that expected to be observed in the effluent. Put in other words, it would be useful to determine if the spatio-temporal distribution of the SBP is similar to the spatio-temporal distribution that the effluent is expected to assume.

As previously stated, the diffuser system is designed so that a significant portion of the rising effluent plume will be trapped beneath the maximum density gradient, especially during periods when a strong seasonal thermocline exists. It has been observed that biological scatterers will often congregate at steep density gradients in the upper part of the water column. Biological scattering layers at the location of the seasonal thermocline maxima in the environs of Massachusetts Bay have been observed [6]. It has also been observed [7] that the location of maximum amplitude in internal waves fields is located about the seasonal thermocline's maximum gradient. Therefore it is logical to assume that acoustic scattering phenomena associated with the perturbation of temperature gradients by internal waves will be located approximately at the upper boundary of the effluent layer. Documentation of biological scattering layers and internal wave activity in Massachusetts Bay may be found in [6][8], and in observations made during our recent study [1].

With historical evidence that surrogate backscattering phenomena would be present near the future effluent diffuser site, a short two and one-half day survey of the water column acoustical background along selected tracks in Massachusetts Bay (Fig. 1a) was undertaken in a joint study between the U.S. EPA and NOAA during September, 1995. The principal data gathered for this survey were measurements of acoustical backscatter at 20kHz and 200kHz. These data were gathered using two transducers mounted in a teardrop shaped towbody deployed forward of the starboard side of the OSV ANDERSON. The towbody was set such that the transducers were approximately one meter below the surface. Towing speed was normally 4-5 knots. Acoustic samples were taken every one half second with one half meter vertical resolution. In addition to acoustical data, the ENSR corporation under contract to the MWRA provided conductivity, temperature and transmissometry casts at selected sites. Full details of this study may be found in [1].

Acoustical data presented here are in the form of an Acoustic backscatter visualization (ABV) and defined as a plot of acoustical backscatter intensity with depth as the Y axis, time as the X axis and contoured backscatter intensity as the Z axis (color scale). The acoustic intensity is represented in decibels. It should be noted that the aspect ratio of the plot is not 1:1 and this may cause topographic and oceanographic features to appear more or less steep than they really are. Fig. 2 is an ABV of a region in Massachusetts Bay east of the diffuser site taken JD256 (Sept 13, 1995) from 04:00 to 04:36 using the 200kHz transducer. This region is selected as it is a fairly quiescent or non-perturbed area, although there is some internal wave activity between 04:02 and 04:16. A CTD cast was taken at 04:20. The peak of the scattering layer ranges in depth from about 15 to 18 meters in depth. In general the scattering layer is fairly homogeneous and continuous. (This will be contrasted with data in Fig. 4.) Fig. 3 is a plot of three selected acoustical profiles and density vs depth from the same region. Disregarding the upper 4 meters of the acoustic profiles which are artificially large due to instrumentation effects, the peak intensity of the acoustic profiles in all three cases are co-located with the density gradient maximum. Fig. 4a is an ABV taken on JD 257 (Sept 14, 1995) from 03:25 to 05:05 also with the 200kHz transducer. Note that the ship turned about between 04:11 and 04:2. Consequently, this image is roughly symmetric about its center. The start and end points are about one and two miles south of the diffuser site, respectively. The center of the plot is within the Stellwagen Basin where internal waves are known to exist. The peak of the SBP undergoes excursions in depth ranging from about 5 meters to 20 meters with a region of relative stability starting at 04:11 to 04:21. The following observations may be made by examining Fig. 4a. The SBP are caused to range in depth due to the presence of internal waves (04:20 to 04:35). A depression and bifurcation of the SBP layers is observed when the sea bed topography rises (04:45 to 04:55).Several coincidences of downward moving acoustic reflector fields associated with topographic highs near the new diffuser site were observed, both in the presence and absence of large amplitude internal waves. This suggests that the presence of topographic highs may influence the vertical distribution of the acoustic reflectors. (The interested reader is referred to [1] for more complete analysis.)

To help provide a quantitative measure of spatial homogeneity for the SBP and to gauge the coherence of the upper effluent plume boundary, a cross-correlation search function (CCSF) is used. Such a function can provide a measure of similarity of acoustic profiles as well as locations of features disrupting that similarity. In calculating the CCSF, a reference acoustic profile location is selected and cross-correlations are computed with the reference profile at different spatial locations. Fig. 4b is the CCSF for the data in Fig. 4a. The degree of similarity of the data to the reference profile is proportional to the CCSF value (at a given depth). The dynamical behavior of the SBP is expressed in the location of the peak of the CCSF on the y axis and in the degree of similitude of the CCSF between profiles. While the CCSF is a gauge of the dynamics that the SBP are experiencing, it must be borne in mind that the effluent plume dynamics are a function of the plume buoyancy, water column density, and water column currents; the SBP (especially the biological portion) may also respond to light levels, prey/predator relationships, etc.

If the assumption that the distribution of the SBP is a reasonable surrogate for the future effluent distribution is accepted, then some inferences may be made about the water column features that might disrupt the simple effluent plume spatial distribution sketch shown in Fig. 1a. A general question is whether the diffuse acoustic reflector field overlaying the effluent field will be caused to intermix because of internal wave perturbations of the respective fields. If internal waves were to break or overturn, then intermixture could occur. Absent overturning, the acoustic reflector layers appear to re-assume equilibrium immediately after passage of an internal wave. The mechanism by which the spatial distribution of the acoustic reflector field is caused to undergo a change from one side of a topographic rise to the other as illustrated in Fig. 4a is unclear. However, because these changes are seen both in the presence and absence of large amplitude internal waves, this suggests that the causative mechanism does not depend upon the presence of large amplitude internal waves, although such waves could conceivably contribute to the effect. A modulation of the ambient current flow (e.g. tidal flow) as it passes over the topographic rise could cause the current to sweep the acoustic reflectors (e.g. plankton) down in the water column. If the distribution in the acoustic reflector field is caused by the ambient current flow, then it is reasonable to expect that an effluent field in the water column would also be swept down by the same ambient current flow. If the distribution of topographic rises is sufficiently numerous in the environs of the diffuser, then a mechanism might exist for effluent distribution other than that illustrated in Fig. 1b. Future studies would be needed to assess the nature, frequency and areal extent of these disturbances and their potential effect on dilution of effluent in the Bay.

Summary

In this brief paper it has been suggested that SBP in Massachusetts Bay are located in the expected location of the future effluent material. Also, it is proposed that the dynamic processes that effect these acoustic reflectors will effect the effluent material in a similar fashion. By observing the SBP, some judgments regarding the deviation from the simplest model of effluent dispersion have been put forth. It cannot be overstated that these must be taken in the context of the limited scope of this study. However the bulk of the data collected in this study leads one to have confidence in these observations.

References

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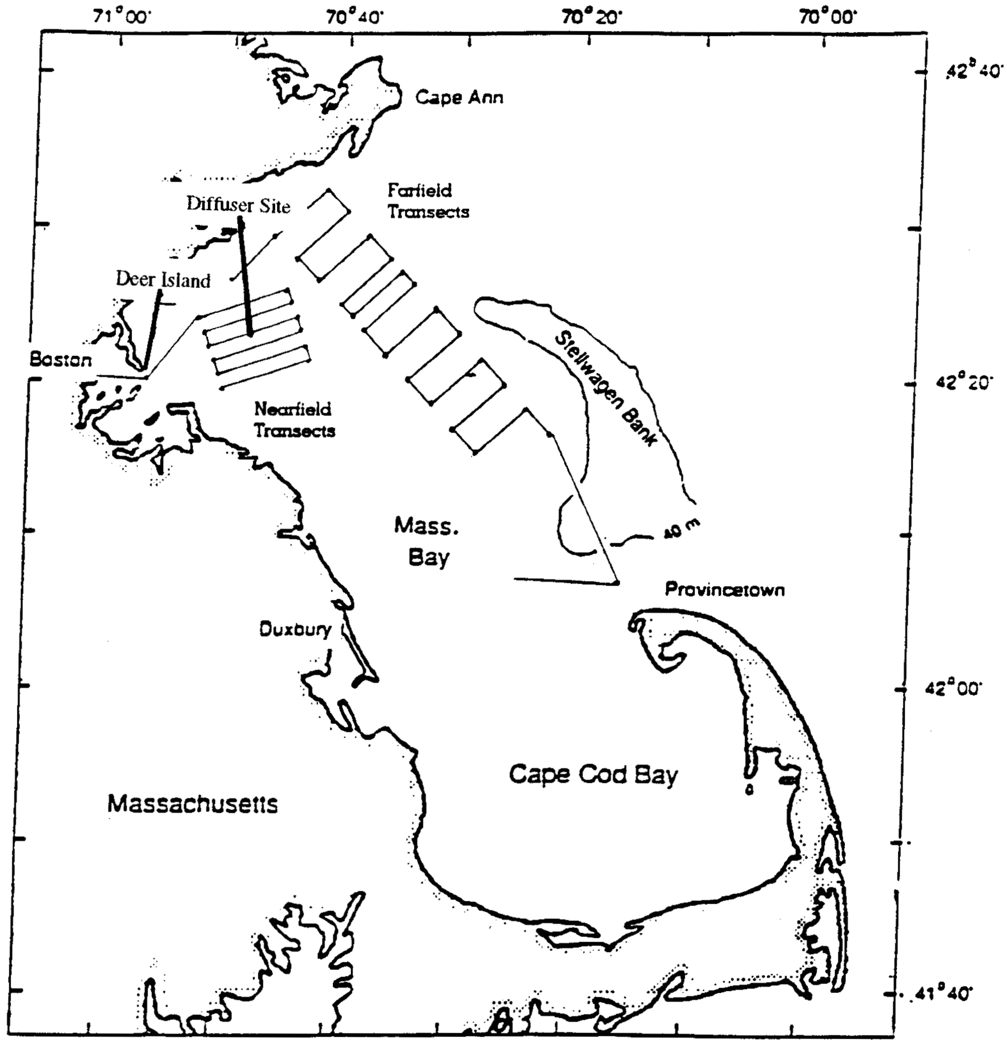
71°00'
70°40'
70°20'
70°00'
42°40'
42°20'
42°00'
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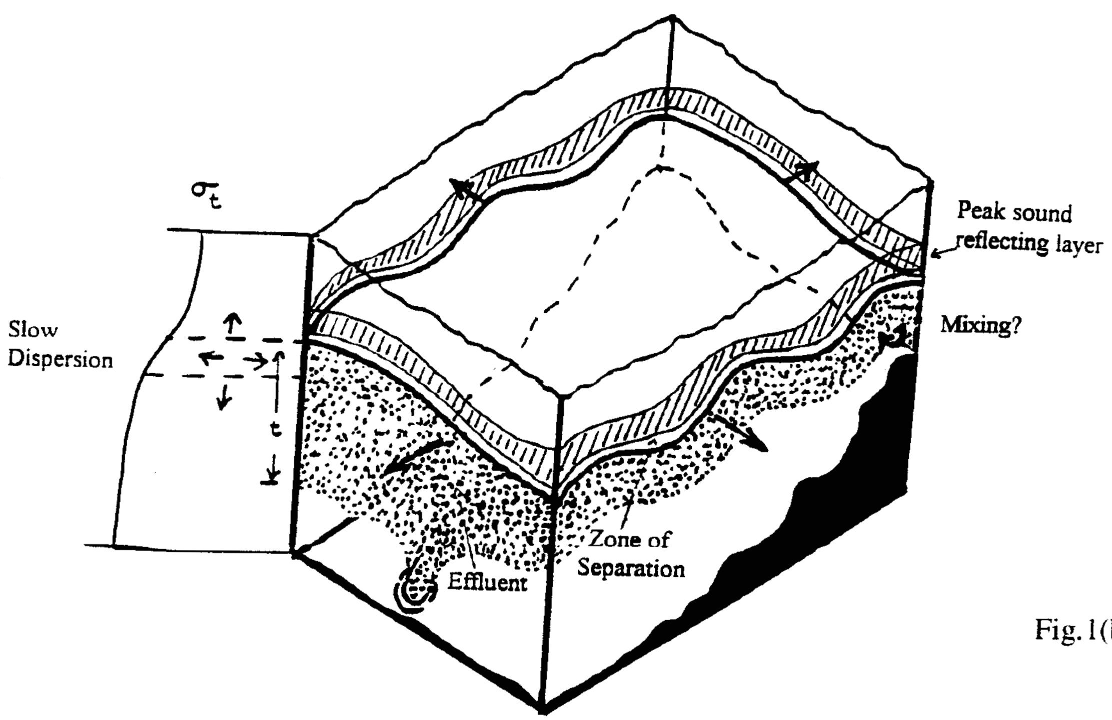
Cape Ann
Farfield
Transects
Diffuser Site
Deer Island
Boston
Nearfield
Transects
Stellwagen Bank
40 m
Mass.
Bay
Provincetown
Duxbury
Cape Cod Bay
Massachusetts

Fig.1(a)


σ_t
Slow
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Effluent

Fig.1(b)

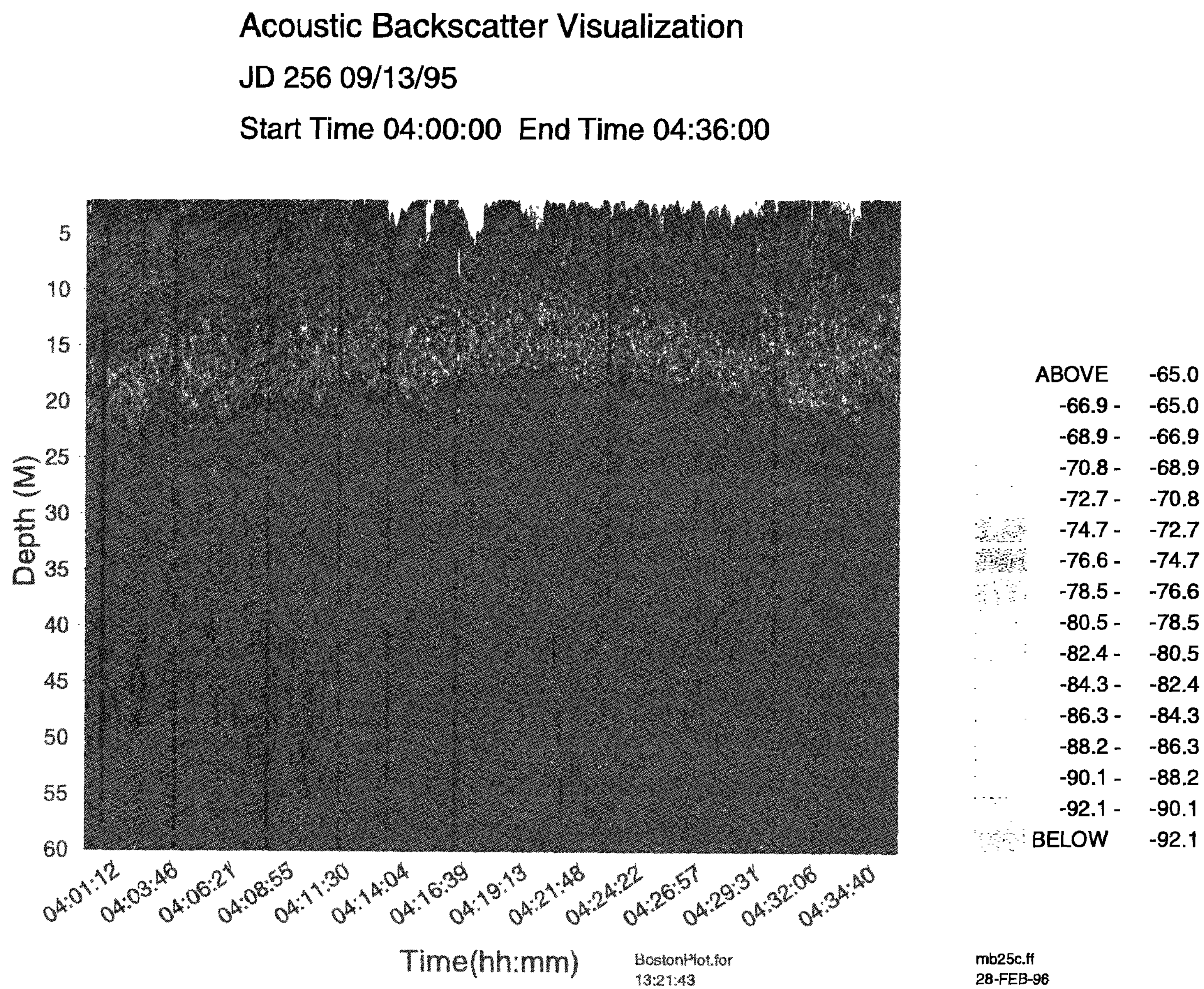
Acoustic Backscatter Visualization
JD 256 09/13/95
Start Time 04:00:00 End Time 04:36:00
Depth (M)
5
10
15
20
25
30
35
40
45
50
55
60
04:01:12
04:03:46
04:06:21
04:08:55
04:11:30
04:14:04
04:16:39
04:19:13
04:21:48
04:24:22
04:26:57
04:29:31
04:32:06
04:34:40
Time(hh:mm)
BostonPlot.for
13:21:43
ABOVE -65.0
-66.9 - -65.0
-68.9 - -66.9
-70.8 - -68.9
-72.7 - -70.8
-74.7 - -72.7
-76.6 - -74.7
-78.5 - -76.6
-80.5 - -78.5
-82.4 - -80.5
-84.3 - -82.4
-86.3 - -84.3
-88.2 - -86.3
-90.1 - -88.2
-92.1 - -90.1
BELOW -92.1
mb25c.ff
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Fig. 2

SIGMA-T AND THREE ACOUSTIC PROFILES

MASSACHUSETTS BAY JD 256 1995

42°23.69' N   070°38.43' W

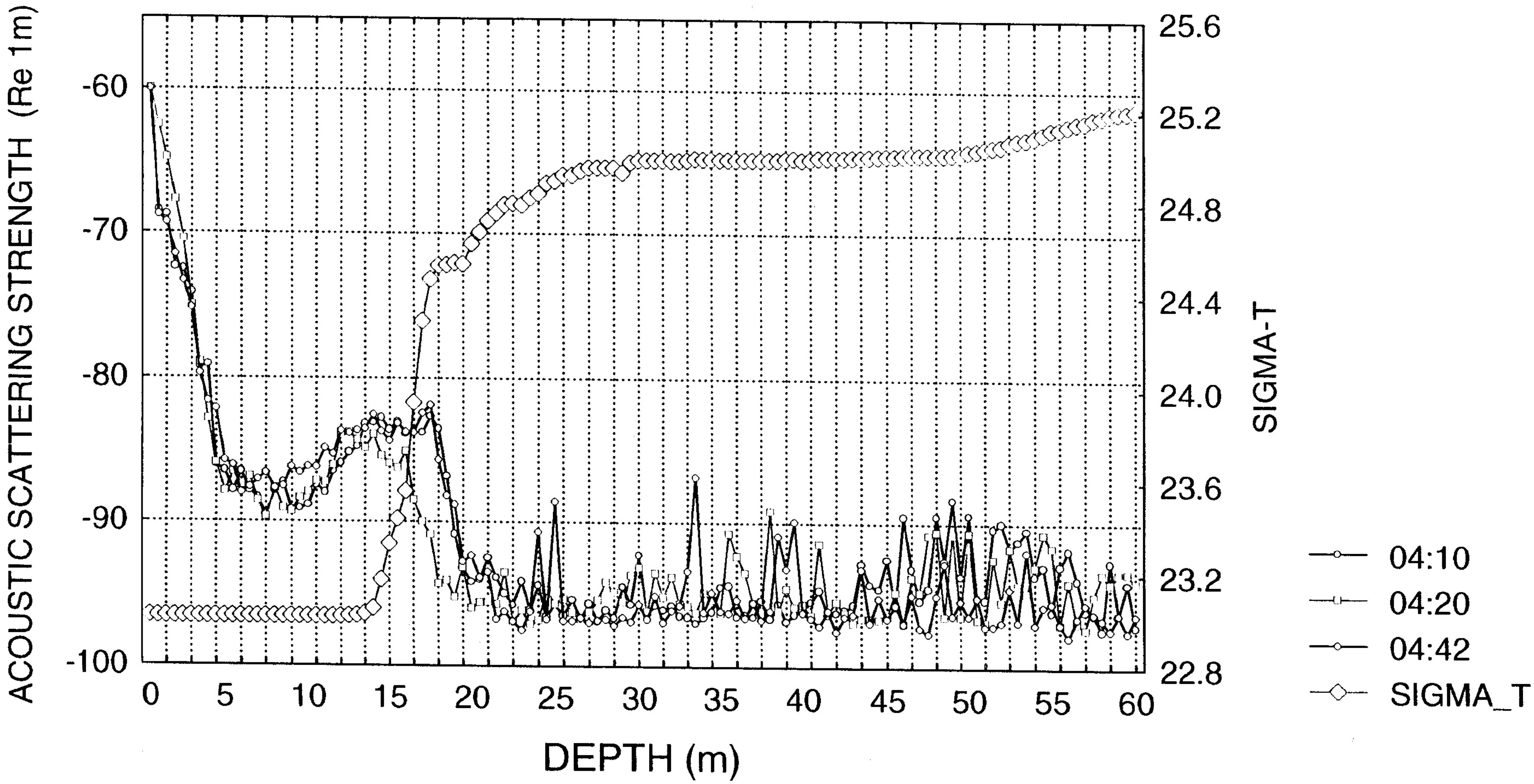

Fig. 3

Fig. 4(a)

Acoustic Backscatter Visualization
Massachusetts Bay JD257 1995