# Sound propagation in regions of variable oceanography*

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## Abstract

In this presentation we have modeled sound propagation in regions having range dependent sound speed profiles. Three scenarios are considered, 1) sound propagation through an internal hydrodynamic wave, 2) long distance sound propagation in a region having a hot core vortex, and 3) sound propagation in a region characterized by a set of solitons.

## 1 Introduction

Coastal waters often exhibit sound propagation features that vary with time, and oceanographic phenomena like internal waves, solitons, and passing vortexes are known to be at least partly responsible for this. In this paper we present a study on some generic oceanographic features presented in the open literature. The oceanographic scenarios we study are all deterministic, the random fluctuations that certainly occur are not included. Further, the features are "frozen" in time, and we merely regard them as special refractive hydrodynamic elements.

For the investigation, we have used the direct integration [1] ray tracing program Ray5. This program requires sound speed input data in the form of analytical descriptions, or as sound speed data files for the region of interest. Also, as the direction of the beam depends on the local sound speed gradients, these must also be provided at all field points. A recent development to the program is the ability to consider the rays as Gaussian beams [3]. This makes it possible to add sound pressures at given receiver points coherently, but also adds to the program requirements in as much as also the second derivative of the sound speed with respect to direction must be provided.

## 2 Sound propagation through an internal wave

This scenario was first presented by O. S. Lee in [2]. It pertains to a sinusoidally shaped thermocline advancing as a wave in the water.

*Paper presented at the $33^d$ Scandinavian Symposium on Physical Acoustics, Geilo, Norway 7 - 10 Febuary 2010

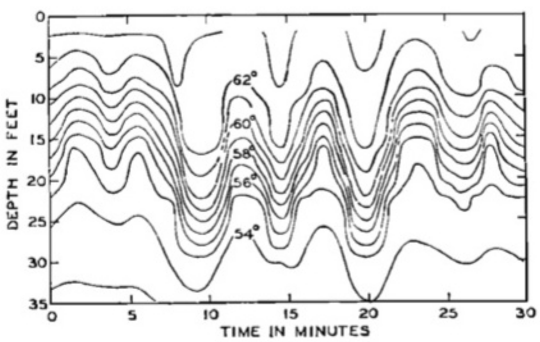


Figure 1: Thermocline measured by Lee (taken from [2]), temperatures in degrees Fahrenheit

With the sound speed in the upper layer set to 1511.8 m/s, the three layer model was idealized by assuming the thermocline to be limited by $z_1$ and $z_2$ given by the equations:

$$\begin{array}{rcll} 0 & \leq z & \leq z_1(r), & \partial c/\partial z = 0 \\ z_1(r) & \leq z & \leq z_2(r), & \partial c/\partial z = -4.8 \\ z_2(r) & \leq z & \leq 100, & \partial c/\partial z = -0.6 \end{array} \quad (1)$$

where :

$$\begin{array}{rcl} z_1(r) & = & 9.14 - 2.44\,sin(2\pi r/91.44) \\ z_2(r) & = & 12.19 - 2.74\,sin(2\pi r/91.44) \end{array} \quad (2)$$

Figures 2 and 3 show sound rays sent out from a source at 3.05m depth between $\pm 8.25°$. The total depth of the water volume was set to 100m. For the first figure, the thermocline is flat and we see a relatively even spread of the rays, while for the second, a portion of the rays seem to follow the descending part of the sinusoid and thereby give more uneven distribution at a given depth.

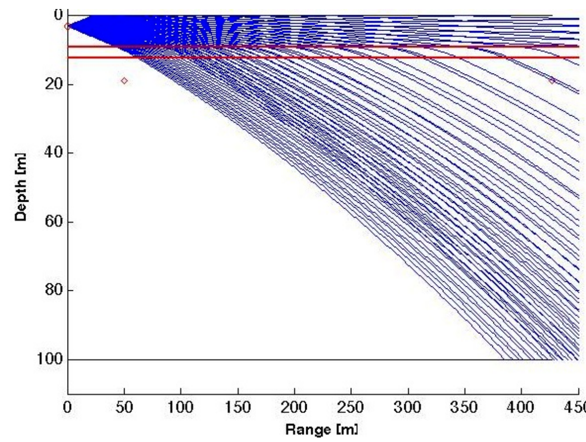


Figure 2: Rays through flat thermocline

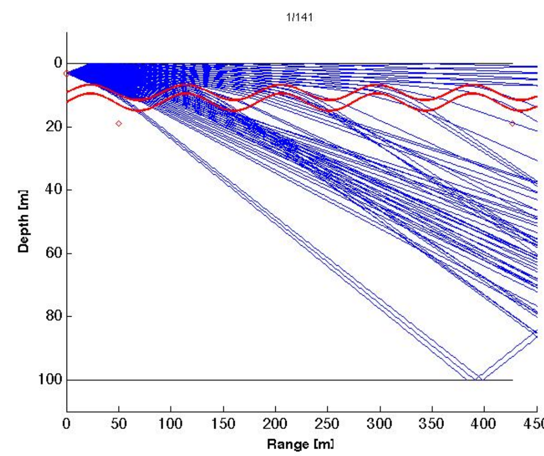


Figure 3: Rays through sinusoidal thermocline

For a receiver line just below the thermocline, at depth 19m, we have traced the eigenrays and calculated the Transmission losses. This can be done both coherently, *i.e.* we take the phase of the signals arriving with each ray into account, or incoherently, where the levels are added on an energy basis. Figures 4 below show eigenrays arriving in the focus region and figure 5 the coherent (1000Hz) and incoherent transmission losses. We see that incoherently the pressures

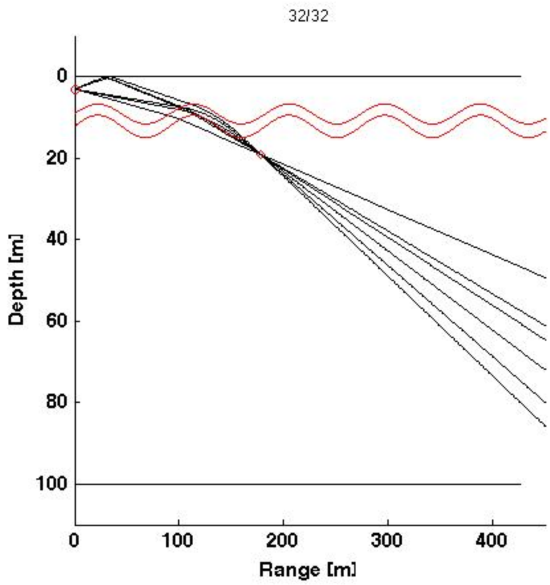


Figure 4: Eigenrays arriving at receiver location r=177m, z=19m

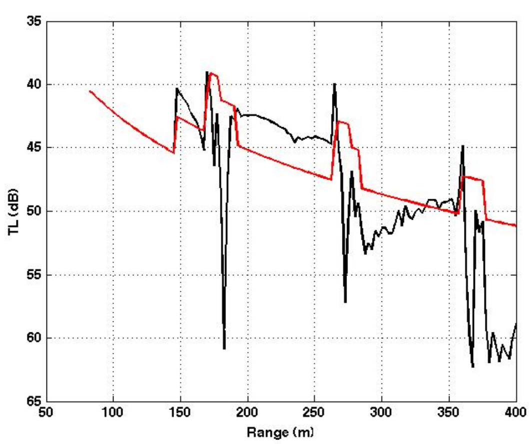


Figure 5: Transmission loss at receiver line at 19m depth, red line for incoherent addition, black line for coherent addition at 1000Hz

will add to local high levels in the focusing region, while coherently the signal varies rapidly in this region due to constructive and destructive interference effects. The wavelength at this frequency is about 1.5m. The result indicate that signal transmission between two stations in a region having such an internal wave is expected to vary strongly as the wave propagates through the region.

## 3 A warm core eddy

Figure 6 is taken from the book by Jensen *et al.*, [1]. It shows 6 sound speed profiles for regular intervals over a 200km range. For a source in the upper region, two transmission ducts are favored, a main SOFAR duct, and an upper duct limited by the sea surface and the eddy. The last duct is only expected to exist for the range where the eddy has an effect.

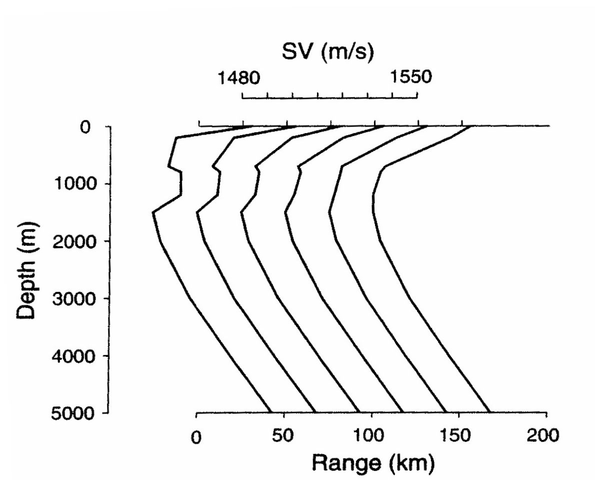


**Fig. 5.17.** Sound-speed profiles through the eddy.

Figure 6: Range dependent sound speed profiles, left profiles through warm core eddy

To use Ray5 for such a situation we first interpolated the sound speed profiles using a 12th order 2 dimensional polynomial. A required local sound speed and it's derivatives could then easily be found.

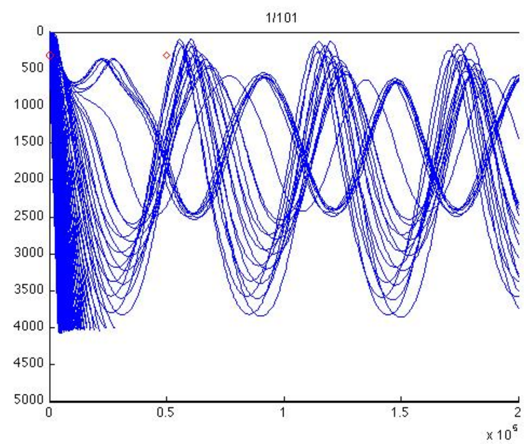


Figure 7: Ray diagram for range dependent sound speed distribution given by figure 6, ray fan ±45°, sourcedepth 300m

We notice from the above figure that the rays divide themselves between the main duct and an upper duct in the vicinity of the vortex. The upper duct energy is seen to be channeled to the central part of the SOFAR duct after about 50km.

# 4 Sound propagation in a region containing solitons

This scenario was posed as a benchmark test in the SWAM99 conference [4]. A given background soundspeed profile is perturbed by a set of solitary waves, or solitons. The mathematical description of the background profile is given as

$$c(z) = 1515 + 0.016z \qquad \text{for } z \leq 26$$
$$c(z) = c_0(1 + a(e^{-b} + b - 1)) \qquad \text{for } z \geq 26$$

where $c_0 = 1490m/s$, $a = 0.25$,
$b = (z - z_{axis})/500$, and $z_{axis} = 200m$

A perturbation describing 6 solitons is given as

$$dc(z,r) = C\frac{z}{B}e^{z/B}\sum_{i=1}^{6} A_i\big(\text{sech}(\frac{R_i - r}{D_i})\big)^2$$

where

$$\text{for } i = 1 \cdots 6 : A_i = 10e{-}0.3(i-1),$$

and $D_i = \sqrt{34300/A_i}$.

$R_1 = 1400m$, and for $i = 2 \cdots 6 : R_i = R_{i-1} - 500(7 - i)$,
$B = 25m$. $C$ defines the maximum speed perturbation. $C = 3.4$ gives $dc = 12.2m/s$ while $C = 5$ gives a maximum $dc$ of $18.5m/s$

Figure 8 shows rays emitted in a situation without solitons. Also, in figure 9, is plotted the number of rays traversing 50m long bins at a depth of 19m. The repetitive pattern of many ray crossings (approximately every 2500m) is clearly visible.

Figures 10 and 11 shows the same number of rays emitted for the same background sound speed profile, but this time with 6 solitons superimposed. Note the added number of rays collecting in the range gap including the solitons and the loss of repetition at further ranges. The $C$ factor for figures 10 and 11 is 5.

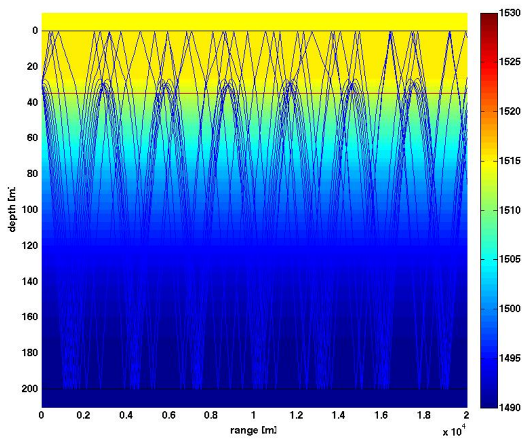


Figure 8: Rays emitted between ± 5 degrees, source depth = 30m, scenario without solitons, Maximum range = 20km, bottom at 200m.

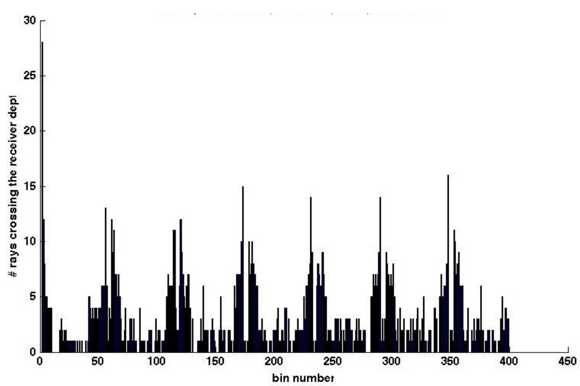


Figure 9: Rays emitted between $\pm 5^\circ$ every $0.1^\circ$. Number of rays crossing 50m long bins from zero to 20 km range,source depth=30m, receiver depth= 35m

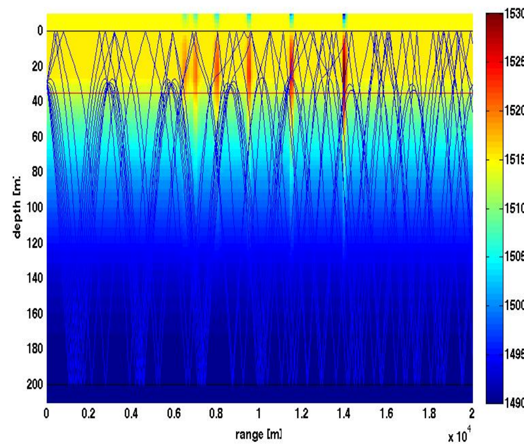


Figure 10: Rays emitted between ± 5 degrees ZS=30, ZR=35, scenario with solitons

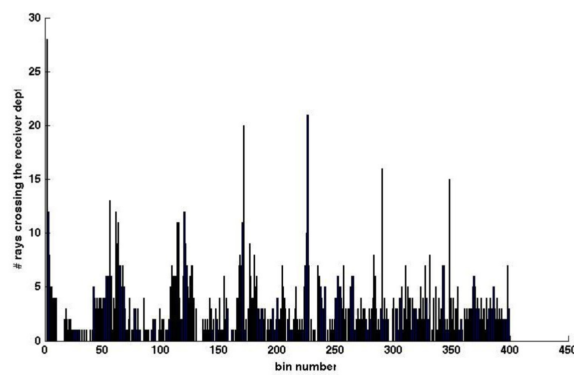


Figure 11: Rays emitted between $\pm 5^\circ$ every $.1^\circ$. Number of rays crossing 50m long bins from zero to 20000m range, receiver depth =ZR = 35m

In figure 12 the upper channel is used as a transmission channel. With a narrow ray fan opening of $\pm 1^\circ$, all rays will stay in the upper channel. In figure 13 , where the solitons are added, we see that they destroy the transmission channel to a large extent. For this figure the $C$ factor was set to 3.4. Also note that the solitons to the right in the figure are the strongest, (strong solitons propagate with a higher speed).

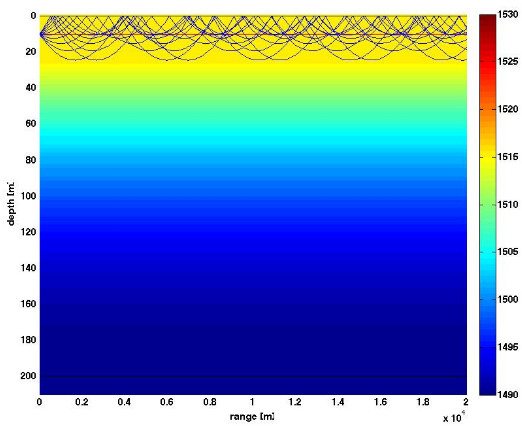


Figure 12: Rays emitted between $\pm 1^\circ$ ZS=10m. scenario without solitons

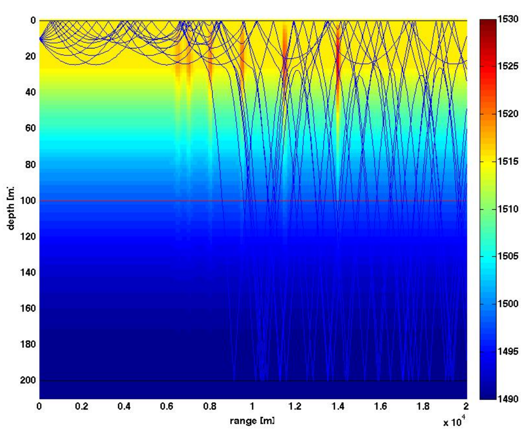


Figure 13: Rays emitted between $\pm 1^\circ$ , ZS=10m, scenario with solitons

# References


[1] Finn B. Jensen, William A. Kuperman, Michael B. Porter, and Henrik Schmidt. *Computational ocean acoustics.* Springer verlag New York, 2000.

[2] Owen S. Lee. Effect of an internal wave on sound in the ocean. *Journal of the Acoustical Society of America*, 33:677–681, 1961.

[3] M.B. Porter and H. P. Bucker. Gaussian beam tracing for computing ocean acoustic fields. *Journal of the Acoustical Society of America*, 82:1349 – 1359, 1987.

[4] SWAM99. Swam99 internal waves. http://web.nps.navy.mil/ kb-smith/SWAM99/swam99.html, 1999.