Chapter 1

STATIONARY SOURCE TRANSMISSION IN SW06

1.1 Shallow water '06 experiment

The multi-institutional SW06 experiment was conducted on the New Jersey continental shelf (Fig. 1.1) from July to September 2006 at a location where internal wave activity has been observed and studied in the past[4] . In this paper, we focus on a particular internal wave event on August 17, 2006, for which a complete set of acoustic and environmental data were collected simultaneously. In addition, ISW surface signatures were captured continuously by the on-board radars of two research vessels prior to the arrival of, and during the passing of, the ISW packet over the acoustic track. The acoustic wave field variation is studied during this process. Other studies of the SW06 data in relation to three dimensional modeling are being conducted separately.

During SW06, both acoustic and environment data were collected simultaneously. In this paper we discuss the acoustic data from a particular acoustic source (NRL 300Hz) on the mooring denoted SW45 (see Fig. 1). The source was located 72 m below the sea surface and 10.5 m above the sea floor at $39^o10.957'$ N, $72^o56.575'$ W, and transmitted 2.0489 second Linear Frequency Modulating (LFM) signals from 270 to 330 Hz every 4 seconds. Transmissions continued for 7.5 minutes and then repeated every half hour. A vertical and horizontal receiver array (the "Shark VHLA") on mooring SW54 was located at $39^o01.252'$ N, $73^o02.983'$ W, about 20.2 km south of the NRL source. The vertical part of the receiver array consisted of

Figure 1.1: SW06 experiment site east of New Jersey shore, moorings are shown as blue dots

Figure 1.2: SW06 mooring locations

Table 1.1: Transmission during Ev50 from stationary source (NRL300) & moving source (J15/R.V. Sharp)

Zone	Time(GMT)	Source
1	20:30-20:37	NRL300
2	21:00-21:07	NRL300
3	21:11-21:26	J15/R.V. Sharp
4	21:30-21:37	NRL300
5	21:41-21:46	J15/R.V. Sharp
6	22:00-22:07	NRL300
7	22:11-22:26	J15/R.V. Sharp
8	22:30-22:37	NRL300
9	22:41-22:56	J15/R.V. Sharp
10	23:00-23:07	NRL300
11	23:11-23:16	J15/R.V. Sharp
12	23:30-23:37	NRL300

16 hydrophones with 3.5 m spacing and was positioned in the water column from 13.5 m to 77.75 m below the surface. The horizontal part of the array consisted of 32 hydrophones on the seafloor with spacing of 15 m, providing 478 m of horizontal aperture. The sampling rate of the array was 9765.625 Hz. The acoustic track and the locations of the source and receiver as well as the horizontal and vertical array configurations are shown in Fig. 1. The water depth along the acoustic track was about 80 m.

1.2 Event 50/Rosy

1.2.1 Ship position and experiment setup

On August 17, 2006, at about 18:00 GMT, the R/V Sharp from the University of Delaware was located at 38o59.262' N, 72o57.492' W and the R/V Oceanus from the Woods Hole Oceanographic Institution (WHOI) was located at 38o57.426' N, 72o56.676' W. Both platforms observed the origination of an ISW near the shelf break. This event was named Event 50 on R/V Sharp and Rosey on R/V Oceanus.

Figures 1(a) and 1(b) show the track of each vessel following this event from 18:00 GMT on August 17 to 02:00 GMT on August 18, 2006. The R/V Sharp's track was semi circular, centered at the WHOI vertical and horizontal line array (Shark VHLA) with the ship being positioned on the trough of the leading ISW front and moving with the advancing front. The R/V Oceanus followed the same ISW packet from its initial location, while keeping a watch on the advancing wave front. Reversals in the track of R/V Oceanus indicate where the wave packet was crossed, and during these periods, intensive profiling of temperature, density, turbulence and sound velocity was conducted.

The two ships observed different parts of the ISW front, thus providing a large spatial coverage. The surface signatures of the ISW were digitally recorded by on-board ship radar images every 30 seconds. Combined radar images from the two vessels, each about 11.1 km in diameter, covered the receiver and about two thirds of the acoustic track. Mm. 1 shows a movie of the ships' radar images following the ISW during this event, from 18:00 GMT on 17 August to 02:00 GMT on 18 August, 2006. In this paper we discuss two situations: (1) when the ISW packet had not reached the acoustic track [time period T_{g1} (20:30 to 20:37 GMT)] and (2) when the ISW occupied most of the acoustic track [time period T_{g2} (22:00 to 22:07 GMT)]. The radar images from both vessels at 20:30 GMT and 22:00 GMT are shown in Figs. 1(a) and 1(b) respectively.

At 20:30 GMT, the R/V Sharp radar showed 10 distinct ISW fronts in a packet. At the same time, the R/V Oceanus radar showed 7 wave fronts with less curvature. The spacing between wave fronts in the packet varied from 0.4 to 0.5 km for the leading wave fronts to 0.2 to 0.3 km for the trailing waves. The ISW direction of propagation was about compass direction 300°.

At 22:00 GMT, most of the acoustic track including the receiver array was occupied by the ISW packet [see Fig. 1(b)]. The physical characteristics of the

ISW packet during this time were similar to those at 20:30 GMT, except that its propagation direction was slightly changed. The R/V Oceanus observed the ISW propagation direction close to the receiver to be about 310o. At the middle of the acoustic track (SW20), a propagation direction of 305o was observed on RV Sharp. Note that the wave front was curved so there is a natural discrepancy between the propagation directions observed by the two ships. The angle between the ISW fronts and the acoustic track at midpoint was approximately 5o and varied along the acoustic track. The average speed of the ships following the ISW packet was about 1.8 to 2.0 knots, which was similar to the ISW propagation speed.

The SW45 mooring had eleven temperature sensors located at depth between 15 m to 72 m and the SW54 mooring had eleven temperature sensors at 5 m to 78.5 m. To get a spatial picture of the water temperature along the acoustic track, data from a third thermistor string (SW20) in the middle of the track was also used. This mooring had three temperature sensors between 14 m and 40 m. All these sensors recorded temperature data every 30 seconds.

1.2.2 Temperature measurement

Figure 1.3 shows the temperature records at the acoustic source mooring SW45, the midpoint SW20, and the receiver mooring SW54 from 20:00 to 23:00 GMT on August 17, 2006. A solitary internal wave arrived at the receiver around 21:15 GMT, followed by a calm period of about 20 minutes. At around 21:40 GMT, the leading front of a strong ISW packet passed the receiver position. The ISW packet caused a sudden increase in the thermocline depth. At 22:20 GMT, the water temperature decreased slowly until 09:00 GMT the next day. The leading wave front was observed at SW20 at 22:02 and at SW45 at 22:15 GMT, respectively. If we assume the leading wave front is linear (it is not) and the wave speed is constant along the wave front, this suggests an angle of about 5° between the advancing front and the acoustic track.

Figure 1.3: Temperature profiles measured at (a) the acoustic source, (b) the midpoint between the source and receiver, and (c) at the Shark WVHLA during internal wave Event 50, August 17, 2006 from 20:00 to 23:00 GMT. T_{g1} = 20:30 to 20:37 GMT and T_{g2} = 22:00 to 22:07 GMT.

Figure 1.4: Received acoustic intensity on the Shark VHLA during two geotimes within the T_{g1} and T_{g2} periods. Upper panel shows the acoustic field on the VLA portion of the array while the lower panel shows the HLA portion. (a) Tg = 20:30:16 GMT, (b) Tg = 20:31:58 GMT, (c) Tg = 22:04:54 GMT, (d) Tg = 22:06:37 GMT.

1.3 Acoustic signal and observations

Next, we show the acoustic signal arrival on the Shark VHLA during the two periods T_{g1} and T_{g2}. In order to show the intensity variations, we show the arrival of two different LFM pings on the array at geotimes separated by 102 sec. In Fig.1.4, the upper panel shows the acoustic signal on the VLA at 20:30:16 GMT while the lower panel shows the same signal arriving on the HLA. Figure 3(b) shows the same two arrays at 20:31:58 GMT. The parallel lines on the HLA data shown in the lower panels are due to the difference of arrival time on the HLA (see array configuration in Fig. 1(c)). The data on the VLA portion of the array shown in the upper panels best represent the modal arrivals. Note the similarity of the intensity values on both vertical and the horizontal array plots in Figs. 3(a) and 3(b), indicating the stability of the arriving signal energy during Tg_1. During Tg_2 the same data format is shown. At 22:04:54 GMT shown in Fig. 3(c), both the VLA and HLA show a drastic change in the arrival. The signal intensity becomes very strong; however, different arrivals are mixed together and difficult to separate. The parallel lines on

the HLA were notably distorted. At 22:06:37 GMT shown in Fig. 3(d), the arrivals show a lack of structure as well as lower intensity. During the time period of T_{g2}, the ISW is occupying a large fraction of the acoustic track. Mm. 2 shows a movie of the acoustic signal arrival on the Shark VHLA during the two periods T_{g1} and T_{g2}. To further quantify these results, we next calculate the average intensity in geotime and depth for the periods, Tg_1 and Tg_2.

1.3.1 20:30GMT-20:37GMT

Figure1.5 shows the radar image at 20:30GMT. The ISWs hasn't arrived at the acoustic path - about 4km away at the closest point (SHARK VLA). In figure 1.6, the received signal on VLA shows a 3-stripe pattern, which, after modal decomposition (Fig1.7), can be contributed to the very strong and steady 2nd and 3rd modes. The modal decomposition figures also show the intensity of the 1st mode grows around 20:36GMT. Although the fluctuation of the total intensity is less than 2.5dB, from the modal amplitude plot, we can see the increase of the intensity mode 1 and 4 and the decrease of mode 2 and 3. The energy exchange among the different modes here suggest the occurrence of the modal coupling.

Figure 1.5: Radar image of ISW at 20:30GMT

Figure 1.6: Received signal on Shark VLA (top), HLA (bottom) and signal intensity (middle) from Aug.17 20:30GMT to 20:37GMT

Figure 1.7: Mode decomposition and amplitude of the signal received on Shark VLA from Aug.17 20:30GMT to 20:37GMT

1.3.2 21:00GMT-21:07GMT

Figure1.8 shows the radar image at 21:00GMT. The ISWs is still about 1km away from the VLA, and very similar to the previous time period (20:30GMT - 20:37GMT), only very little fluctuation of the total intensity is shown (Fig.1.9). On the modal decomposition plot (Fig.1.10), the 3rd mode grows while the other modes decrease to various extends. The modal coupling might cause this as well.

Figure 1.8: Radar image of ISW at 21:00GMT

1.3.3 21:30GMT-21:37GMT

Radar image shows the major ISW reaches the VLA at about 21:37GMT, but the signal received on SHARK VLA and HLA shows the effects of ISW on the acoustic propagation starts a bit earlier at about 21:33GMT when the HLA shows the slope caused by the movement of the ISW. A 5dB dip on the total intensity plot implies the energy could be transferred out of the VLA plane. Mode 1 and 2 are steady and strong when pushed to the deeper water by the downward movement of the thermocline. On the other hand, mode 3, 4 and 5 show strong (8dB) and fast(period = 50sec) oscillation starting about 21:33GMT, confirming the effects of ISW on acoustic propagation.

Figure 1.9: Received signal on Shark VLA (top), HLA (bottom) and signal intensity (middle) from Aug.17 21:00GMT to 21:07GMT

1.3.4 22:00GMT-22:07GMT

ISW occupies the most of the acoustic path. Slopes on the HLA show the strong effects of ISW on the acoustic propagation. On the VLA, the focusing induces the intensity fluctuation of 15dB. Modal decomposition shows mode 1 is the dominant play of the focusing with a sudden increase in amplitude.

1.3.5 22:30GMT-22:37GMT

The acoustic path is at the middle of the ISW package, where the wavelength is shorter than the leading fronts. Two focusing events are observed with 15dB variations on total intensity. Mode 1 and 2 show more fluctuation than mode 3, 4 and 5. On HLA, regular slopes are shown, sometimes not consistent with the signals on VLA.

Figure 1.10: Modal decomposition and amplitude of the signal received on Shark VLA from Aug.17 21:00GMT to 21:07GMT

1.3.6 23:00GMT-23:07GMT

The acoustic path now is at the coverage of R/V Sharp's radar, and escapes from R/V Oceanouse's radar. From the temperature plot, the acoustic path is still affected by the ISW package. Tow focusing events are shown with about 15dB fluctuation.

1.3.7 23:30GMT-23:37GMT

No radar image, but the temperature plots shows the acoustic path is still under the influence of ISW. Tow focusing events are recorded on HLA with fluctuation about 15dB.

Figure 1.11: Radar image of ISW at 21:30GMT

1.4 Intensity variations

Based on the theory proposed in our previous work, the angle between the ISW fronts and the acoustic track determines the mechanism of the intensity fluctuations. Small angles provide horizontal refraction and focusing while larger angles cause mode coupling. Between these limits, there is an angular region for which the propagation is adiabatic. During internal wave Event 50, the ISW fronts passed through the acoustic track at an angle of about 5o providing the condition for horizontal refraction. Prior to the ISW arrival, we observe stable adiabatic propagation in a stable water column. Hence, a transition can indeed be observed between these two mechanisms.

To show a focusing event, we consider two geotimes: (a) T_{g1} when the leading internal wave front had not reached the acoustic track and, (b) T_{g2} when the internal wave packet occupied most of the acoustic track. We calculate the total intensity integrated over the depth H as

$$I(T) = \int_0^H I(z,T)dz \tag{1.1}$$

Figure 1.12: Received signal on Shark VLA (top), HLA (bottom) and signal intensity (middle) from Aug.17 21:30GMT to 21:37GMT

where $I(z,T) = \dfrac{1}{\rho c} \int\limits_{\tau}^{\tau+\Delta\tau} p^2(z,T,t)\,dt$ is the intensity of the signal arrivals integrated over a pulse length $\Delta\tau$ at a given depth z, where p is acoustic pressure,ρ is water density, and c is sound speed. The distribution of the ISWs in the horizontal plane can be assessed by carefully examining the radar image and the depth distribution of the temperature at three points (SW45, SW20, SW54) along the acoustic track.

The temperature distribution starting at 20:30:00 GMT (T_{g1}) for the transmission period (i.e. $\sim$ 7.5 minutes) at three different moorings shows very little fluctuation along the acoustic track (see Fig. 2).This indicates that the ISW has not reached the acoustic track during T_{g1}, as is also shown in the radar image. In Fig.1.14(a) we show a plot of I(z,T) for the VLA. It is shown that for a repeated pulse of the same radiated intensity, only minor temporal intensity variation exists. In Fig.1.14(b) we plot the depth integrated intensity for all geotimes, I(T). The very

Figure 1.13: Modal decomposition and amplitude of the signal received on Shark VLA from Aug.17 21:30GMT to 21:37GMT

small fluctuations (3 dB) at T_{g1} indicate a quiescent condition without ISWs in the track. This means that during this period of observation there is no redistribution of sound energy in the horizontal plane, i.e. there is no horizontal refraction. Small variations of the depth distribution of the sound intensity correspond to the adiabatic case. Fig.1.14(c) shows the acoustic intensity on the HLA. There are no apparent temporal intensity variations on the HLA during this geotime.

I(z,T) for T_{g2} is plotted in Fig.1.14(d). Here we see increasing and decreasing trends in sound intensity over the VLA, which are synchronous in depth. The average intensity I(T) using Eq. (1) peaks to 35 dB around 22:04:30 to 22:05:00 GMT, and decreases to 20 dB around 22:06:37 GMT as shown in Fig.1.14(e). This significant fluctuation corresponds to redistribution of the acoustic energy in the horizontal plane, which in the limit can be referred to as focusing or defocusing

Figure 1.14: Received acoustic intensity during a 440 sec (7.33 mins) transmission period for two geotimes, T_{g1} (from 20:30:00 to 20:37:20 GMT): (a) depth distribution of total intensity per pulse I(z,T), (b) depth integrated intensity, I(T) for VLA, (c) total intensity I(x,T) for HLA; and T_{g2} (22:00:00 to 22:07:20 GMT): (d) depth distribution of total intensity per pulse I(z,T), (e) depth integrated intensity, I(T) for VLA, (f) total intensity I(x,T) for HLA.

events and is related to the position of the source and/or receiver with respect to the internal wave crests. The focusing and defocusing are also shown in Fig.1.4(c) and Fig.1.4(d). In this case (i.e. T_{g2}), the receiver is between two adjacent maxima of the thermocline displacement, and the high intensity fluctuations (15 dB peak to peak) are due to horizontal refraction effects similar to those shown in previous studies.3 Temporal fluctuations correlate with oscillations of the thermocline layer at the receiver (see Fig. 2) due to ISWs (period is 7-8 min). The fluctuations in the presence of internal waves (i.e. at T_{g2}) are about 15 dB, which are much larger than those of T_{g1} (3 dB) with no internal wave in the acoustic track. Although the total jump in the thermocline thickness (i.e. from 15 m to 30 m) could make a difference in the 'absolute' value of the acoustic intensity, it does not play a significant role in the temporal intensity fluctuation with periods corresponding to the ISW.

As in the quiescent case shown above, Fig.1.14(f) shows the acoustic intensity on the HLA for the active period (T_{g2}). During the geotime of about 7.33 minutes, we see the variation of the sound field at the horizontal array. For the variation observed during the first 3 minutes, there are two large intensity maxima observed at the HLA. These become weaker and disappear during the second half of the time period (after 22:03 GMT). This behavior, in our opinion, is a manifestation of horizontal redistribution of the sound intensity, which we call focusing/defocusing phenomena. The sloped intensity modulations correspond to the motion of an interference pattern registered on the horizontal array, which can be a result from any motion of the water layer (such as an ISW packet). The velocity of this interference pattern is estimated as 1-1.5 m/s from the acoustic data [shown as a slope in Fig. 4(f)]. This may not be directly related to the velocity of the internal solitons (measured from shipboard radar to be about 1 m/s). Further detailed modeling is needed to understand the nature of these fluctuations and their relationship to the slope of the lines shown in

Fig. 4(f).

1.5 Computer modeling results

BIBLIOGRAPHY

[1] Badiey, M., Y. Mu, J. Lynch, J. R. Apel, and S.Wolf, "Temporal and azimuthal dependence of sound propagation in shallow water with internal waves," IEEE J. Oceanic Eng. 27(1), 117-129 (2002).

[2] Badiey, M., B. G. Katsnelson, J. F. Lynch, S. Pereselkov, and W. L. Siegmann, "Measurement and modeling of three-dimensional sound intensity variations due to shallow-water internal waves," J. Acoust. Soc. Am. 117(2), 613-625 (2005).

[3] Badiey, M., B. G. Katsnelson, J. F. Lynch, and S. Pereselkov, "Frequency dependence and intensity fluctuations due to shallow water internal waves," J. Acoust. Soc. Am. 122(2), 747-760 (2007).

[4] Newhall, A. E., T. F. Duda, J. D. I. K. von der Heydt, J. N. Kemp, S. A. Lerner, S. P. Liberatore, Y.-T. Lin, J. F. Lynch, A. R. Maffei, A. K. Morozov, A. Shmelev, C. J. Sellers, and W. E. Witzell, "Acoustic and oceanographic observations and configuration information for the WHOI moorings for the SW06 experiment," WHOI technical report WHOI-2007-04, (2007).

[5] Collis, J. M., T. F. Duda, J. F. Lynch, H. A. DeFerrari, "Observed limiting cases of horizontal field coherence and array performance in a time-varying internal wavefield," JASA, this issue (2008).