HIGH FREQUENCY INTENSITY FLUCTUATIONS

S.D. Lutz, D.L. Bradley, and R.L. Culver

Steven Lutz, David Bradley, and R. Lee Culver, Graduate Program in Acoustics and Applied Research Laboratory, The Pennsylvania State University, State College, PA 16801, USA
e-mail: slutz@psu.edu, dlb25@psu.edu, rlc@enterprise.arl.psu.edu

Intensity fluctuations were measured during August 2002 near San Diego using 20 and 40 kHz cw and fm signals. Source-receiver separation was 1km; source depths were 10m to 67m; receiver hydrophone depths were 44m to 217m. A 15-element chain of CTD sensors was towed to measure horizontal temperature and salinity with 1m resolution. Comparing the spectra of the acoustic intensity fluctuations and sound speed fluctuations indicate that much of the energy in the oceanic processes occurs at time scales not captured in the acoustic records.
(Work supported by ONR Code 321US under the ARL Program)

1. INTRODUCTION

The intensity scintillation index of signals in underwater acoustics has multiple applications. These include, but are not limited to, acoustic communications, and current and turbulence measurements [1]. Several closely related theories, developed by Flatté [2] and Uscinski [3] exist relating the expected acoustic scintillation index to physical quantities in the ocean. In general these theories require the measurement or estimation of the correlation function (i.e. length scale) and the index of refraction along the acoustic path. However, these theories do not directly include the duration of an acoustic transmission used to calculate the scintillation index.

An experiment has been conducted in which the two-dimensional sound speed field has been measured and relatively short acoustic records have been captured. Direct comparison of the intensity scintillation index and the length scales and index of refraction of the sound speed field have not shown direct agreement with the theories mentioned above. Here, an explanation for this difference is given and a method for resolving the difference is suggested.

The terms intensity scintillation index and index of refraction enjoy widespread use in the underwater acoustics community. However, the exact definitions vary. In this paper, the term, intensity scintillation index, is defined as
\[ \sigma_i^2 = \frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}, \]  

(1)

where \( I \) is the acoustic intensity. The angle brackets indicate the time-average of the quantity inside. Also, the mean square fluctuation of the index of refraction is defined as

\[ \mu^2 = \left( \frac{\Delta c}{c(z)} \right)^2, \]  

(2)

Here \( c(z) \) is the mean sound speed at a given depth and \( \Delta c \) is the local deviation from \( c \).

2. BACKGROUND

It is possible to imagine an acoustic experiment that occurs in a “frozen ocean.” That is, an ocean where the there are inhomogeneities in temperature, salinity, density, and, accordingly, the sound speed, but there is no current and the homogeneities are perfectly still. Acoustic transmission through this ocean from a fixed source to a fixed receiver will have a scintillation index of zero. However, and the spatial variation of the index of refraction could be measured, and of the above reference theory applied to produce an estimate of the intensity scintillation index. This estimate would not be zero and therefore it would not agree with the measured scintillation index.

The “frozen ocean” discussion illustrates the requirement for movement of the inhomogeneities if their spatial structure is to affect the acoustic scintillation index. For the inhomogeneities affect the acoustic scintillation index, they must be advected through the acoustic path during the transmission. The ocean current is the primary cause of advection. Therefore, we expect that only inhomogeneities that have sizes comparable to, or smaller than, the product of the current and duration of the transmission to be manifest in the acoustic scintillation index. Larger inhomogeneities are effectively “frozen”.

Other processes factors can affect the scintillation index. One process is turbulence on scales smaller than the local current. Also, larger inhomogeneities, which tend to have larger index of refraction variations, that have boundaries that intersect the acoustic path are not accounted for even though the location though the intersection between these inhomogeneities changes by a small amount during the transmission. As will be shown below the change in phase of the received signal due to this effect is significantly smaller than the effect of the smaller inhomogeneities.

It is not unreasonable to assume that the frequency spectrum of the acoustic intensity fluctuations will be related to the frequency spectrum of the sound speed. However, for the reasons described above, we will see that the acoustic records fail to capture the lowest frequency changes in the sound speed field (i.e. largest scale inhomogeneities). To successfully apply scintillation index analysis to a measurement of short duration, we need a way to limit the spectrum of the sound speed field to include only those inhomogeneities that are observed by the acoustic measurement. To eliminate the low frequency (large scale) inhomogeneities in the sound speed field a high pass filter can be used. The cut-off frequency of this filter will depend on the duration of the acoustic record and the velocity of the currents during the acoustic transmission.

3. EXPERIMENTAL SETUP
An experiment was conducted in August 2002 approximately 2500m east of San Clemente Island and 50nm west of San Diego. The water depth was about 550m. During this experiment, acoustic data were recorded over a number of direct, refracted, and reflected paths. Acoustic instrumentation consisted of a vertical string of four transmitters attached to the riser of a bottom-moored surface buoy, and a vertical string of five receivers suspended from the research vessel Acoustic Explorer. The research vessel was placed in a three-point moor. Figure 1 shows a rough layout of the experiment geometry. The transmit and receive strings were separated by 1km. The transmitting electronics were located in the buoy and controlled by a compact PCI computer. Communication between the research vessel and the transmit computer was via 900MHz and 2.4GHz radio frequency links. The receive electronics were on board the research vessel. This paper will focus on the direct path from a transmitter at a depth of 25m to a receiver at a depth of 150m.

In addition to the acoustic measurements, environmental data were collected, using an anemometer, a directional wave rider buoy, an acoustic Doppler current profiler (ADCP), and most significantly a towed CTD chain that provided a two-dimensional characterization of the sound speed field. While the CTD chain provides excellent horizontal resolution, the vertical resolution is limited to the number of elements and the element spacing along the chain. Much better vertical resolution was obtained from several vertical CTD casts made during the experiment.

![Fig. 1: Layout of the acoustic instrumentation and CTD chain. The ADCP was mounted to the R/V Acoustic Explorer, facing down. The tow track of the CTD chain was parallel to, but offset from the acoustic instrumentation.](image)

4. DATA COLLECTION
4.1. Acoustic Data Collection

The acoustic signals used included CW pulses and FM sweeps at 20kHz and 40kHz center frequencies. The CW pulse lengths were 1.0ms and 0.14ms, corresponding to bandwidths of 1kHz and 7kHz. The FM sweeps had bandwidths of 1kHz, 7kHz, 13kHz, and 22kHz and duration of 10ms. The signals were transmitted from one transmitter at time and recorded on all receivers simultaneously. The transmit repetition rate was 10 Hz and each signal was transmitted continuously for about 30 seconds before cycling to the next signal. The receive electronics band pass filtered and sampled continuously on all five receivers at 312.5 kHz during the 30 second transmission periods.

4.2. Environmental Data Collection

A towed CTD chain with fifteen elements was used to characterize the sound speed field. The spacing along this chain placed 11 elements at a depth of 30m or less and the remaining four elements at 40, 70, 100, and 190m when the chain was under tow. Each element contained a conductivity, temperature and pressure sensor. The research vessel Independence was used to tow the chain along a path parallel to, but not directly coincident with, the path of acoustic propagation. The sampling rate for each CTD element was 1Hz and the mean ship speed was 1.6 knots, approximately five to ten times faster than the currents. This gave a spatial sampling period of 0.8m in the horizontal direction. The horizontal resolution of the CTD chain allows for the investigation of inhomogeneities down to about 1m in size. In addition to the towed CTD chain, an acoustic Doppler current profiler was employed to measure the current.

5. DATA PROCESSING

5.1 Acoustic Data Processing

The CW acoustic signals were post-processed with a matched filter [4] according to Equation 3 to increase the signal to noise ratio.

\[ y(T) = \int_0^T s(t)x(t)dt \]  \hspace{1cm} (3)

Here \( s(t) \) is a replica of the transmit signal, normalized to give the filter unity gain, and \( x(t) \) is the received time series in volts. The output \( y(T) \) of this matched filter is proportional to the voltage squared. As voltage is proportional to the received pressure, the matched filter output is proportional to the intensity of the received signal. In this investigation the actual intensity \( I(t) \) of the acoustic signal is not computed, rather \( |y(t)|^2 \) is used. The peak intensity of each ping is then used to construct a time record with a 10 Hz sampling rate. Figure 2 shows some sample records. The scintillation index of these records can then be computed according to Equation 1.
Fig. 2: Three intensity records from the same transmitter-receiver pair but recorded at different times during the experiment. These records are from the 0.14ms 20kHz CW pulse from the transmitter at 25m depth to the receiver at 150m depth. These samples were recorded on 16 Aug 2002, 17 Aug 2002, and 18 Aug 2002.

5.2. Environmental Data Processing

After accounting for the speed of the ship, the slight variations in CTD element depth, and the catenary of the tow chain, the data from the towed CTD chain were interpolated onto a grid with 1m spacing. This grid allows for relatively quick computation of the index of refraction and the inhomogeneity scale size. Figure 3 shows an image of the sound speed inhomogeneities. Here the mean vertical sound speed profile $c(z)$, shown on the left has been subtracted from the measurements to display the scale and magnitude of the sound speed inhomogeneities. Also shown in Figure 3 is an acoustic ray between the 25m source and the 150m receiver.

Applying the theory discussed above for the scale size, range of propagation, acoustic frequency, and mean square fluctuation index of refraction predicts that the scattering should be fully saturated, which means that the scintillation index should be $\sigma_I^2 = 1$. However, as shown in Figure 2 this is clearly not the case. The scintillation index is significantly less than one for all the acoustic records.

As shown in Figure 3, the towed CTD chain nicely captures the structure of the two-dimensional sound speed field. A horizontal high pass filter can be applied to the data in the to limit the scale sizes. If we limit the scale sizes to just those observable by the acoustic transmission and re-calculate the mean square fluctuation of the index of refraction, we find that the scintillation index analysis now places the experiment in the weak scattering regime. Thus, we expect the scintillation index to be less than one. We can justify re-calculating $\mu^2$ based only on the smaller inhomogeneities (patches) by considering the effect of the larger patches on the phase shift of the acoustic transmission.
The change in time of arrival due to the acoustic path encountering a patch of water with a sound speed that differs from the surrounding environment can be found by

$$\Delta t = \frac{\mu^2}{\Delta c} d, \quad (4)$$

where \(d\) is the size of the patch. In this case \(\mu^2 = 10^{-9}\) for the smaller patches and \(10^{-7}\) for the larger patches. On average, for the small patches \(\Delta c = 0.1\) m/s and 1.0 m/s for the large patches. However, the entire acoustic path is in contact with small path boundaries so \(d = 1000\) m. Only a small part of the acoustic path intersects the boundary between two larger patches, \(d = 1\) m. Thus \(\Delta t\) due to the small patches is two orders of magnitude greater than \(\Delta t\) due to the large patches.

![Image](image_url)

**Fig. 3**: 1000m of the towed CTD data is shown from 16 Aug 2002. The greyscale indicates deviation from the mean sound speed profile (shown on the right) in meters per second. Lighter shades indicate faster inhomogeneities and darker shades indicate slower inhomogeneities.

### 6. SPECTRA COMPARISON

The spectra of a sample acoustic record and a sound speed field from the towed CTD chain are shown in Figure 4. Here current measurements (0.1 m/s) were used to establish a time record of the sound speed field. The most interesting thing feature in Figure 4 is the significant amount of large-scale (low frequency) energy that is present in the sound speed field that is not captured by the acoustic records. Most of the energy in the CTD data is below 2 cycles per minute with periods greater than 30 seconds. This energy is due to
inhomogeneities with scale sizes greater than 3m. This energy is not observable in the 30 sec acoustic records.

The sampling interval of the towed CTD chain data, before interpolation, is 0.8m. To convert to the time domain, we multiply the spatial sampling frequency 1.25 samples/m, by the measured current (0.1 m/s) to get 0.125 samples/sec. Thus the maximum observable frequency is 3.75 cycles per minute. For the acoustic data, the sampling frequency is 10 Hz. Using a 256 pt FFT, the bin width is 2.34 cycles per minute. Due to this difference in the sampling strategies only two points in the acoustic spectrum overlap the CTD data. In this frequency range the spectrum of the acoustic data is flat. The CTD spectrum is also relatively flat for frequencies greater than 2 cycles per minute.

![Spectra of Acoustic Intensity and CTD Records](image)

Fig. 4: Sample frequency spectra from the acoustic intensity and towed CTD records. Note that the towed CTD data were converted from horizontal distance to time using measured current. The resulting spectra have greater frequency resolution due to its longer observation time. The spectrum of the acoustic records has a higher cut-off frequency due to the higher sampling frequency.

This difference at lower frequencies suggests that by high pass filtering the sound speed field to remove the larger scale inhomogeneities the scintillation analysis can still be valid. Using the current and the duration of the record as a guide for setting the filter frequency would introduce a method for incorporating finite time records in to the scintillation index analysis. Filtering the CTD with a cut-off frequency of approximately 2 cycles per minute will eliminate much of the low frequency energy and result in significantly lower values for the length scales and variation in the index of refraction. A scintillation index analysis performed on a filtered sound speed field is expected to be comparable to the measured scintillation indices. Several techniques have been employed to limit the scales of variability
used in scintillation index analysis. Here, we have suggested a technique that is driven by the duration of the acoustic transmission and the current.

7. ACKNOWLEDGEMENTS

The authors would like to thank several students in the Graduate Program of Acoustics at Penn State University, Tom Weber, Rachel Romond, and Steven Adelman were all intimately involved in the planning, preparation and execution of the experiment. Also thanks to the captains and crew of the research vessels Acoustic Explorer and Independence.

REFERENCES