Broad band reverberation measurements were collected in deep water (2067m) off Vizag. TNT scare charges (0.450kg) were used as sound sources which were expended from the ship. The signals were recorded using two hydrophones deployed from the ship. The sound speed profile exhibits 63m duct with a limiting ray angle of about 4.47° and lower cut off frequency of 177 Hz. A flat plateau and then sudden fall of 10 dB near ~12-13s on the reverberation characteristic in deep water is related to the effect of sound speed profile and water depth. This strong reverberation return will have major consequences on the reverberation limited sonar performance. This effect is correlated with ray theory based model and the results are presented.

[Key words: Broad band reverberation, lower cut off frequency, sound speed profile, 1/3 Octave bands, ray theory.]
reverberations are precisely those that create useful echoes (reflection and scattering) and the characteristics of resulting signal are very often close to those of the useful signal. This creates many difficulties when trying to get rid of reverberation. As far under water detection signal concerned, the reverberation acts like noise: it adds an undesirable random component to the expected signal. Its main differences from ambient noise are: for a given transmission, the level of reverberation in reception process decreases with time. Spectral characteristics are of reverberation and the signal (target echo) is nearly identical, except, for a Doppler effect if the target is moving with sufficient speed. This makes it difficult to filter out reverberation in spectral domain \(^1,3\).

Accurate prediction of active sonar performance requires the knowledge of sea surface and bottom scattering features that govern the reverberation. Explosive charges have been in use for a long time as sound sources in underwater acoustics research. Several reasons exist for their widespread popularity such as broad bandwidth and high-energy density, ease of deployment, and relatively low cost \(^2\).

The purpose of the present work is to analyze and understand the broad band reverberation characteristics data collected at deep water site off Vizag. Charges are detonated at approximately 9m depth. One third octave band analysis between 100-12500 Hz was carried out on these signals. In deep waters, the paths of the sound from source to bottom and back to the receiver are relatively few and easily visualizable.

**Materials and Methods**

*Description of the experiment*

Experiments were conducted with underwater explosions at deep water site off Vizag. The experimental setup presented in Figure1. Explosives (TNT 0.450kg) were used as the sources which were expended from the ship. Ship was drifting in silent regime. The average depth of the water column is 2067m. Two hydrophones were lowered from the deck of the ship with depth 13m and 29m respectively. Miniature depth sensors were also attached to the hydrophones for
accurate depth measurements. Acoustic signals from the hydrophones are recorded in a Sony
tape recorder with a sampling rate of 48 kHz. Conductivity Temperature Depth (CTD) cast was
taken at the site during the experiment.

Environment and Source level of underwater explosion

The sound speed profile (SSP) is derived from the CTD data and presented in Figure 3(a). The
zoomed profile from surface to 100m range is presented in Figure 3(b) to highlight duct thickness.
SSP exhibits 63m duct with a limiting ray angle of about 4.47° and lower cut off frequency of 177
Hz. Bottom type and bottom roughness at the sites are not known. Sea state during the
experiment was 01.

The source signals levels in 1/3 octave bands were estimated based on simulated pressure-time
(p-t) waveform. The p-t waveform can be modeled based on the Wakeley equation. Inputs are
weight of the explosive and depth of explosion. Based on the Wakeley equation, the received
pressure signature as a continuous function of time can be represented as

\[ P(t) = P_0 \exp\left(-\frac{t}{t_0}\right)U(t) + \sum_{i=1}^{n} \left[ P_i \exp\left(t - t_{B_i}\right)/t_i \right] + P_0 \sin\pi\left(\frac{t - t_{B_{i-1}}}{t_{B_i} - t_{B_{i-1}}}\right)\left(U(t - t_{B_{i-1}}) - U(t - t_{B_i})\right) \]

where \( t_{B_{i-1}} = 0, \quad U(t - t_{B_k}) = \begin{cases} 0 & t < t_{B_k} \\ 1 & t \geq t_{B_k} \end{cases} \), \( P_i = -\frac{\pi}{2} \left( \frac{P_{i-1}t_{i-1} + P_it_i}{t_{B_i} - t_{B_{i-1}}} \right) \),

where \( P_0 \) is the peak pressure and \( t_0 \) is the decay time constant of the shock wave, \( P_i \) is the peak
pressure and \( t_i \) is the time constant of the \( i_{th} \) bubble pulse, \( t_{Bi} \) is the time interval between the peak
of the shock wave and peak of the \( i_{th} \) bubble pulse, and \( n \) represents the number of bubble pulses
to be considered. It is assumed that the rise and decay time constants of the bubble pulses are
equal. \( P_{ii} \) is the minimum pressure between the \((i-1)_{th}\) and \( i_{th} \) peak, where the \( 0_{th} \) peak is the shock
wave. Details of the equation are provided in ref. 5. Source level spectra in 1/3 octave bands for
the explosives (0.450kg TNT) is presented in Figure 3.
Results and Discussion

*Rays trace plots and observed reverberation characteristics*

It is necessary to visualize what kind of reverberation is likely to be encountered at different times after emission of sonar pulse and where it coming from. For this purpose, a rough ray diagram is necessary, for it indicates not only possible sources of reverberation but also grazing angles involved in encounters of sonar beam with surface and bottom. Modeling of the ray path in the medium with the appropriate SSP at the site presents the area of in-sonification due to the source (Figure. 4).

The explosive source is modeled as an omni-directional source. From the ray geometry, the direct path (fathometer return) from the source to the bottom and back to the receiver (not shown in figure) should arrive after 2.6s (2070m). The second fathometer returns (source-bottom-surface-bottom-receiver) should arrive after 5.2s. In Figure 4, rays from -40° deg to +40° deg (from the horizontal axis) are only presented to highlight certain effect of ducted propagation on the reverberation time series. Due to the strong gradient in the sound speed profile some rays from the source is trapped in the duct and the rest will cut through the duct to reach the bottom. Rays penetrating below the duct will travel to a range of not more than 9-10km ($R_L \text{m}$). Reverberations coming from the bottom will start after $2xD/1500$ s, where $D$ is the water column depth and will persist till $2*R_L/1500 \sim 2*(9-10\text{km})/1500$ s. This will correspond to ~12-13s. Rays marked in blue and black color in Figure 4 undergo bottom interaction and contributes to the bottom reverberation. Rays in black color initially traveled to the surface immediately after the explosion, but after the surface reflection they travel downwards along with the blue rays reaching a maximum range of $R_L$(Figure 4). Rays from this omni directional source interact with bottom for all horizontal ranges from 0 to $R_L\text{m}$. No direct rays reach the bottom beyond $R_L$ due to the refraction of sound rays in presence of the SSP gradient, and a shadow zone is present beyond that range at the bottom. The total two way travel distance from the source to $R_L$ is approximately 18.5 km corresponding to a travel time of ~12s. Ranges beyond $R_L$ will not contribute for the first
bounce scattering process, thereby causing a sudden decrease in reverberation level (Figure 6). The flat plateau till 12s followed by steep fall in the reverberation level in deep water is visible at the lower frequency (within 6 kHz). This strong reverberation return will have major consequences on the reverberation limited sonar performance. The second bottom bounce in distinctly visible at 3 and 6.3 kHz.

Rays marked red and green, due to the strong SSP gradient bends towards surface and travels in the duct. Such rays have no effect on bottom reverberation. Rays marked in red does not interact with surface or bottom. Rays marked in green has surface interactions. They interact with the surface and the volume (bubbles, suspended sediments etc) causing surface reverberation and volume reverberation. Back scattering strength from surface will be low due to the small angle of interaction at low sea state. So the expected surface reverberation should be low in comparison with bottom reverberation.

Octave band analysis results corrected to per Hertz are plotted for different center frequencies (Figure 6). Data from three explosives each are considered for the analysis. Uniform smoothing of the signal is used with 2400 samples (50ms) on the band level by moving average method. Variance in the signal is more at the low frequency than at the higher frequency due to band averaging. As evident from the graphs the direct signal from the source reaches the hydrophone after 0.5s, which also includes bubble pulses. The RL falls to a low from 0.5s to 2.6s, contributed by surface and volume scattering as predicted by the ray modeling due (effect of strong SSP gradient). At around 2.6s a strong signal is received corresponding to the first fathometer returns. Then at 5.2s (approx), the second fathometer returns is observed. RL level is approximately 20 dB down than the first return at low frequency, but increased to almost 30dB as frequency reached 8 kHz.

At around 2s before the onset of bottom path, there is an increase in signal level. This rise in level starts at 1000 Hz which reaches maximum at around 3150 Hz with 20 dB rise from back ground and then is disappears after 8 kHz. This rise may be due to the breaking of smaller surface
bubbles, after the bigger bubbles from the explosives reaches the surface. This is consistently observed in the three explosions.

Conclusions

Reverberation analysis for deep water is presented for a broad band source. Sound speed profile exhibits 63m duct with a limiting ray angle of about 4.47° and lower cut off frequency of 177 Hz. A flat plateau and then sudden fall of 10 dB near ~12-13s on the reverberation characteristic in deep water is related to the effect of sound speed profile and water depth. This strong reverberation return will have major consequences on the reverberation limited sonar performance. This effect is correlated with ray theory based model and the results are presented

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References

5. Wakeley,Jr,J(1978), Coherent ray tracing measured and predicted shallow water frequency spectrum., JASA 63(6), 1820-1823.

Figure Captions:

Figure. 1. Experimental geometry for reverberation measurement.

Figure. 2. SSP at the experimental site, Zoomed (100m) SSP of the site.
Figure. 3. Simulated source signal (at1m) spectrum level in 1/3 octave bands for explosives used in the present experiments based on Wakeley equation.

Figure. 4. Ray trace plot of the deep water site, depth of explosion 9m.

Figure. 5. Ray trace plot of the deep water site, (zoomed to the surface 100m).

Figure. 6. Received reverberation spectrum level (/ Hz) at selected one third octave center frequencies plotted against time. Source - TNT. Receiver depth -13m.

Figure. 7. Time-frequency representation of deep water explosion. Source - TNT. Receiver depth -13m.