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Underwater target detection analysis using spherical acoustic sensor arrays.

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Underwater Target Detection Analysis Using Spherical Acoustic Sensor Arrays

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***Abstract*—The need to identify and monitor the target by taking active measurements before it gets close enough to attack has grown due to advancements in marine technology. As underwater vehicular technology continues to progress, there is an increasing interest in using UAVs for target tracking behavior. Numerous methods have been put out to improve tracking performance despite the challenges in harsh underwater environment. SONAR has replaced the radiofrequency signals with the acoustic array signals which is the most modern way of communication. This study demonstrates how to model targets in an active monostatic sonar for multipath propagation paths between source and targets. An isotropic projector array and a single hydrophone unit make up the sonar system for this research work. This paper implemented the form of the projector array which is spherical, and hydrophone receives the backscattered signals. Both direct and multipath contributions are present in the signals that were received on arrival from both targets and are plotted in MATLAB.**

Keywords—*Underwater Targets Detection, SONAR, Spherical Arrays, Acoustic Images, Features Extraction, UAVs.*

I. Introduction

Underwater acoustic target recognition is the most challenging task in noisy, salty and volatile oceans. Signal processing is of various forms such as ships, marine organisms, turbulence, and tides etc. Sensing and imaging of underwater is an extensive field with its applications in seawater. Underwater monitoring is performed with sonar systems which use ultrasound for high-resolution imaging. Sonar systems as shown in fig. 1 are usually hull-mounted or towed by ships that span an area of interest. Sonar is the state-of-the-art underwater sensing technology because of low attenuation in water and long-range capabilities offered by short acoustic wavelengths [1].

Sonar waves are basically caused due to vibration of particles and have great applications in underwater investigation and estimation purposes. SONAR system consists of sensors for converting acoustic pressure underwater into electrical signals. For one-way or two-way sound propagation, the sonar equation [3] is employed in underwater signal processing to match received signal power to transmitted signal power. The received signal-to-noise ratio (SNR) is calculated using (1) which also accounts for target strength, sensor directivity, transmission loss, and noise level from the broadcast signal level.

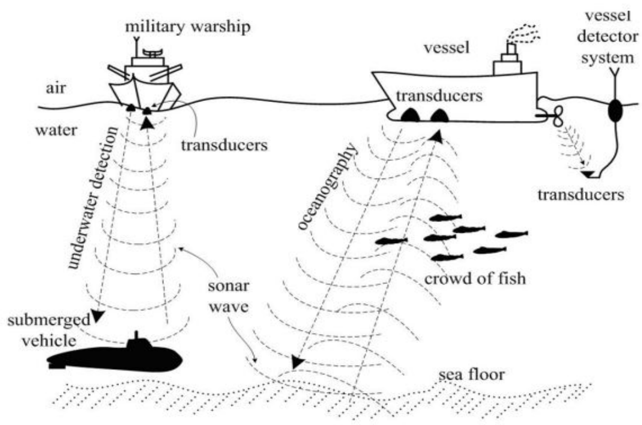

Fig. 1. Sonar System in underwater activities [2]

Underwater sonar communication has two modes for signals transmission and receiving in order where passive remote sensing requires the object of interest to emit the acoustic signals that are measurable by sensor arrays. Sound travels straight from a source to a receiver in a passive sonar system. Equation (1) shows relationship for passive sonar,

$$SNR=SL-TL-(NL-DI) \tag{1}$$

Where SNR is signal to noise ratio which gives acoustic power of received signal to noise measured in dB. SL represents source level which is the ratio of the transmitted intensity from the source to a reference intensity, expressed in db. It is denoted by relation as shown in (2).

$$\mathrm{SL}=10\log\frac{I_s}{I_{ref}} \tag{2}$$

[4] gives the information about acoustic emission, where I_s is the transmitted signal's intensity as measured one meter away from the source and I_{ref} is the intensity of a sound wave with a root mean square (rms) pressure of 1 µPa. The pressure and intensity of sound are related to each other given by (3).

$$I = \frac{p^2{}_{ms}}{\rho c} \tag{3}$$

where ρ is the density of seawater, which is 1000 kg/m^3, c is the speed of sound in water taken as 1520 m/s for this research. For current research, the non-directional source such as isotropic which will radiate the energy in all directions is given by the (4) for a source placed at 1m away from sensors.

$$I=P/4\pi \tag{4}$$

An active acoustic pulse projects through the underwater environment and extract the features of object of interest upon reflection measured by sensor. The reflected signals encode the estimated distance and direction which are also function of active sonar in angle estimation and range detection. For one-way or two-way sound propagation, the sonar equation is employed in underwater signal processing to match received signal power to transmitted signal power. The received signal-to-noise ratio (SNR) is calculated using the (5), which also accounts for target strength, sensor directivity, transmission loss, and noise level from the broadcast signal level. In sonar, the sonar equation performs the same function as the radar equation in radar. Active Sonar creates the situation where sound is sent from a transmitter, reflects off a target, and then returns to the trans-receiver.

$$SNR=SL-2TL-(NL-DI)+TS \tag{5}$$

Where, $2TL$ represents two-way transmission loss (in dB) and TS shows the target strength calculated in dB. The transmission loss is calculated by the outgoing and incoming transmission losses (in dB) and adding them. Identifying and categorizing underwater objects automatically in sonar imagery is an extremely difficult undertaking. Any sonar system's performance is inevitably influenced by the underwater environment and how the targets of interest interact with it. This entails creating techniques that can evaluate an algorithm's performance in advance of deployment (performance prediction), evaluate it while data is being gathered from the environment in real time (performance estimation), and potentially modify the system to meet predetermined performance objectives (performance optimization) [5].

II. UNDERWATER TARGET DETECTION TECHNIQUES

A number of challenges and limitations on transmission of signals have made the development of a robust communication strategy a difficult task to handle in time varying and high frequency channels [6]. Fisher & Simmons model addressed the effects of salinity and temperature on channel capacity [7]. It has analyzed the model by considering the dependence of capacity on temperature, depth absorption coefficient and the ambient noise in the channel. Study in [8] has achieved the multi-path propagation and time variability and showed better results with the development of accurate thorp equations and approximations for the evaluation of capacity, bandwidth, and transmission power. In ocean's water Gaussians and continuous power spectral density play important role in recognition of the ambient noise. Ocean noise is majorly characterized by the sources including turbulence, pressure distribution, shipping, flow separation, waves interference and fluid forces. Low SNR and high variability degree coming from the same source adversely affects the signals and gives poor identification and classification at low SNR. A number of classical approaches such as Integration techniques [9] has shown indicative classification of signals. Still there exists the problem of time frequency analysis for SONAR which possibly creates multipath interference in detection, estimation and tracking of the objects of interest.

Lidar [10] and video based monitoring achieved the estimated location using the acoustic sources and produced valuable results for underwater localization. Acoustic arrays as shown in fig. 2 are of great importance for underwater localization which are comprised of the multiple hydrophones or transceivers for signals reception.

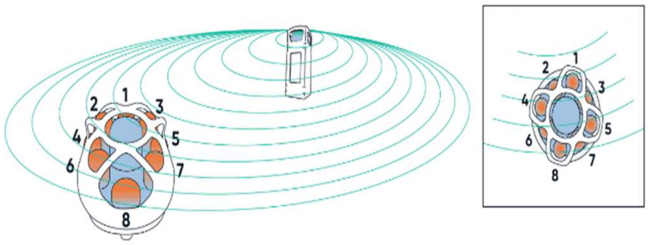

Fig. 2. Underwater Acoustic Communication Channel [11]

Sound waves may travel over water at a fair distance with reasonable reliability due to their comparatively low frequency. The frequency determines the appropriate range of distance. Greater distance is achieved at lower frequencies, but data bandwidth is reduced. Table I gives the description of frequency ranges and measured distances.

TABLE I. DISTANCE AND FREQUENCY RANGES [12]

Frequency Range	Distance Measurement
8 to 15 kHz	10 km
19 to 36 kHz	2 km
32 to 63 kHz	1 km
55 to 110 kHz	500 m

In [13] used the measurement signals' time and frequency domain information to construct an adaptive threshold for such high frequency varying signals. This threshold value was employed to ascertain whether the target signal is a part of the relevant observed interval. The technique of target classification is adapted by [14] before the target identification and detection. The study conducted by Shin utilised size/frequency statistics of the observed signal and integrated the target signal to be used as input for SVM. According to Dawe's research the target identification performance of Sonar Equation is enhanced when the Receiving Operating Characteristics (ROC) curve is utilised. To categorise underwater signals, Chin [15] used a neural network using the Two-Pass Split-Windows (TPSW) algorithm. In order to compute the Detection Threshold (DT), Abarahm used a non-Gaussian function [16]. In [17] explained forecasting the probability of target existence in a search region while considering both detection and non-detection situations. The DEMON algorithm for target detection in passive sonar is described by [18]. The conducted study is useful to provide a thorough analysis of underwater target detection algorithms and their mutual comparison in terms of methodologies, structure, and operation to highlight their effectiveness and robustness. The discussion concludes that deep learning models need to be trained to acquire the information patterns hidden in the input datasets so as to predict the objects in the testing phase. In this way the use of deep learning techniques [19] enhances the computational delay due to its processing struggle with computational efficiency. Therefore this paper simulated the SONAR signals for targets in deep and shallow water and predicted the position of objects with high efficiency and less time cost.

III. Proposed Method for targets detection

This research has considered two targets to imitate an active monostatic sonar environment an isotropic projector array and a single hydrophone unit which make up the sonar system. The hydrophone receives the backscattered signals, observed numerous paths for sound to propagate between the source and the target. The fig. 3 shows the flow of operations in a proposed active sonar system. The system begins with the synchronizer, which ensures that all operations are correctly timed. The transmitter sends out acoustic signals, powered by the power supply. These signals travel through the water, and upon hitting a target, they reflect back toward the sonar system.

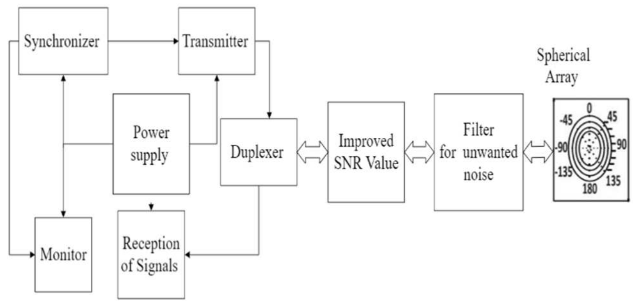

Fig. 3. Underwater Active Sonar Model

The duplexer ensures that the system switches from transmitting to receiving mode seamlessly. The spherical hydrophone array captures the returned signals from various angles. The received signals pass through a filter to remove unwanted noise and then undergo processing to improve the SNR. Finally, the cleaned and enhanced signals are passed to the receiver for further analysis, and the resulting information is displayed for the user.

A. *Methodology*

The proposed methodology presents a well-integrated sonar system designed for efficient detection of underwater targets while maintaining high signal quality and reducing noise interference.. The research initializes with simulation set up on PC equipped with Intel Core i7 CPU at 2.99 GHz and 1TB memory. The underwater environment is modelled in MATLAB R2023a. Bellhop model is selected to process the signals within the frequency range of 300 Hz to 300KHz. In addition to this other environmental parameters are also considered which could be adjusted according to the scenarios. The underwater environment is defined using the parameters given in Table II. which defines the shear sound velocity, seawater depth, arrays depth, source signals modulation method.

TABLE II. PARAMETERS FOR UNDERWATER MODELING

Water depth	400 (m)
Underwater density	1025(kg/m^2)
Arrays Depth	166 (m)
Underwater sound velocity	1520 (m/s)
Signal Modulation Method	Binary Phase Shift Keying

Both range estimation and arrival angle estimation are features of active sonar. Beamforming is primarily used to estimate the arrival angle, whereas matched filtering is used to estimate the range. As a spatial filter, beamforming amplifies the signal of interest while attenuating the signal in other directions. Because beamforming in the time domain requires a lot of calculations and is challenging to process in real time, it is typically used in the frequency domain to minimise computation. Since baseband processing is the norm for active sonar signal processing, complicated band shift, low-pass filtering, and the down-sampling of the array data are required. The flowchart for the study conducted is presented in fig. 4

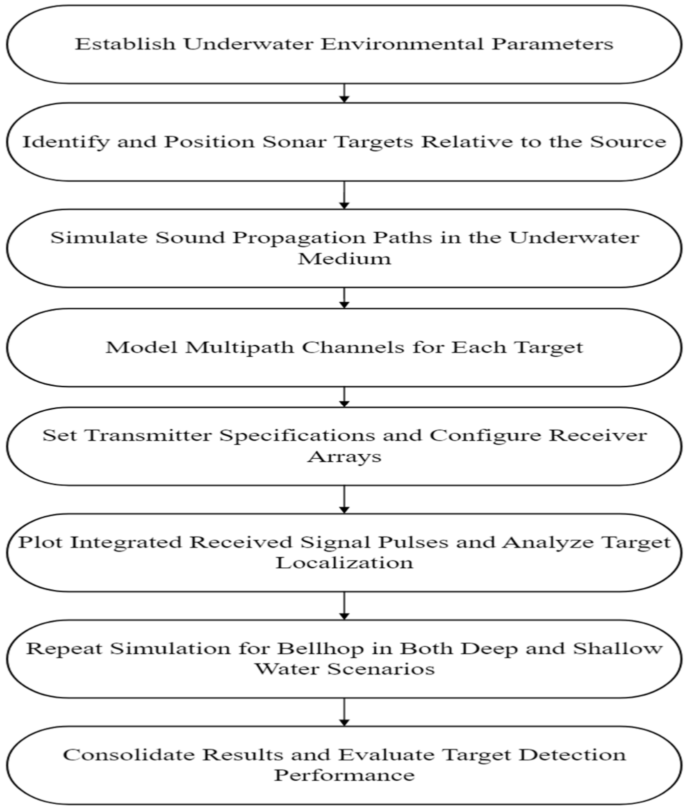

Fig. 4. Flowchart of work

The process begins by establishing underwater environmental parameters, which involves setting the physical properties of the underwater medium, such as temperature, salinity, and water depth, that affect sound propagation. Next, identifying and positioning sonar targets relative to the source helps define the spatial relationships and orientations that influence how sonar waves travel and reflect. Once targets are defined, the system simulates sound propagation paths in the underwater medium, modelling how acoustic signals travel from the sonar source to the targets and back, considering various factors like absorption and refraction. To account for the complexity of real-world environments, the system models multipath channels for each target, considering the multiple routes that sonar signals can take due to reflections off the seabed, surface, and other obstacles.

Afterwards, the system sets the transmitter specifications and configures the receiver arrays, ensuring that the acoustic signals are properly transmitted and received for optimal detection. The next step carried for simulation is to plot integrated received signal pulses and analyse target localization, visualizing the strength and timing of returned echoes to accurately locate and characterize the targets. To enhance the robustness of the analysis, the system repeats the simulation using the Bellhop model for both deep and shallow water scenarios, ensuring that performance is evaluated under different environmental conditions.

Finally, the results are consolidated, and the target detection performance is evaluated, summarizing key findings and analysing the effectiveness of the sonar system in detecting and locating targets under various underwater conditions.

IV. SIMULATION RESULTS

A. Shallow Water Analysis

For the current work, a canal with a depth of 100 meters and a constant sound speed of 1520 m/s is supposed to have seven routes with a 0.7 dB bottom loss to emphasize the impact of the various pathways. The underwater scenario is created by characteristics of the submerged environment, such as the depth of the channel, the quantity of propagation pathways, the speed of propagation, and the bottom loss. Reflections and refractions cause multipath at underwater channels. While refractions happen due to sound channels formed by the sound speed in homogeneities, reflections happen at the underwater channel surface at its bottom. The multipath under noise level is disregarded. Acoustic energy loss is typically represented by multipath signals. The operating frequency for creating multiple paths for each target is 30×10^3 Hz. The waveform is propagated over the several pathways by the multipath channel. This two-step procedure can be compared to filter design, where a signal is filtered using the generated coefficients. The two underwater targets are isotropic and stationary. While the second target is closer but has a lower target strength, the first target is farther away but has a greater target strength. The initial position of the target 1 and target are defined at angles of -80 and -50 degree along the z-axis. The range of the targets is observed along x-y plane as shown in fig. 5.

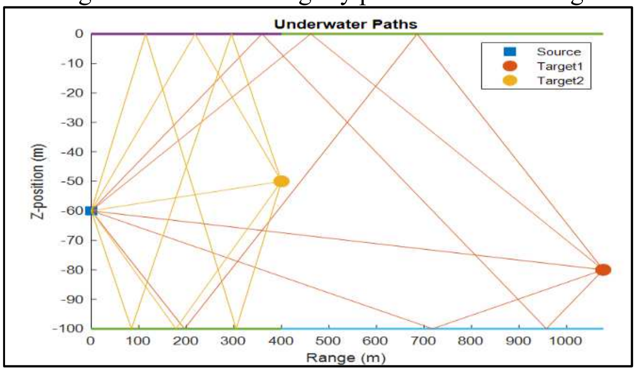

Fig. 5. Underwater Targets and Multiple Paths from Source

The underwater pathways that the signals travel along are determined by the target positions and the channel characteristics. It determines the routes that each target takes to come to the sonar system. A rectangular waveform is generated by transmitter to the targets. The waveform's characteristics are determined by the maximum target range and required range resolution as given by Table III.

TABLE III. RECTANGULAR PULSE CHARACTERISTICS

Parameters	Values
Maximum Range	5000m
Range Resolution	10m
Propagation Speed	33×10^8 m/s
Sampling Rate	fs = 2 × pulse bandwidth

Utilizing the transmitted waveform sample rate, it updates the multipath channel's sample rate. A hemispherical array of back-baffled isotropic projector elements as shown in fig. 6 makes up the transmitter. It is 60 meters below the surface where the transmitter is situated. At 0 degrees of elevation, it observes the array's pattern. The azimuth angle measures the direction of the target in a horizontal direction with respect to the reference object of interest within range of -180 to +180 degrees. This omnidirectional capability ensures that the array can effectively propagate sound energy into the water and receive echoes from various directions, even if the exact location of the target is unknown. The elements are arranged in such a way that they minimize interference and maximize sensitivity across different regions of the hemisphere. This hemispherical array consists of eight projector elements. These elements are strategically positioned to ensure that the array provides uniform coverage across a wide angular range. This arrangement allows the sonar system to transmit and receive sound waves efficiently from various angles, which is crucial for detecting targets in different locations within the hemisphere.

By leveraging the geometry of the hemisphere, the array maximizes its field of view while minimizing gaps in coverage, making it particularly useful in complex underwater environments where targets may approach from any direction.

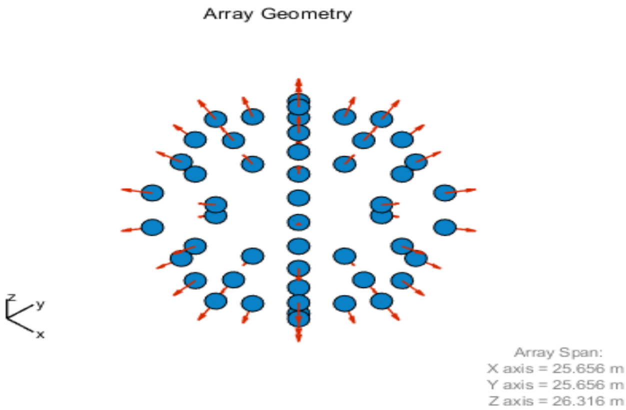

Fig.6. Hemispherical Arrays for Underwater SONAR Signal Transmitter

An amplifier and a hydrophone make up the receiver. The frequency range of the single isotropic element hydrophone, which includes the multipath channel's operational frequency, 0 to 30 kHz gives -140 dB as the hydrophone voltage sensitivity. The received signal represents the signal after being processed by the receiver with the specified gain, noise figure, and sample rate. The gain represents the amplification of the received signal is set to 20dB and the lower noise figure desired for preamplification of the received signal is set to 10dB. An acoustic wave which is transmitted to the target, scattered by the targets, and picked up by a hydrophone in an active sonar system. Because of the geometry of the array, the radiator produces the spatial dependency of the propagating wave. Similarly, the hydrophone element's backscattered signals from the far-field target are combined by the collector. The received pulse is shown in fig. 7.

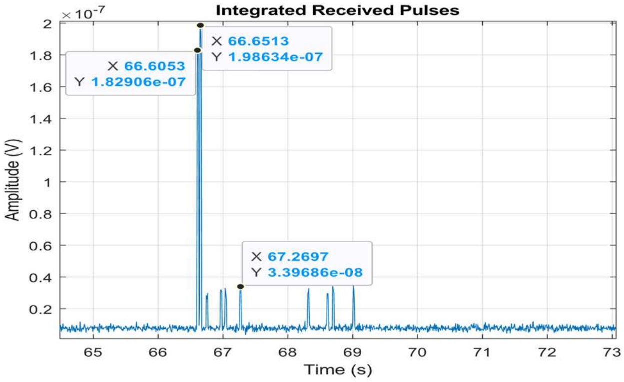

Fig. 7. Integrated Received Pulse in SONAR System

The integrated received pulses obtained by implementing SONAR signals in MATLAB process and evaluate the echoes. SONAR systems measure the length, width, and form of objects in the water by examining the intensity and time delay of the pulses they receive. Each transmission of the rectangular waveform simulates the signal that was received at the hydrophone and be sent out across ten repetition intervals. The computed radiated signals steer the array towards the target and propagate through the channel. The collector simulated in MATLAB collects the magnitude of non-coherent integration of the received signals to locate the returns of the two targets and plot the acoustic image after detection. The targets seem distinct returns since they are separated by a considerable range. Each target has several peaks due to the superposition of pulses from different propagation pathways.

B. *Deep Water Analysis*

An extremely effective beam tracing programmer called Bellhop can be used to forecast the acoustic pressure fields in oceanic environments. In this modelling of Bellhop the depth of the channel is 5000m. The receiver is placed at a depth of 800 meters, whereas the source is located at 1000 meters. The speed of sound is 1550m/s and the density is 1000kg/m^3. Their range defined is 100 Km apart. Eight paths in this scenario have reflections at both the top and bottom surfaces, and two direct paths have no interface reflections. The sound speed in the channel reaches its maximum of 1550 m/s around the top and bottom, with the lowest point being about 1250 meters below the surface as shown in fig. 8.

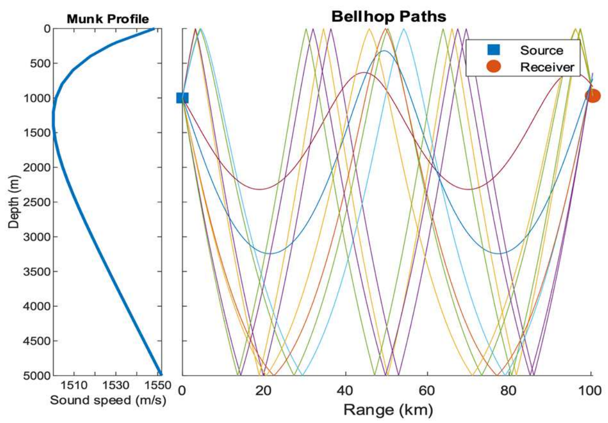

Fig. 8. Munk Profile for Sound Propagation and Bellhop Model

In the response, the transmitted pulses are shown as peaks. It is notable that that the two direct pathways have the largest amplitude and arrive earliest since they lack interface reflections. The second pulse to arrive has the larger amplitude of the two when comparing the direct path received pulses. This indicates a shorter propagation distance. Due to numerous reflections at the channel bottom, each of which adds to the loss, the surviving pulses are smaller in amplitude than the direct pathways.

The analytical solution for the reflection coefficient of the fluid-solid interface is given as

$$R = (Z_{tot} - Z_1)/(Z_{tot} + Z_1) \tag{7}$$

Where Z_{total} is representing the total effective impedance of medium. It is equivalent to equation (8).

$$Z_{tot} = Z_p\, Cos^2(2\theta_s) + Z_s\, Sin^2(2\theta_s) \tag{8}$$

where the effective impedance $Z_i = \rho_i c_i / \sin\theta_i$ gives the ratio of the underwater pressure to the vertical particle velocity for a plane wave propagating in the positive z-direction in the i^{th} medium [20].

C. *Comaprision of Result*

The comparison of the reflection coefficient of the bottom against the grazing angle gives nearly and approximated angle variation results for both Bellhop and analytical solution. The results shown in fig. 9 clearly depicts that there is very small angle reflection differences for both the targets simulated. From our simulations, grazing angle for target I calculated is 89. 49^o and target II is 92.29^o.

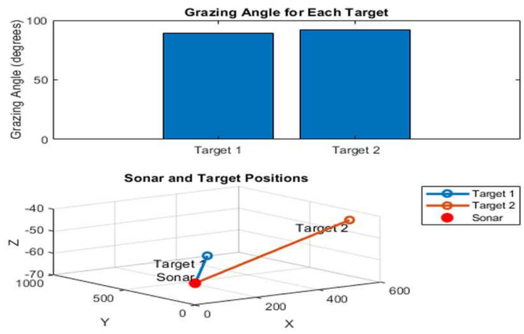

Fig.9. Targets positions and Grazing Angles

However the analytical solution for shallow water and deep water case study gives the same results for both with reflection coefficient 0.627781, and grazing angle 6.565174^o. From the study [21] conducted for sound propagation in underwater shows the comparison of the reflection coefficient of the bottom. It shows that the Bellhop gives the exactly same result with the analytical solution as calculated for equation 8. Their research work has fixed the receiver while in our research SONAR is fixed for transmission of signals only. The study [22] compared three distinct methods for modeling acoustic scattering from a simplified submarine model in only shallow water environment using the eigenray tracing method, the ray-Kirchhoff hybrid method, and the boundary integral equation (BIE) method. Results showed that while the ray-Kirchhoff method accurately predicted the dominant, leading portions of the echoes, it significantly underestimated the amplitudes of weaker, trailing echoes. Similarly, the eigenray method provided reasonable predictions for hull echoes but failed to capture the sail echoes and trailing parts with precision. Both methods demonstrated significant deviations from the more accurate BIE method, particularly at lower frequencies like 1 kHz, where the deviations reached up to 10-20 dB for laterarriving signals. These conventional techniques struggle with limitations in resolution, range, adaptability to changing environments, and automatic target detection and classification. However, our method has been adaptive with respect to noisy environments, weak noise signals, multipath scattering and for a challenging static underwater model .

From fig. 10 it is obvious the dotted line following the analytical solution and both are producing the same result values which show the independency of the depth and the elasticity of the medium.

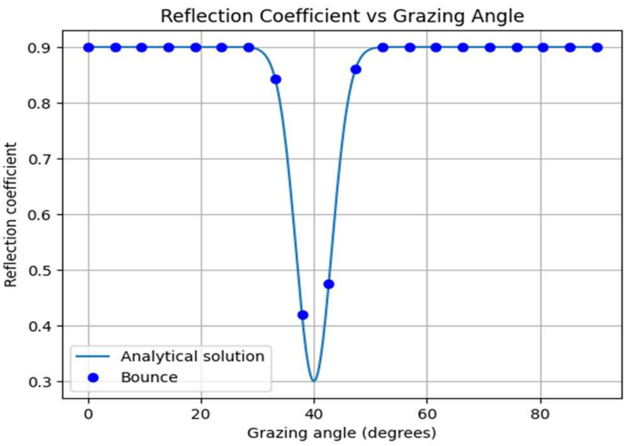

Fig. 10 Comparison of the reflection coefficient of the bottom

The figure above presented that reflection is minimized for a particular angle of incidence showing how the amount of reflection changes dramatically at a specific angle, while remaining relatively constant at other angles.

V. CONCLUSION

This research work has been carried out in MATLAB by simulating acoustic pulses in both deep- and shallow-water environments. An active sonar system found two distinct targets upon reception of signal between a projector and hydrophone in deep water with the 'Munk' sound speed profile. The study has shown that the effect of resolution is independent of the frequency. The first set of peaks occurs around 66.5 seconds. This set of peaks upon reception in simulations results shows super converging methodology of detection of sources giving a very high amplitude, reaching nearly 2×10^{-7} V. There are several smaller peaks between 67 and 69 seconds, at regular intervals with amplitudes significantly lower than the first set of peaks. These peaks have amplitudes ranging between 0.3×10^{-7}V and 0.6×10^{-7} V. The baseline noise level remains relatively low, with values around 0.2×10^{-7} V. This low noise level helps in distinguishing the smaller peaks from the baseline which is underestimated in conventional methods. The subsequent smaller peaks are indicative of weaker pulse events but still noticeable above the baseline noise. The sharp and high peaks around 66.5 seconds indicate strong and transient pulse events. The received signal conclude the presence of numerous pathways. There are direct and multipath components in the signals that were received which are faster mean of detection underwater. Utilizing Bellhop-generated routes, pulses estimated signal arrival times simulated the performance of sonar systems.

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