Noise effects on Surface Ship Passive Sonar and possible ASW solution
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Abstract— The deteriorated global political climate and the battle for supremacy in recent years among world’s advanced countries have yielded significant changes in the way in which military sonars are designed. Sonar operating environment i.e. ocean is absolutely different from that of wireless, free space, and conventional wired mediums. It has a complex background in which sonar system has to achieve Anti-Submarine Warfare (ASW). Since the passive sonar performance is largely affected by the ocean behavior and also submarine detection with a ship borne passive system chiefly requires competent sonar operator to get target signature which is a very difficult task due to dominant background noise and becomes more challenging if surface ship itself is generating much noise. This article describes in detail, the background noise factors affecting and limiting passive sonar performance and subsequently possible ASW solution.

Key Terms: ASW, Noise, Passive Sonar Equation, Figure of Merit, Performance Parameters, Airborne Active Dipping Sonar (AADS)

I. INTRODUCTION

The principle role of SONAR (an acronym for Sound Navigation And Ranging) is to detect, locate, track and classify a submarine contact, whether friend or foe through sound signals received from different directions by a transducer array. The most complex sound wave is one in which it consists of numerous frequencies across a wide band. Such form of unwanted sound is called noise because it has no tonal quality. Noise is ever present entity in electronics, communications and medical equipments. It degrades the performance and resultantly the output from the equipment for which it has been made. During submarine signal travelling, noise through various sources takes account in the corruption of desired signal. An appropriate filtering technique is required to extract the information signal from a noisy environment [1]. Noise is the background against which sonar, active or passive must detect signals from the targets. Thereby, detection, classification or recognition in presence of background noise is a process of gathering information of underwater target in the ocean environment and then estimating its performance [2]. Efficient target signature detection in passive sonar and power transmission in active sonar require highly directive radiation patterns and maximum signal to noise interference ratio. This can be achieved by accurate beam forming [3]. Confirmation of presence of an object serves various purposes for ASW mission commander. However, absence of any detection of subsurface target limits the advance utilization of sonar system in modern ASW applications and forced the ASW mission commander to ensure various stages prior to placement of attack.

The most important military use of underwater sound has been the detection of underwater targets at as greater distance as technology and costs let the sonar equipment [4]. The propagation of sound waves underwater categorically depends upon the physical characteristics of the underwater environment, such as temperature, pressure, salinity and water density. These physical characteristics also change with depth, time of operation, season and geographical area [5]. Due to the incompetence of target detection and classification by passive sonar systems, employment of experienced sonar operator [6] is the only approach which is being practiced to discriminate the noise background from actual target signature through listening of received signal. However, classification of target by the operator is a highly experience dependent job due to presence of background noise. Additionally, despite utilizing experienced staff, same is still subjected to human error. Therefore, a suitable option for an ASW mission commander capable to identify a target and provision for valid classification through acoustic signal analysis may enhance the underwater detection capability. The problem of detecting underwater target in presence of background noise and estimating parameters such as range have fascinated great interest in the last few decades. Acoustic signal analysis of sonar for identification of underwater object is actually analogous to sound recognition system above surface [7]. Noticeable examples are speaker recognition system, speech recognition system, vehicle recognition system, machine error/ fault diagnosis/ inspection systems, finding the species of animals from their sounds inspection of noise, analyzing the earthquake waves, finding the mines under water, systems distinguishing music or instruments and lastly environmental sound classification systems [8]. However, the elementary difference in achieving the classification from sonar acquired signal and above surface sound signal is the presence of noise in the same acoustic frequency band. In ASW, due to limited underwater target information and other known evidence, desired goal can be achieved with utilization of airborne active dipping sonar (AADS).

II. HISTIRICAL BACKGROUND OF SONAR

Modern era sonars are said to be date back more than 25 years to the start of World War-II (WW-II). They have their origin deep in the past. Although, some animals like dolphins and bats have
been using sound for communication and object detection for millions of years, use of the same by human being in the water was initially recorded by Leonardo Da Vinci [9] in 1490, when a tube inserted into the water was said to be used to detect vessels by placing an ear to the tube.

The idea of listening to underwater sound by means of an air filled tube between the sea and the listener’s ear led to wide spread use in World War-I (WW-I), by the addition of a second tube between the other ear and the point in the sea separated from the first point, the direction could also be obtained. Perhaps the first quantitative measurement in underwater sound occurred in 1827, when Daniel Colladen, a Swiss physicist used an underwater bell to calculate the speed of sound underwater to an unexpected degree of accuracy in Lake Geneva, Switzerland. This premature research led to the invention of dedicated sonar devices by the other researchers in this field.

Lewis Nixon invented the very first sonar type listening device in 1906, as a mean of detecting icebergs. This increased the interest in sonar during WW-I, when there was a need to be capable of detecting submarines.

The use of sound for echo location underwater in the same way as bats use sound for aerial navigation seems to have been prompted by the disaster of Titanic in 1912. The world’s first patent for an underwater echo ranging device was filed at the British Patent Office a month after the sinking of the Titanic by an English meteorologist Lewis Richardson [10]. A Canadian engineer Reginald Fessenden, while working for a Submarine Signal Company in Boston, made an experimental system beginning in 1912, a system later tested at Boston Harbor and finally in 1914 from the U.S Coast Guard on the Grand Banks off Newfoundland Canada [11]. In the test, depth sounding, underwater communications (Morse code) and echo ranging (detecting an iceberg at two miles range) was demonstrated. The so-called Fessenden oscillator, at a frequency of 500 Hz, was unable to determine the bearing of the iceberg due to the 3 meter wavelength and the small dimension of the transducer’s radiating face.

During WW-I, the necessity for detection of submarines encouraged more research in the use of sound propagation underwater. The U.K made early use of underwater hydrophones, whilst the French physicist Paul Langevin, working with a Russian Electrical Engineer, Constantin Chilowski, worked on the development of active sound devices for detecting submarines. In 1915, Paul Langevin devised the first sonar type device to detect submarines which was named "Echo Location to Detect Submarines". This device employed the piezoelectric properties of the quartz. Unfortunately, he was too late to help much in the WW-I. Although piezoelectric and magnetostrictive transducers later superseded the electrostatic transducers they used, however, this work greatly influenced the future sonar designs and developments. Lightweight sound-sensitive plastic films and fiber optics have been used for hydrophones.

In 1916, under the British Board of Invention and Research, (BBIR), a Canadian physicist Robert William undertook an active sound detection project with A. B. Wood and fabricated a prototype for testing in 1917. This effort, for the Anti-Submarine Division (ASD) of the British Naval Staff, was assumed in utmost confidentiality and used quartz piezoelectric crystals to yield the world’s ever first practical underwater active sound detection gear.

By 1918, both French and UK had built prototype active systems. The first ASDIC shipboard set with a covered dome that allowed the sonar set while the ship was moving, were installed in 1919 with operating frequencies between 20 to 50 KHz. During 1920 and 1930, ASDICs were developed for use on destroyer against submarine detection [12]. At the start of WW-II, British ASDIC technology was shifted to the United States. Research on ASDIC and underwater sound was stretched in UK and US. Many new types of military sound detection technologies were developed. These included sonobuoys, first developed by the Royal Navy in 1944. Said efforts shaped the basis for post war developments related to encountering the nuclear submarines. Work on sonar had also been carried out in the Axis countries, particularly in Germany, which encompassed submarine countermeasures.

After WW-II, the advancement in electronic equipment technology, signal processing techniques, computer equipments, understanding ambient noise and underwater (UW) sound propagation powered up the further progressions of UW acoustics. Thereby, advancement in both platform and sensor has been achieved. Presently, active and passive sonar and sonobuoys are deployed through different platforms.

III. PASSIVE SONAR

Passive sonar listens to the radiated noise from the surface ship or submarine without transmitting any energy. These are generally for military purpose although a few are scientific. Passive sonar sets commonly have large sonic databases. A computer system repeatedly uses said databases to identify classes of ships and submarines i.e. the speed of a ship or the type of weapon released and even particular submarine. This sonic database is regularly updated for future employments. Basic principle of passive sonar is shown in figure 1. Sound signals received by the hydrophone array are amplified and further processed at different electronic equipment and then fed to operator's headphone or display unit.

![Fig.1 Passive Sonar](image-url)
IV. SUBMARINE RADIATED NOISE

Surface ships, submarines, and torpedoes are the prominent sources of underwater noise. The fact of being machines of great complexity and sophisticated nature, these require numerous rotational machinery components for their propulsion. This propulsion machinery causes vibrations resulting in underwater sound through the hull and the sea. Here propeller is of vital importance that keeps the vessel in motion, resultantly, generates a lot of its own sound. Noise emitted by submarine and received by hydrophone is the source of signals for passive sonar [13].

A. Practical Values of Submarine Radiated Noise

From the ASW viewpoint, knowledge of the sound output of submarines is needed for the prediction of maximum listening ranges and classification for passive sonar [14]. From the submarine angle, it is imperative to know the related sound output of different maneuvers so as evasive action will not be terminated by excessive detectable sound. The problem of design control and the design of propellers, engines and other auxiliary components, all mandate the measurement of sound output.

Available information on the radiated noise of surface ships, categorically submarines and torpedoes is extremely confidential and the sonar designer must resort to the classified literature for details of source levels and frequencies of tonal radiated from modern submarines. Same is provided worldwide by U.S office of the Naval Intelligence.

Figure 2 shows radiated noise spectra for different sonar targets. Frigate radiated noise is also shown for comparison with others. The spectra are to be considered a worst case especially in the regions dominated by the discrete lines. Torpedo submarine quieting measures have succeeded significantly in reducing many discrete lines, categorically at higher frequencies. Thereby creating need for sonar to operate at even more lower frequencies, therefore, they need ever longer towed arrays.

B. Sources of Radiated Noise

The major sources of radiated noise on submarine may be classified into three groups.

1) Machinery Noise

This noise is produced as mechanical vibrations by the moving submarine. It originates from inside the vessel and reaches the sea water by transmission and conduction through the hull. These vibrations are combined to the ocean via hull of the vessel. The main propulsion plant, reduction gears, propeller shafts, auxiliary machinery and various other underwater discharges from the submarine produce machinery noise. This noise covers low frequency band.

2) Propeller Noise

Propeller noise is created by a purely hydrodynamic mechanism such as cavitation at the tips of the blades or cavitation on the blades themselves or by mechanical vibrations of the propeller blades. The primary source of propeller noise is cavitation induced by the fast rotating propeller of the submarine.

As cavitation noise consists of a large number of random small bursts caused by the bubble collapse, it has a continuous spectrum. It covers frequencies from 100 Hz to 1 KHz [15]. In ASW, this propeller noise is of paramount importance as these sound waves travel thousands of miles and even then these are detected by passive sonar provided alertness of the sonar operator and the equipment conditions.

It is evident that as the speed of the submarine increases and propeller cavitation arises, with increase in the speed, radiated noise vividly increases.

At high speed when cavitation occurs, the resulting radiated noise of submarine is perceived to as first increase as the submarine dives underwater. Many other factors other than depth and speed affect the propeller noise. A damaged propeller radiates more noise than undamaged one. Also more noise is generated while taking turns and acceleration in speed than normal straight cruising.

3) Hydrodynamic Noise

Hydrodynamic noise originates in the asymmetrical and fluctuating flow of fluid past the moving vessel. The noise emitted by the turbulent boundary layer is sometimes called flow noise. Under normal environments, hydrodynamic noise adds only a slight quantity in the total vessel radiated noise. This noise is masked by the machinery and propeller noise.

V. PASSIVE DETECTION

The offensive purpose of all applications of the underwater acoustics in ASW is the detection, location and tracking of enemy craft. In passive detection, the signal is the sound/ noise emitted by the target involuntarily, since it is the primary source. As this transmission is a one way process, this suggests that the
transmission losses will be smaller and detection should be possible at greater ranges by listening, provided only that the sound radiated from the target is comparable to that of the standard echo ranging transducer. In order that passive listening to be a tactful aid, the sonar operator must be able:

- To distinguish between the various sounds radiated by the submarine from the background noise. It is achieved by having complete familiarity with both.
- To distinguish between the various types of ship radiated noise with a view to possible identification of the type of vessel radiating them and also to attain information on its operating conditions.
- Upon detection and perhaps partially identification of a target, obtain information about its approximate location and speed while it is still at longer distance.

A. Basic Factors in Listening

The ability of human ear or electronic equipment to recognize the sound signal from background noise depends upon following basic factors [14]:

- The nature of the sound signal radiated by the source
- Transmission and propagation losses of sound in the water
- The nature of noise masking the wanted sound signals
- The response and directivity characteristics of the listening equipment
- The recognition differential (RD)

VI. NOISE

The most complex sound wave is that in which it is consist of numerous frequencies across a wide band. Such form of sound is known as noise as it has no tonal quality. For active sonar set, noise is enlarged by reverberations from unwanted objects and the signal is an echo from the target submarine. Whereas, for passive sonar, the signal is also noise, the radiated noise of the underwater submarine. There are three major sources of noise to be considered primitive for target detection with the passive sonar.

A. Thermal Noise

Similar to the electrical receiving system, a sonar transducer adds its own noise to the sound signals received [13]. The sonar engineers must ensure that the noise acquaint from this source is negligible as compared to the noise coming from the ocean itself. All the results established for the classical case of radios are valid for sonar if antenna is replaced by the hydrophone array.

Any resistance, R, is the source of a thermal noise EMF (Electromotive Force), resulting from the thermal agitation of its electrons. The value of this EMF is given as:

$$e_n = \sqrt{4RT} \delta f$$  \hspace{1cm} (1)

Where, \( K = \) Boltzmann’s constant = 1.38 x 10\(^{-23}\) Joule/ Kelvin. \( T = \) absolute temperature (K) of the resistance, R

$$\delta f = \text{Bandwidth (Hz)}$$

A passive circuit yields a noise proportional to the resistive component of its equivalent impedance. For a sonar transducer, energy exchange takes place with the sea water through the motional resistance, \( R_m \) of the transducer, generating a noise EMF given by the above equation 6.1, where, R is replaced with \( R_m \). Here, the EMF noise does not come from thermal agitation of the electrons but from the thermal agitation of the molecules of water producing pressure fluctuations at the face of the hydrophone array.

The thermal noise from the ocean can only be the dominant background to a sonar system at higher frequencies from at least 30 kHz where it equals the ambient noise. This thermal noise is an absolute minimum and may only be perceived in the absence of any other noise source, i.e.

- If the sea water has no other agitation except thermal agitation and if it is completely isolated from any source of sound (Dead Sea).
- If the sonar receiver was perfect and has added no noise. Therefore, the noise factor of the receiver is \( NF = 0 \text{ dB} \)

The thermal noise is given as

$$N_{\text{thermal}} = -15 + 20 \log(f)$$  \hspace{1cm} (2)

Where \( N_{\text{thermal}} \) is in dB and \( f \) is in KHz

B. Ambient Noise

It is the background noise in the sea due to natural causes. Numerous different phenomena contribute to this noise. According to the Oxford English Dictionary, ambient means surrounding on all sides. In practical, ambient noise surrounds hydrophones from all sides unequally and in non-isotropic pattern. This shows its non-directionality nature. When the sea is not dead that means it is perfectly isolated from all sources of sound or noise and only subject to thermal agitation, even though it may appear as perfectly calm, it is subjected to an agitation much greater than the thermal noise, particularly at frequencies below 30 KHz. Following are some prominent sources of ambient noise.

1) Sea Surface Noise

Sea surface noise also contributes a lot in making background noise dominant against desired sound signal. Sources of sea surface noise are given below:

a) Wind/ Sea state/ Waves

The ocean surface is seldom smooth and flat at all. Whenever the wind blows over the surface, waves are produced. Some of these produced waves are broken and the resulting noise produced increases as the wind speed goes higher. Considerable amount of noise is produced over a wide range of frequencies from 100 Hz to 15 KHz.
These winds cause higher sea states. Sea state may be taken as to be one of the most critical variables in underwater target detection. It is a factor which almost cannot be measured accurately. Each value of the sea state illustrates a range of conditions with the boundaries between these conditions generally defined in term of wave height. The effect of sea state is dominant in shallow water than in deep ocean water. Sea state, wind speed and wave height are illustrated in table 1.

Table 1. Sea state, wind speed and wave height

<table>
<thead>
<tr>
<th>Sea State</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Speed (K)</td>
<td>2.3</td>
<td>5</td>
<td>13</td>
<td>16</td>
<td>19</td>
<td>22</td>
<td>28</td>
</tr>
<tr>
<td>Wave Height (m)</td>
<td>0</td>
<td>0.5</td>
<td>1.3</td>
<td>1.3</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

It is difficult to narrate the actual noise level to the prevailing wind speed or sea state as the wind speed can be measured but the sea state is often based on a subjective judgment of height of the waves produced. Although wind speed and sea state are clearly related, their maximum or minimum values rarely coincide in time.

b) Rain & Hail

The existence of rain and hail over the sea surface may produce a substantial increase in the ambient noise at frequencies ranging from 100 Hz to 15 KHz thereby affecting desired sound signal adversely. This increase in noise level will vary with the intensity of the precipitation and the extent of the area upon which rain is falling.

Rain can noticeably increase the ambient noise. Figure 3 shows that the spectrum of noise due to rain is quite flat with frequency. It plots the theoretical values which are agreed with the measurements. Heavy rain can dominate at all frequencies, but rainfall less than about 3 mm per hour is not of much significance.

c) Ice

The ambient noise level can be affected strongly due to the presence of ice on the sea surface. The ocean regions, where the ice covers are broken and collisions between these ice pieces cause 5db increase in the noise comparing to the same wind conditions in the open sea where ice breakage does not exist.

2) Biological Noise

Biological noise adds considerable amount to ambient noise in many areas of the ocean. Because of the distribution, habits and sonic characteristics of the various sound sources, certain areas of the ocean are much sniffed than others regions. The effect of biological activity is more observed in shallow water areas than the open sea. It is found more in the tropics and in temperature zones than in cold water.

The sound produced by the marine life may be varied ranging from the calls of porpoises to the frying sound of a bed of snapping shrimps. The frequency range of 50 Hz to 30 KHz is affected because of this biological noise. Although marine animals produce noise of some sort, certain sorts are so dominant in the respect that the study of only these few is a key to prediction of the intensity, space and time distribution and spectrum of significant noise generated by marine life.

3) Sea Traffic Noise

Near the busy harbors, the sea noise is overlaid with the movements of sea traffic. Surface, merchant ships, small high speed crafts and the noise of industrial operations contribute a lot in this type of ambient noise. Consequently, passive listening in harbor becomes extremely difficult. In areas of dredging, riveting on the hull of ships, oil drilling and exploration, large amount of traffic noise may be passed into the sea affecting the wide range of frequencies falling into the passive sonar operating band. Traffic noise is highly inconstant depending upon the strength and type of sources.

C. Self-Noise

If passive detection is being carried on board a moving surface ship, the noise of the ship itself is probably the chief source of noise. It is different from vessel radiated noise in a way that the detecting sonar system is located onboard the noise generating vessel and travels with it instead of being fixed in the sea at some distance away. In self-noise, different paths are followed by the noise to reach the hydrophone and are also varied and play a vital role in affecting the magnitude and the type of noise received by sonar set. Major sources of onboard self-noise are:

1) Machinery Noise
This originates from the diverse parts as mechanical vibrations and is coupled to the sea through the hull of the moving ship. This machine vibration may occur in the manners:

- Unbalanced rotating parts like shafts and motor armatures.
- Repetitive discontinuities such as armature slots, gear teeth and turbine blades etc.
- Explosion in cylinder of reciprocating engines
- Mechanical frictions in bearings and journals etc.
- Cavitation and turbulence in the flow of fluid in pumps, pipes and valves.

For a surface ship, this noise is of extreme significance at low speed as it interferes and superimposes as the background ambient noise making Under Water contact detection more difficult for passive sonar. Being focused in the low frequency band, it undergoes less attenuation than noise of high frequencies when travelling through the ocean medium. Some dominant sources of machinery noise are listed in table 2.

Table 2. Machinery Noise

<table>
<thead>
<tr>
<th>Propulsion Machinery</th>
<th>Auxiliary Machinery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel engines</td>
<td>Generators</td>
</tr>
<tr>
<td>Main motors</td>
<td>Pumps</td>
</tr>
<tr>
<td>Reduction gears</td>
<td>Air conditioning equipment</td>
</tr>
</tbody>
</table>

Besides these machinery noise sources so far, there are also many other sources onboard ship over which ASW mission commander will probably has no control such as fire and flushing pumps, air compressors, refrigeration system machinery, gasoline pumps, blower motors and other portable power tools etc. If any or all of here mentioned equipments is under operation at any time, may add greatly to the self-noise and therefore may enter the sonar receiver system.

2) Hydrodynamic Noise

In a surface ship, hydrodynamic noise is due to the movement of the ship through the sea water and is dominant at speeds from 12 knots to 20 knots. It has two main components, flow noise and cavitation of the sonar dome.

- Flow noise is produced by the turbulent flow around the underwater hull causing pressure fluctuations at the face of the sonar transducer.
- When speed of the speed is made high enough, the sonar dome will cavitate hence noise will be generated. Moreover, if the ship’s bottom is not cleaned properly, any attachments will cavitate when the ship’s speed is boosting.

3) Propeller Noise

Propeller noise originates from outside the ship’s hull due to propeller rotation in the sea water. It has different source and frequency spectrum from that of the machinery noise. It is produced by a purely hydrodynamic mechanism i.e. cavitation at the tips of the blades or cavitation on the blades themselves or by mechanical vibrations of the propeller blades. The basic source of this noise is cavitation produced by the fast rotation of the ship’s propeller. Due to fast rotation of propeller in sea water, regions of negative pressure are created at the tips and on the surface of the propeller blades. When this negative pressure becomes high enough, cavities in the form of minute bubbles are appeared. These bubbles produced, collapse in a short time, creating a sharp pulse of underwater sound.

This cavitation is interrelated with the speed of the ship, it is logically stated that firstly, cavitation appears at the tips of the propeller blades, as much as the speed of the blade tips is considerably more than the speed of the propeller hub. This occurrence is known as blade tip cavitation. As the propeller speed increases, a greater part of the propeller’s surface is rotating fast enough to cause cavitation and the cavitating area begins to move down the trailing edge of the propeller blade. As the speed increases more, the entire back face of the blades initiate cavitation, subsequently, produce sheet cavitation. This noise consists of a large number of random small bursts covering frequency range from about 100 Hz to 1 KHz [15]. In passive detection, this propeller noise is of paramount importance as this noise may mask the desired submarine signature thereby affecting adversely the detection performance of the sonar set.

It is understood that as the speed of the ship and propeller cavitation increases, the propeller radiated noise also increases. An impaired propeller emits more noise than safe one. Similarly more noise is generated while taking turns and acceleration in speed than normal conventional sailing. This noise is not radiated equivalently in all directions. Instead, it has directional pattern characteristics in horizontal plane around the vessel. A lesser amount of noise is radiated in the fore and aft directions than abeam due to screening by the hull in the forward direction and by the wake in the rear.

VII. PASSIVE SONAR EQUATION

Tactical performance of a sonar system is a function of sonar set performance and the sound propagation characteristics of the ocean medium [5]. The main logic behind said statement are:

- Sonar set is designed to detect the arrival of certain minimum sound signal level at the face of hydrophone
- The range over which this sound signal travels to produce said minimum detectable signal depends upon how much energy is lost during its travel from source to the sonar transducer

The sonar equation is established on the equality between the desired (signal) and undesired (noise) portion of the received sound wave. The design engineer is aimed to find means for increasing overall system’s response to the signal and reducing response to the background noise. It may also be stated as to increase the signal to background noise ratio (S/N).

Practical sonar system has certain signal to noise ratio. The task of sonar operator is to detect the radiated noise by the underwater submarine. Assume that the target initially is at greater range where the noise level is greater than the signal level approaching towards the sonar face. The operator will hear only the background noise. As the target gets closer to own ship, the target signal level will increase gradually. Now, when the target submarine has reached at a place, where the average target signal
level is equal to the undesired background noise, the operator may have an opportunity to detect the target signature.

\[
\text{Signal Level} = \text{Background Noise Level}
\]

When expressed in ratio:
\[
\frac{\text{Signal}}{\text{Noise}} = \frac{\text{Signal level}}{\text{background noise level}} = 1
\]

Taking the log of both sides of the equations

\[
\log(\text{SL}) - \log(\text{BN}) = 0 \quad (3)
\]

The passive sonar equation is written as:

\[
\text{PL} = \text{TN} - (\text{BN} - \text{DI}) - \text{RD} \quad (4)
\]

Where PL is the propagation loss in dB

TN is the target radiated noise in dB

BN is the total background noise in dB

DI is the directivity index of sonar array

RD is the recognition differential of sonar system

Whereas, target radiated noise at receiver (SL) will be:

\[
\text{SL} = \text{TN} - \text{PL} \quad (5)
\]

Propagation Loss (PL) during travelling is:

\[
\text{TN} - \text{PL} = 0 \quad (6)
\]

The background noise level seen at the receiver hydrophone against which the sonar system has to detect the submarine signature is:

\[
\text{Noise} = \text{BN} - \text{DI} \quad (7)
\]

As it is evident that sonar performance is largely dependent on signal to noise ratio [15], hence, sonar engineers are always looking towards means of increasing this ratio. It is apparent from the signal part of the equation 4 that both the PL and TN components are not under the control of the design engineer or the ASW mission commander. Since it is clear that any gain to be achieved is made in the system response to the background noise is by eliminating the total components of background noise.

A. Background Noise (BN)

Total background noise is labeled as BN. For discussion above, ambient noise component may be labeled as LNA. If the gain achieved by rejecting part of the LNA i.e. DI is subtracted from ambient noise component LNA, then this part of the total noise may be expressed as:

\[
\text{LNA} - \text{DI}
\]

Consider here the self-noise caused by the flow of water and specific machinery noise of the surface ship or submarine over hydrophone array. It is apparent that this noise component is both directional and incoherent (non-sinusoidal) [6]. For low and moderate speed sonar operations, the ambient noise is so dominant that for analytical operational this ambient noise is generally used for background noise. The noise component in the sonar equation is written as BN – DI. The resulting sonar equation becomes:

\[
(TN - \text{PL}) - (BN - DI) = 0 \quad (8)
\]

Signal – Noise = 0

The passive signal to noise ratio at the receiver is therefore given by:

\[
\text{SNR} = \text{Signal} - \text{Noise}
\]

\[
\text{SNR} = (TN - PL) - (BN - DI) \quad (9)
\]

B. Recognition Differential (RD)

The desired sound signal radiated from the target submarine must reach a certain level compared to the background noise if sonar operator has to detect the presence of the target underwater. The difference in level significantly depends upon the experience of the operator, his state of alertness during ASW mission as well as design and the state of the maintenance of the sonar set. Hence, RD is the ratio of signal radiated by the target to the unwanted background noise to have a 50% chance of making signature detection [14]. It is denoted by RD. At this stage, passive sonar equation can be expressed as:

\[
(TN - PL) - (BN - DI) = \text{RD} \quad (10)
\]

\[
\text{Signal} - \text{Noise} = \text{Recognition Differential}
\]

Observing the relation above in the context of probabilities that differ from 50 % level, it can be assumed that for getting higher probability level, a higher signal to noise ratio would be required.

It can be achieved by placing competent operator in the system and improving RD. It can also be accomplished with reducing the distance between the target and the own surface ship in which the signal has to travel thereby reducing propagation and transmission losses. Another way to increase S/N ratio is to decrease vessel’s speed, if own ship noise component is greater than the ambient noise.

This discussion indicates that change in S/N ratio is a function of change in recognition probability. For achieving 90% detection probability, 4 or 5 dB greater S/N Ratio is required than with a 50 % detection probability. If system is performing 4 or 5 dB less than the design parameters, the detection probability [6] left is only about 10% with which ASW mission cannot be achieved at all.

C. Detection Threshold (DT)

It is the required threshold level at the input to the sonar system processing network, which is necessary to provide the sonar operator with a 50% probability of detection.
The complete passive sonar equation (equation 10) shows the expression for relationship between sonar design parameters, sound propagation parameters and background noise in the operating ocean. In terms of DT, the passive sonar equation becomes:

\[ DT = (TN - PL) - (BN - DI) \]  

(11)

D. Figure of Merit (FOM)

Now here, if DT is substituted for SNR in the passive equation, and propagation loss becomes associated with PL of 50% detection probability, a special propagation loss known as Figure of Merit (FOM) is emerged. Substituting FOM in the passive sonar equation, we get:

\[ DT = (TN - FOM) - (BN - DI) \]

\[ FOM = TN - (BN - DI) - DT \]  

(12)

VIII. PERFORMANCE PARAMETERS

As discussed in earlier, ocean environment is highly variable, which significantly contributes to the difficulty in target detection with passive sonar. The understanding and exploitation of the velocity profile and maximum detection range against dominant background noise will probably determine the winner of the ASW. It is generally acknowledged that the advantage belongs to that who gains the initial detection.

As a sensor in the ASW operation, the major task of the sonar system is to provide target position information with sufficient accuracy for effective placement of ASW weapon. The problem presented by passive sonar in target localization for weapon placement is different from that of active sonar, because passive sonar measures target bearing and does not the range. Calculation of target range, course and speed for predicting the future position of the target is highly a matter of tactical doctrine including various ship maneuvers [6].

The detection range is subjected to the ocean and the tactical ASW mission success depends not only on sonar equipment design and target but also relies on the ocean behavior where the dunking mission is being conducted. Therefore sonar performance parameters may be written as:

Sonar Performance = Sonar Equipment Parameters + Ocean Medium Parameters + Target Parameters

A. Parameters under Control of ASW Mission Commander

Sonar equipment design parameters can be measured and expressed quantitatively. However, sound signal transmission characteristics in the interested ocean region are season dependent. Thereby, stating and predicting sound signal characteristics is a difficult quantitative job. The expected detection range in a particular ocean area can be computed by combining above three parameters in Sonar Equation as stated in above discussion.

The principle assets available to the sonar operator to measure its performance are data from former geophysical surveys, previous measurements made by the other sonar systems in the same sea area at the same season, time and the bathythermograph furnished by all ASW platforms today. Data gathered in the past, correlated with the current ocean environment and season may present a general depiction of what is to be expected in the way of velocity profile during a given period. This information is of paramount importance for ASW mission commander in planning phases of the mission.

Following are some parameters which ASW commander can control onboard surface ship:

- Own sonar conditions
- Own sonar operator training
- Own ship operation
- Own sonar operation

B. Parameters Not under Control of ASW Mission Commander

Parameters which cannot be controlled by the mission commander are as follows:

- Own ship design
- Own sonar design
- Tactical geometry
- Ocean environment
- Under Water target design
- Under Water target operation

IX. POSSIBLE ASW SOLUTION

At present, almost every navy in the world holds helicopter onboard surface ships for search and rescue and other ferry and vertical replenishment purposes. If that helicopter is marinized with Active Dipping Sonar (ADS), this sonar will perform very well in ASW missions with following merits of platform.

A. Advantages of Platform - Helicopter

Super Lynx, Seaking, Chinese Super Frelon and Zulo helicopters can be used for ASW by deploying fields of active or passive sonobuoys or can operate active dipping sonar. Advantages of airborne platforms are as under:

- Speed of the platform
- Ability to deploy ADS over a large area but once at a time
- Not in submarine’s environment
- Flying altitude increases radar horizon
- Most effective when great mobility is required for fast reaction
- ADS equipped helicopters are well suited for redetection of contacts, target localization and weapon placement against shallow and deep water threats
- ASW helicopters are often required to search areas which are difficult for other ASW platforms such as shallow water with high noise areas, coastal regions, constrained passages, high density shipping lanes and zones of focused naval activity.

B. Airborne Active Dipping Sonar (AADS)

An airborne ADS system is a helicopter borne long range active dipping sonar. The system detects, locates, identifies and maintains contact with underwater targets through a transducer lowered into the sea water from a hovering helicopter. Active echo ranging determines the range and bearing of a target and opening or closing rate relative to the helicopter.

![Image](Fig.4 Seaking Helicopter Lowering ADS [16])

It consists of a sonar transducer array (as shown in fig above), reeling machine, sonar transmitter unit/ receiver unit (TXU/RXU) and signal and display processors. It is designed to be fully compatible with all types of naval helicopters being operated by all navies in service today [17]. The sonar transducer encompasses the acoustic projector for sonic pulse generation and an expandable array of receiving hydrophones. It is capable of generating maximum acoustic source level at any operating depth below 6 meters. Centre frequencies can be selectable for optimum acoustic performance in different marine environments. Rapid deployment and retrieval of the submersible unit (SU) is provided by the lightweight reeling machine called sonar winch. The sonar transmitter/ receiver unit (TXU/RXU) generates the transmit pulses and provides the output power to drive the acoustic transducer.

1) Measurement of Target Range

To measure the range of a target, the time from transmission of a pulse to reception is calculated and converted into a range by knowing the speed of sound.

2) Measurement of Target Bearing

For measuring the target bearing, transducer arrays are used, and the equipment measures the relative time of arrival to individual transducer by measuring the relative amplitude of beams formed through a process called beam forming [16].

3) Measuring Target Location & Classification

Signal processing carried out by the sonar set so far, further digital processing is carried out for classification and localization of the target.

4) Measurement of Target Radial Speed

The transmitted pulse may be at constant frequency or a chirp of changing frequency that allows pulse compression on reception. Simple active sonars usually use the previous with a wide filter to cover possible doppler changes due to target movement, whereas, more complex systems generally utilize the pulse compression technique. Mostly, when single frequency pulse is transmitted, the Doppler Effect can be used to measure the radial speed of a target [16]. The difference in frequency between the transmitted and received sound signal is measured and converted into speed.

C. Advantages of Airborne Active Dipping Sonar

Following are the advantages of the proposed airborne ADS over ship borne passive system:

- Provides detection, localization, identification and autotracking of submarines
- ADS provides true bearing, range and radial speed of the underwater target
- Long cable length up to 750 m to achieve maximum depth [18].
- High sink and retrieval rate of transducer array/ submersible unit
- Built-in multiplex system to permit use of a single conductor cable
- Flexibility to increase the number of sonar beams, type and length of pulses
- Different modes of operations i.e. search, sector scan and autotracking
- Long range up to 24,000 yards due to high source level available above 210 dB [19].
- The operator is provided with audio, range, bearing, Doppler and sector sonar information
- The system may be employed in either surveillance or attack control mode, or both simultaneously
- Transmitted pulse length and detection ranges are operator selectable to optimize the system according to the prevailing conditions or tactical requirements
- Offers improved S/N ratio hence detection probability increases
- State of the art electronics offers greater immunity to environmental interference
- Provides sufficient figure of merit (FOM) to accomplish convergence zone detections in deep water
- The Adaptive Processor in ADS Sonar increases detection capability in shallow water and reverberation
limited conditions, while eliminating false alarms from the video display
- Adaptive Processing mode, combined with the narrowband analysis, also improves operation in the non-reverberant conditions typically in deep water
- Airborne ADS also offers FM mode operation that enables detection of low Doppler targets in shallow waters, strong reverberation conditions and maximum range resolution
- FM pulses of extended duration are also available to detect the near zero Doppler target
- It also offers specific software tools and operator aids intended to meet the requirement for detection in rocky bottom waters
- Provides performance prediction based on environmental data collected during past or current ASW missions
- Operation in continuous wave short (CWS), continuous wave long (CWL) and Frequency Modulation (FM) modes is available to detect short range, long range and low Doppler targets
- The dipping transducer array provides a large acoustic aperture for increased sensitivity and directivity of received echoes.

X. LIMITATIONS OF PROPOSED SOLUTION

Following are the limitations on the proposed methodology:

A. Limitations of Platform – Helicopter

Besides many advantages of airborne platform, there are also some limitations listed below:
- Low time on station
- Limited weapons capacity
- Limited range
- Vulnerable to weather
- Less available manpower
- Variety of detection equipment does not available

B. Limitations of airborne ADS

The detection, classification and localization performance of active sonar set depends upon the operating environment, receiving equipment, as well as the transmitting equipment. Although airborne ADS performs very well in presence of background noise and provides accurate target detection, location, bearing and tracking. There are also some limitations on its performance which are listed below:
- Limitations of sonar set due to physical properties of sound travel in water
- Two way propagation losses
- Reverberation limitations
- Target strength (TS)
- Doppler shift
- State of maintenance of the equipment

This article presents a detailed discussion of submarine radiated noise (the actual signature), surface ship self-noise and background noise as a whole and its adverse effects over performance of ship borne passive sonar.

In ASW, it is universally believed that the advantage belongs to that who gains the initial detection. For a passive system, the detection, classification and localization of a target depends upon the ocean environment and the receiving equipment as well as the target radiated noise. Furthermore, submarine detection with a ship borne passive system chiefly requires competent and well trained sonar operator to get target signature which is a very difficult task due to dominant background noise and becomes more challenging if surface ship self-noise become problematic to eliminate.

As platform and type of sonar used, largely influence the ASW mission. Therefore, keeping in view the outlined advantages of both platform and type of sonar, it is concluded that for an ASW mission commander, using airborne ADS is far more better an option than the use of surface ship passive system.

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