Modelling of coastal ocean environment for underwater surveillance

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Significance of ocean environment for underwater surveillance, namely for sonar systems, has been discussed in this paper. The passive as well as active sonar equations and the various parameters which are important for assessing sonar performance from environment point of view are highlighted. Some important published results which are available in the literature on the modelling of thermohaline structure of our coastal waters have been reviewed in this paper. Among 1-D mixed layer ocean models the model by Niiler and Kraus shows lesser deviations on Mixed Layer Depth (MLD) and Mixed Layer Temperature (MLT) when compared to the observations. The model given by Price et al simulates the Sea Surface Temperature (SST) and the vertical profile of temperature. The comparison of simulated values with observations revealed that the diurnal variability of SST is well represented through this model but deviations are noticed in the thermocline zone. The 1-D ocean models are simple and easy to implement for operational purposes because they are computationally less intensive. However, it was found that these models accumulate more error for long-term simulation due to non-inclusion of advection processes which are important in coastal as well as open ocean conditions. The observed and predicted results of a 3-D model proposed by Blumberg and Mellor, also known as Princeton Ocean Model (POM), showed a reasonable good comparison and this model could simulate successfully the Arabian Sea mini warm pool which is an important phenomenon that occurs in the south-eastern Arabian Sea before the onset of summer monsoon.

Keywords: Ocean environment, Underwater surveillance, Sonar performance, 1-D mixed layer models, Thermohaline structure

Introduction

Underwater surveillance is of paramount significance for any sovereign nation and for a country like India with its coastline covering more than 7500 km it becomes all the more important. Similar to RADAR, which is used for air Defence, the SONAR systems are used for underwater surveillance. The acronym SONAR stands for Sound Navigation and Ranging and the prime functions of a sonar system are detection, localisation, tracking and classification of underwater targets. Like the electromagnetic waves in the case of radar, sound waves are important for sonar. The ocean environment which includes water column, surface and bottom boundaries plays a vital role for operations of sonar. In fact the ocean environment models form as basis for sonar performance models and the acoustic propagation models serve as a link between them. Unlike sea bottom characteristics (bathymetry and nature of sediments) which are considered time-invariant for sonar applications, the water column properties like temperature, salinity, density and currents are highly variable both in time and space. The sea bottom characteristics can be obtained relatively easier by making at least onetime measurements in a given location. Therefore, the real challenge lies for sonar in predicting water column properties in coastal waters which is an important input for estimation of sonar ranges. Sound speed in the ocean is a function of temperature, salinity and pressure (depth) and vertical profiles of sound speed over a given region are needed for running acoustic propagation models.

Materials and Methods

In this paper firstly a brief perspective on sonar performance prediction from underwater surveillance viewpoint is given followed by a description on ocean as an acoustic medium to highlight the significance of ocean environment for sonar. Considering the importance of coastal ocean environment for sonar applications, more focus is given for discussion on modeling of thermohaline features in our waters. Summary of the important published results on the studies so far conducted in our waters on thermohaline modeling both on 1-Dimensional mixed layer models as well as 3-D circulation model are presented.

Results and Discussion

Sonar Performance Prediction- A Perspective

As has been mentioned already, sonar systems are used for underwater surveillance. Such systems can
be used from surface or sub-surface vessels or from an aircraft. The sensors of these systems are either fitted to the hull or bow of a vessel or towed behind the vessel. In some situations for coastal and harbour defense purposes sonar arrays can also be laid on the seabed. Whatever be the mode of its deployment the detection of underwater targets is based on the propagation of acoustic waves between the target and sonar. Sonar systems can be broadly classified into two categories, namely, active and passive. Active sonar uses echo-ranging principle wherein acoustic waves propagate from transmitter to the target and back to the receiver of the sonar. A device known as transducer converts electrical energy from the transmitter into acoustic energy. If the transducer can only receive it is called as hydrophone, and if it can only transmit then it is called a projector. In many situations, it can work both as transmitter and receiver device, so it is called as transducer which is the case with active sonar. The output of transducer is termed as Source Level (SL). In the case of passive sonar system the target itself is the source and the radiated noise from the target is received by the sonar. Normally SL of underwater targets is not known beforehand and such data have to be acquired over a period of time through measurements, modelling and simulations for various classes of targets. Passive sources may be categorised into broadband and narrowband sources. As the name suggests broadband sources create acoustic energy over wide range of frequencies radiated by the propellers, shaft, and flow noise and propulsion systems of underwater targets. Noise from propeller and shaft is generally at low frequencies. Narrowband sources radiate within a small band around particular frequency which can be related to specific machineries like pumps, motors, electrical generation equipment and propulsion systems.

Another important aspect is the acoustic Transmission Loss (TL) which needs to be estimated correctly by using inputs from a given ocean environment. There are some standard empirical formulae available for the estimation of spherical spreading loss (in deep water) or cylindrical spreading loss (in shallow water) and attenuation of acoustic energy due to absorption and scattering within the ocean medium and also from the sea surface and sea bottom boundaries. Scattering of underwater sound might be due to several factors like particulate matter, biomass, schools of fish and rough boundary surfaces, all these put together makes estimation of TL more complex. Further the propagation paths of acoustic waves depend on the variation of sound speed which is a function of temperature, salinity and depth. Different acoustic propagation models are available in literature based on either ray theory or normal mode or parabolic equation which are quite useful for estimating TL values for a given ocean environment.

Naturally occurring noise in the ocean is another significant parameter which is normally referred as ambient Noise Level (NL). Though there are wide variety of noise sources in the ocean the prime ones that are to be considered are sea-state dependent noise which includes winds and the noise caused by shipping activities. Therefore for estimation of NL one needs to consider the noise levels of these two categories in a given geographical region. Again one has to depend on modelling as well as noise measurements using hydrophones for characterising NL. In addition to it there can be some noise emanating from own ship, electronics, and turbulent flow noise which is referred as self noise (SN) and this has to be combined ultimately with ambient noise and treated as NL for estimation of sonar performance. Apart from it, acoustic reverberation may also take place when we transmit and receive simultaneously in the ocean and it is a common phenomenon for active sonar system. Reverberation is usually defined as that portion of the sound energy received back by the transducer after it is scattered by the ocean boundaries like sea surface or sea bottom or from the particles of the medium itself. The scattered sound energies received back in this manner are also known as surface/bottom/volume Reverberation Level (RL). If the RL>NL then it is known as reverberation limited and for NL>RL it is termed as noise limited case. In the case of active sonar the term NL will be replaced by RL under reverberation dominated conditions.

Transducers (or hydrophones) are used in sonar for receiving acoustic energy and if they are designed to receive from all directions, then they are called as omni-directional. However, they can be designed with some directionality having beam width such that it receives energy from a given direction. When a transducer array receives acoustic energy in a narrow bandwidth it allows to reject other interfering noise present in the ocean since the ambient noise comes from all directions. This is known as Directivity Index (DI) of a sonar system which is analogous to antenna gain in the case of radar. The
parameters like source level (SL), transmission loss (TL), noise level (NL), reverberation level (RL), directivity index (DI), detection threshold (DT) and finally signal-to-noise ratio (SNR). Now we can look for the relationships of these parameters to know the sonar performance and write the equations for passive as well as active sonar systems. Therefore, SNR for a passive system (includes only one-way transmission) can be written as:

\[ \text{SNR} = \text{SL} + \text{DI} - \text{TL} - \text{NL} \]  \hspace{1cm} (1)

In the case of an active system we have one more additional term to quantify the reflection of acoustic energy from the target which is known as target strength (TS). This term acts as a source level after reflection and includes directional effects also. TS is a function of the target size, surface material and shape as in the case of radar. It may be noted that for an active system a two-way transmission loss is to be included and hence SNR of active sonar is given as:

\[ \text{SNR} = \text{SL} - 2\text{TL} + \text{TS} - \text{NL} + \text{DI} \]  \hspace{1cm} (2)

It may be noted that in the case of reverberation limited condition NL to be replaced by RL. More details on sonar systems and estimation of various parameters of sonar equation are given by Waite. In the next section the importance of ocean environment for underwater propagation is highlighted which makes sonar performance prediction unique and difficult compared to radar.

Ocean – As an Acoustic Medium

In the previous section various parameters that are needed for sonar performance prediction were discussed. Among these parameters, TL is the most important parameter of the sonar equations which are described above. The significance of thermohaline conditions in the ocean for estimation of TL will be covered in this section. Before that we will briefly discuss the importance of ocean, as an acoustic medium for TL estimation. The undulating rough sea surface reflects and scatters the sound energy and thereby limits the performance of sonar. Sea state information is therefore needed for estimation of surface-coupled reflection losses. Ocean wave forecasting models can be used for obtaining sea state and wave information. Although the sea floor also affects sound in a similar way to that of sea surface, the attenuation of sound due to bottom interaction is more complex. Some of the reasons are: i) irregular bottom topography with different sediment composition ii) variation of compressional and shear sound speeds for stratified bottom (layered sub-bottom) iii) sudden changes of composition and roughness and iv) Complex reflection and refraction of sound through sub-bottom sediment layers and water medium. It is an essential prerequisite to have detailed bathymetric and sub-bottom sediment characteristics of the region by conducting marine geophysical surveys with multi-beam echo-sounder and sub-bottom profiler in order to know the bathymetry and sediment composition of the region for estimation of sea-bottom losses for performance prediction of sonar. Thus the information on sea surface and the sea bottom are also required in addition to the water column properties for estimation of Transmission Loss (TL) characteristics in the ocean.

However, as mentioned earlier the water column properties or the thermo-haline conditions are very critical in estimating TL in the ocean. As we know, the sound speed in the ocean is the most important characteristic parameter for acoustic propagation. It is determined by the density of sea water which in turn is a function of temperature (T), salinity (S) and pressure (depth). The variation of T and S, both in vertical and horizontal are often referred as thermo-haline variability in the ocean. The surface layer is mixed due to mechanical (wind and waves) and buoyant (heat loss by evaporation) mixing processes and base of this well mixed layer is called as Mixed Layer Depth (MLD). The upper mixed layer in the ocean is also known as Sonic Layer Depth (SLD) and it acts as a wave guide for surface duct propagation which is quite important for ship hull mounted and aircraft dunking sonar. A schematic of ocean environment from sonar point of view is shown in Fig. 1. Right below at the mixed layer a sharp gradient in temperature (or density) exists which is known as thermocline (or pycnocline). The waters within the thermocline are highly stratified and this zone separates the upper and deeper oceanic waters. Thermocline region is also characterised by a negative sound speed gradient. As we see wind generated gravity waves at the sea surface, similar waves also
present within the ocean and these are known as oceanic internal waves. Energy from tides, winds and current shear can excite the thermocline which manifest as internal waves. These internal wave crests or troughs converge or diverge acoustic energy when sound waves propagate in the ocean. Below the thermocline and extending up to the sea bottom is the deep isothermal layer. Therefore, observation and prediction of spatial and temporal thermohaline fields in the ocean is important for understanding acoustic propagation and estimation of TL characteristics.

The research investigations on 1-D mixed layer models and 3-D circulation models carried out on the prediction of thermohaline structure in our coastal and offshore waters are discussed in the next section.

**Modelling of Thermohaline Structure in our waters**

Ocean prediction in the surface and near-surface layers (waves and MLD) is normally treated as a boundary-value problem, whereas in the below layers (thermocline and below) it is considered as an initial value problem. Therefore, the mechanical wind mixing and the convective buoyancy mixing together contribute for the thickness of the mixed layer or MLD. Fig. 2 gives a schematic representation of the incoming \( Q_h \) and outgoing radiation \( Q_B \), evaporative \( Q_E \) and sensible \( Q_S \) heat fluxes and wind stress across the air-sea interface. The temperature of the mixed layer (MLT) is determined by the heat fluxes across the air-sea interface and entrainment of colder waters from below. For more insight and understanding of the physics of the oceans one might refer to Pickard and Emery\(^5\) as well as Pond and Pickard\(^6\). Mixed layer models can be categorised into two types: differential and bulk models. These models use equations for the conservation of momentum, heat, salt and turbulent kinetic energy (TKE) in their primitive form. For differential models these equations are not integrated over the mixed layer. The mixed layer for these models is defined by the region where local TKE is large enough to provide certain level of vertical mixing. In the case of bulk (or integrated) models the mixed layer is well defined layer which is homogeneous for both temperature and salinity. The governing equations for these models are obtained by integrating primitive equations over the depth of the mixed layer. Forcing mechanisms used for mixed layer are wind mixing, heating and cooling. Due to wind forcing the mixed layer deepens and this happens due to erosion of the stably stratified region at its base by wind generated turbulence. The depth of mixing is determined by the strength of density stratification and wind speed. Under heating conditions normally mixed layer shallows due to balance between positive surface buoyancy flux and wind mixing. Remarkable deepening of mixed layers occur when cooling takes place due to surface heat loss or negative buoyancy flux leading to convection. Very deep mixed layers can be seen due to convective activity in winter.

In early 1970s, 1-D numerical ocean models were first introduced in order to predict mixed layer depth (MLD) and mixed layer temperature (MLT). Denman and Miyake\(^7\), Miller\(^8\) and Niiler and Kraus\(^1\) were some examples of these 1-D Mixed Layer (ML) models which were used initially for operational ocean predictions. Based on the initial temperature profile and near surface atmospheric parameters the 1-D ML models predict the diurnal and synoptic variations of MLD and MLT. Kraus and Turner\(^9\) first postulated a systematic approach for mixed layer modelling by considering energy inputs across air-sea interface and entrainment of cold waters from below.
Later Denman\(^{10}\) modified this model by incorporating time dependent meteorological inputs which was further modified by Miller\(^{8}\) to include salinity effects also. Subsequently several improvements to the mixed layer dynamics were given by Kim\(^{11}\), Garwood\(^{12}\) and Niiler and Kraus\(^{1}\). The formulations of these models and the standard governing equations are not shown here in this paper as they can be easily referred from the references cited above.

Hareesh Kumar \textit{et al.}\(^{13}\) Joseph \textit{et al.}\(^{14}\) Murthy and Hareesh Kumar\(^{15}\), Hareesh Kumar and Murthy\(^{16}\) utilised Miller’s\(^{8}\) model for simulation of mixed layer characteristics in the coastal waters off the west coast of India. Sanil Kumar \textit{et al.}\(^{17}\) simulated the short-term variability of mixed layer off the west coast of India during summer monsoon using 1 D models of Miller\(^{8}\) and Niiler and Kraus\(^{1}\). Some important studies were also done in the Arabian Sea and Bay of Bengal using 1 D mixed layer models by Rao\(^{18}\), Shetye\(^{19}\), Molinari \textit{et al.}\(^{20}\), McCreary and Kundu\(^{21}\), Rao and Mathew\(^{22}\), Rao \textit{et al.}\(^{23}\) and Mathew \textit{et al.}\(^{24}\) which highlighted the importance of advection, but these studies were mostly in the deep oceanic regions.

The performance of the 1 D model was evaluated under fair weather and rough weather conditions. A study carried out by Hareesh Kumar and Murthy\(^{16}\) based on time series oceanographic and surface met data collected off Karwar (depth 95 m) from an anchored ship during Oct-Nov 1986 (rough weather/Deep Depression) and in Sep 1987 (fair weather) revealed the efficacy of the model (Denman\(^{10}\) and Miller\(^{8}\)) for deepening/shallowing of MLD and cooling/heating of MLT. In rough weather condition the mixed layer deepened by 20 m and cooled by 1.2°C. Though the model was able to simulate the trends of cooling and heating of mixed layer the deviations did exist between observed and predicted values of MLD and MLT. The rms error reported in this study was 4 m and 0.2°C and the maximum deviation of 8°Cm and 0.4°C for MLD and MLT respectively.

One of the unique features of the north Indian Ocean and especially the Arabian Sea is the cooling of upper-ocean in the summer season due to summer monsoonal forcing. Therefore this region has become...
important for various studies both for modelling and observations. Another study by Sanil Kumar et al.\textsuperscript{17} which was carried out in the summer monsoon period using 3-h timeseries of vertical temperature profiles and surface marine met data collected in the coastal waters off Mumbai during Jun-Jul 1988. The authors used 1D models of Miller\textsuperscript{8} and Niiler and Kraus\textsuperscript{1}. Lesser deviations (rms error of 5 m and 0.1 °C) between observed and predicted values of MLD and MLT were seen in the case of Niiler and Kraus\textsuperscript{1}. The larger deviations of predicted and observed values in the case of Miller\textsuperscript{8} were attributed to improper parameterisation of convective efficiency and absorption of solar radiation.

In the pre-monsoon season the heating of upper ocean takes place due to net oceanic heat gain. Such heating leads to stratification of upper oceanic layers and inhibits vertical mixing. If the surface winds are also weak along with solar heating the mixed layer shoals. On the contrary, strong winds associated with net heat loss from sea surface enhances vertical mixing resulting in deep MLD. The balance of these two processes ultimately results into diurnal thermal cycle in the upper ocean. Lukas\textsuperscript{25} reported the diurnal cycling of sea surface temperature (SST) which is of non-sinusoidal nature. 1D model of Miller\textsuperscript{8} as well as Niiler and Kraus\textsuperscript{1} assume a homogeneous mixed layer with a density jump at its base (base of mixed layer). But the field measurements on mixed layer do not support a sudden density jump at the base and instead a smooth transition layer occurs below the mixed layer. Price et al.\textsuperscript{2} considered this aspect and presented a 1D mixed layer model which can simulate diurnal thermal cycle. Utilising this model Hareesh Kumar et al.\textsuperscript{26} successfully simulated the diurnal cycle of SST and vertical profile of temperature with reasonable accuracy for the west coast of India. Timeseries data on 1-h surface marine met parameters and 3-h vertical profiles of temperature from an anchored ship off Kochi obtained during April 1991 were used for 1D model simulations. The observations mostly reflected fair weather conditions with wind speed < 5 m/s and wind direction varying between south and west. Due to clear skies, considerable net heat gain by the ocean and SST > 30.5 °C were observed. Interestingly the SST variation exhibited a non-sinusoidal diurnal nature with maximum occurring around 1500 Hours and minimum around 0600 Hours. The authors simulated SST and the vertical temperature profile using Miller\textsuperscript{8} and also by following the model of Price et al.\textsuperscript{2}. It was found that the Price et al.\textsuperscript{2} simulated diurnal cycling of SST was far superior to Miller\textsuperscript{8}. Though this model simulated well the SST, some deviations of temperature in the thermocline zone were noticed which were attributed to the internal waves occurring in the ocean.

1D mixed layer models so far discussed do not take into account the advection of heat and salt and therefore less accurate compared to 3D circulation models. Blumberg and Mellor\textsuperscript{3} had given a 3D ocean circulation model which was initially developed at Princeton University. Hence this model is also known as Princeton Ocean Model (POM). This model has a free-surface, bottom-following vertical sigma coordinate and a turbulence closure sub-model for surface and bottom mixed layer dynamics. It was applied to coastal and estuarine waters and many other oceanic regions. The model equations describe the velocity and surface elevation, salinity and temperature fields. It uses two simplifying approximations: 1) that the weight of the fluid identically balances the pressure (hydrostatic assumption) and 2) density differences neglected unless the differences are multiplied by gravity (Boussinesq approximation).

Hareesh Kumar et al.\textsuperscript{27} utilised the Princeton Ocean Model (POM) and simulated the Arabian Sea mini warm pool. Temperature and salinity data collected with mini CTD off southwest coast of India along two zonal transects (9N and 10.5N) during May 2000 were utilised in the study and model simulations were compared well with the observations. Specific numerical experiments were also carried out to understand role of the heat flux and salinity stratification for the formation, growth and dissipation of the warm pool. These experiments revealed that the inclusion of heat flux terms in the model captured well the increase of temperature (~ 1.25 °C) during heating regime and decrease of temperature (~1 °C) during the cooling regime. When heat flux terms are not included in the model an unrealistic continuous cooling resulted. Another important result of the study was that the salinity stratification was found to be favourable factor for the simulation of mini warm pool in the southeastern Arabian Sea.

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References


