The Ocean Acoustic Environment in the Lower Chesapeake Bay: Factors Influencing the Forward Problem

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Abstract: Seasonal changes in the vertical and horizontal sound velocity field in the lower Chesapeake Bay were found to produce conditions favorable to cross bay sound transmissions in the summer and not in winter.

The Chesapeake Bay is the largest estuary in the United States with great scientific, economic and military importance. It contains the world's largest naval base at Norfolk and several important seaports. Solution of the forward problem would be the first step in attempting to use the inverse method of acoustic tomography in studying hydrographic conditions in the Bay. If the forward problem could be solved for this body of water, the inverse method could be applied to study the hydrographic conditions of the Bay more frequently.

Attempts to express the relationship between sound velocity and the hydrographic conditions have led to two different problems referred to as the forward problem and the inverse problem. Monk et al. (10) defines these two problems as follows: The forward problem: "Given C(X,Y,Z) and U(X,Y,Z) together with the characteristics of the sound source, compute the detailed structure of the signal at the receiver." The inverse problem is the opposite: "[It] demands calculation of the ocean properties, C(X,Y,Z) and/or U(X,Y,Z) given the properties of the transmitted and received signal."

The forward problem was not solved for the open ocean until the late 1980's upon the completion of the SLICE89 experiment. Even that experiment, however, includes some discrepancies between measurements and predictions for sound travel time (10). The fact that the forward problem is difficult to solve even for open ocean conditions where horizontal stratification may be assumed and surface and bottom interactions minimum alludes to the potential difficulties in a shallow, inland body of water such as the Chesapeake Bay. The mixing of Atlantic Ocean and fresh water from rivers which discharge into the Bay lead to complicated patterns of horizontal stratification for the mouth of the Chesapeake Bay. The generally shallow nature of the Bay, combined with the presence of three relatively deep channels, Thimble Shoals, Chesapeake and Beach Channels, create many opportunities for sound traveling through the water there to be reflected.

Despite the difficulties, it would be useful to solve the forward problem for the Chesapeake Bay. The most notable reason for this is that a good solution for the forward problem would allow the inverse method to be used in studying the Chesapeake Bay. Application of the inverse method would make it much simpler to study the hydrographic conditions of the Bay. If good predictions of the travel time for sound waves in the Bay were available, they could be compared to actual measured values for sound traversing the Bay to make conjectures about changes in the hydrographic conditions of the Bay. Solving and applying the more desirable inverse problem, however, is impossible without first solving the forward problem.

For the past eleven years, the Center for Coastal Physical Oceanography of Old Dominion University, has been conducting hydrographic surveys of the mouth of the Chesapeake Bay at roughly monthly intervals. These survey cruises are conducted on the highest spring tide of the month and provide a useful climatological data set (8). Coastal Physical Oceanographers use these data to study hydrographic conditions of the lower Bay and the exchange of water in and out of the Bay (3). Data from these cruises, July 2000 and December 2001, are used in this study.

METHODS AND RESULTS

The data for this research was collected on the December 17, 2001 and the July 3, 2000 monitoring cruises on the R/V LINWOOD HOLTON using either a Sea-Bird SBE25 SEALOGGER CTD or a Sea Bird SBE 19SEACAT Profiler. The instruments collect temperature, conductivity, chlorophyll concentration, oxygen saturation, density and pressure and store the data averaged for 1-meter intervals (8). Data are collected at 20 stations as shown in Figure 1. The Conductivity/salinity, temperature and pressure data were used to generate sound velocity values using Wilson's equation (12).

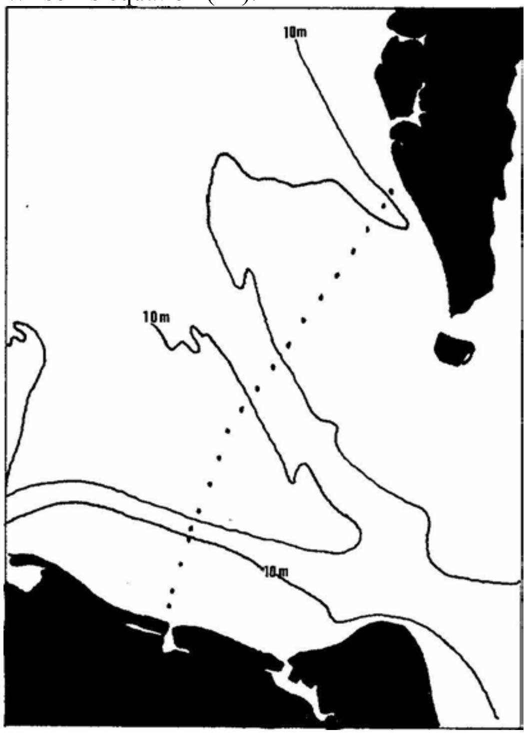

Figure1: Map showing the 20 stations where data was collected.

The data were used to produce charts showing sound velocity isopleths (Figures 2 and 3) and possible ray paths were calculated from these data. One of the authors, Anderson, wrote a computer program in JAVA to aid in the analysis of the data. This included computation of ray paths and travel times from the July 3, 2000 cruise. This program will be referred to as RTP. Because of the significantly differing conditions in the winter when there was no ray path solution, the RTP was only used for the summer, July, analysis.

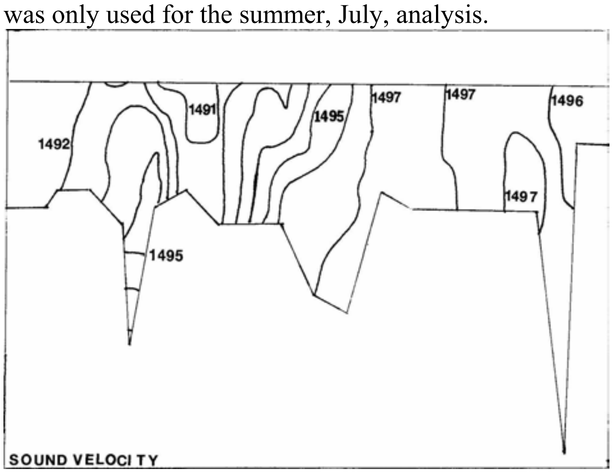

Figure 2: Sound velocity profiles for the Chesapeake Bay in winter.

The speed of sound in seawater may be expressed as the square root of the bulk modulus of elasticity divided by the density of seawater. An increase in temperature will decrease the density resulting in a change in the speed of sound of about 3 m/sec/degree Celsius in shallow water. An increase in salinity will increase the density and decrease the bulk modulus of elasticity resulting in an increase in the sound velocity of about 1.3 m/sec/part per thousand. An increase in pressure, depth, will result in an increase in sound velocity of about 1.8 m/sec/100 m. Due to the shallowness of the study area, less than 22 m, the effects of pressure are not significant in this project.

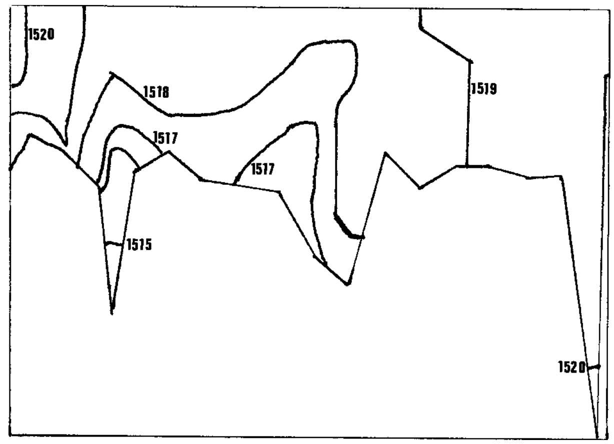

Figure 3: Sound velocity profiles for the Chesapeake Bay in summer.

In the winter sound velocity was not dependent upon temperature (Figure 4). It was, however, dependent upon salinity (Figure 5). This was largely because of the near isothermal conditions of the lower Bay and relatively large variability of the salinity during the winter.

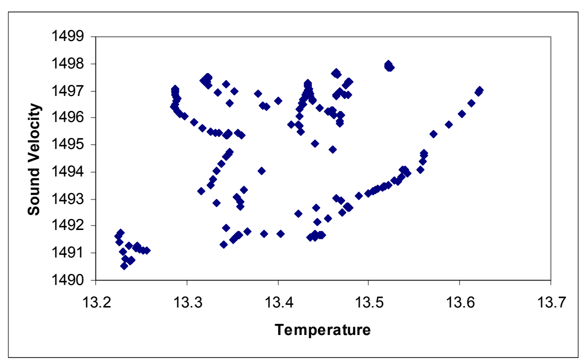

Figure 4: Winter Sound Velocity vs. Temperature

During the summer, when both temperature and salinity varied over wider ranges, there was a weak positive correlation between temperature and sound velocity and a weak negative correlation between salinity and sound velocity (Figures 6 and 7). This can be understood by examining Figure 8, which shows temperature as a function of salinity. Here we see a strong negative correlation between temperature and salinity. This would tend to weaken the correlation between sound velocity and either of these parameters since when temperature, for example, is high (tending to produce a faster sound velocity) salinity is generally low (tending to produce a slower sound velocity). The reverse is also true. This negative correlation between temperature and salinity can be explained by the relative temperature of the ocean water and fresh water, which meet to form Bay water in July. Ocean water would tend to be cooler than fresh water, which can be heated more readily.

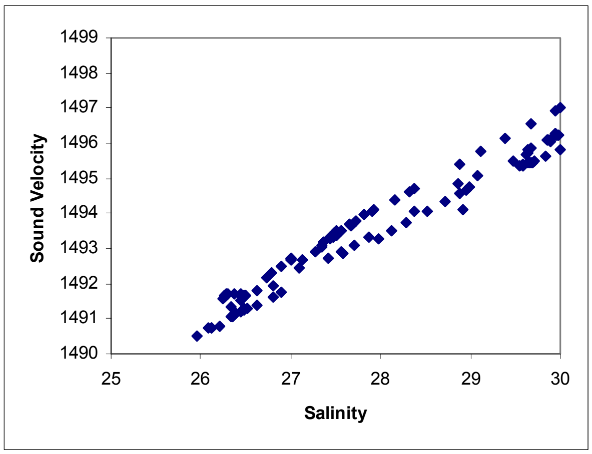

Figure 5: Winter Salinity vs. Sound Velocity

The sound velocity profiles for the July cruise are shown in figure 3. These computer-generated profiles show the significant vertical stratification of the lower Chesapeake Bay. They also show some horizontal variation, not typically encountered in the open ocean (2, 4 & 6). The complexity of the sound velocity profiles make solving the forward problem for the Chesapeake Bay much more challenging than it is for the general open ocean conditions.

In writing the RTP, the first step was to have the program compute the path of a single ray across the mouth of the Bay. To this end, basic ray path computation techniques were incorporated into the program. Based on a starting depth, angle (90 degrees being horizontal and 0 degrees being vertical) and direction (either toward the surface or toward the bottom), the ray path was generated piecewise until it reached the far side of the virtual Bay created in the program. Data for each station was assumed to hold up to the location of the next station, with station 18 being discarded because of its very limiting four-meter depth. Thus, the ray was assumed to travel through a cross section of water like the one in figure 3.

We can manipulate Snell's Law from its traditional form to a modified form:

C1/Cosine (angle of incidence) = C2/Cosine (angle of refraction)

Angle of Refraction = Arccosine (C2/C1 X Cosine (angle of incidence)) so that it will be useful for the computer.

Also the Critical angle = arccosine (C1/C2) which indicates the maximum angle at which total internal reflection will occur.

For each piecewise step in the process of computing the ray path, the angle was calculated then a horizontal displacement was determined based on the vertical difference between the current depth and the previous depth. In this fashion, the ray path was computed for the width of the station. When it reached the edge of the station, where the data for the next station takes over, the Snell's Law equation was used again to determine the refraction across the station-to-station boundary. When the ray reached the surface of the water or the bay floor, it was assumed that each was flat and therefore that the ray reflected at the incident angle.

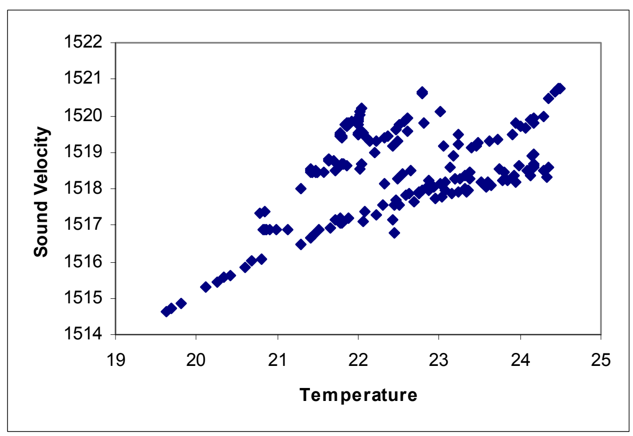

Figure 6: Summer Sound Velocity vs. Temperature

A number of situations were left to be dealt with after this basic ray-tracing pattern was functioning. First, since the "bottom" for the sound velocity profile used by the RTP shows each station as being a vertically oriented rectangle, sometimes a ray collides with the vertical edge of one station, below the deepest part of the next station. In this case, the ray would in reality be reflected back in the direction from which it had come and might still, through a series of reflections, reach the end of the Bay it was originally destined for. However, for the purpose of this study it was assumed that those rays would not reach the opposite end of the Bay and therefore were discarded. The second unusual situation that had to be dealt with was when a ray moving between stations was incident at such an angle that it was reflected back because the change in sound velocity was too great In this case, also, the ray was discarded. Each of these situations produced what was called a broken ray.

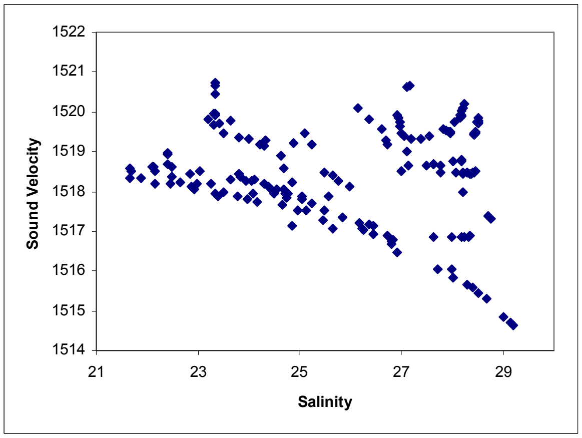

Figure 7: Summer Sound Velocity vs. Salinity

Once the program was successfully drawing rays, which traversed the bay, the next step was to calculate the travel times for those rays. This was accomplished by using a distance formula to determine the distance traveled by the ray in one of its constant velocity steps and dividing that distance by the sound velocity associated with the step. The results for each step were tabulated to determine a total travel time for the entire ray. Broken rays were given no travel times and were not included in saved data sets.

The program was then adapted to compute the numeric results for a ray without actually drawing the ray, which increased calculation speed greatly. At that point, a feature was added which allowed the program to calculate large sets of ray travel times given an initial depth. The program calculated a ray travel time and arrival depths for initial angles between 80 degrees and 90 degrees going either up or down starting at the initial depth. A set was calculated for each whole meter of depth between one meter below the surface and one meter above the bottom of the first station. The results were then compiled into a single large data set for analysis.

The range of travel times was from 20.625 seconds to 20.925 seconds. The final depths ranged almost from the surface to the bottom of the 22 meter deep Station 17. The only additional analysis was an attempt to determine where it would be best to place the transmitter and receiver if actual measurements were taken, such as might be done in an attempt to solve the inverse problem. Two of the best possibilities were a transmitter at 3.0 meters and a receiver at 21.0 meters and a transmitter at 1.0 meters and a receiver at 20.0 meters (each with five rays arriving at approximately the receiver depth). It was difficult to arrive at even a tentative decision for this, however, because of the complicated influences on the ray paths, which scatter the final depths of the paths all over the range of the depths for the final station.

For the December cruise, the sound velocity isopleths show a much stronger horizontal stratification (Figure 2). Due to the 1022:1 vertical exaggeration, the isopleths appear to be almost vertical. This was necessary because it is almost 30 km across the Bay mouth and the average depth is 9.45 m. The angles of the isopleths for sound velocity are in fact quite small, less than five degrees in most cases.

Ray paths were computed initially for the December cruise by assuming a uniform horizontal sound velocity field. This was accomplished by taking the data from a single station and using it as the vertical profile across the Bay. These computations indicated that only a zero degree ray path would be able to move across the Bay without strongly interacting with the surface and bottom.

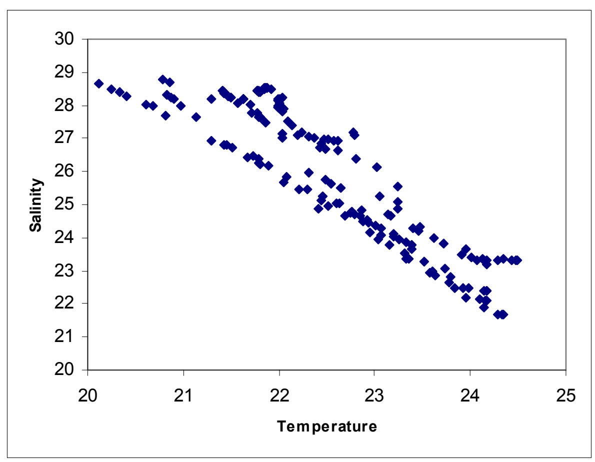

Figure 8: Summer Temperature vs. Salinity

The critical angle at which total internal reflection occurs for a 1.0 m/sec. change in sound velocity is 2.09 degrees. When a horizontal ray reached the 1492 m/s isopleths, the angle of incidence is 0.229 degrees, which is much smaller. This results in total internal reflection. The isopleths on both sides of Thimble Shoals Channel and Chesapeake Channel have similar slopes except for the fact that they are reversed (Figure2). This leads to the result that transmitting a ray across the Bay in winter with strong interaction with the surface and bottom is not feasible.

As given by Medwin and Clay (9), the coefficient of reflection of sound at a boundary may be described using the equation:

$$\frac{\text{D2C2 X Cosine (Angle of Incidence) - D1C1 X Cosine (Angle of Refraction)}}{\text{D2C2 X Cosine (Angle of Incidence + D1C1 X Cosine (Angle of Refraction).}}$$

Where D1 and D2 are the densities of the first and second mediums and C1 and C2 are the sound velocities in these mediums. Because the density of air and sound velocity in air are much smaller than those for water, the reflection coefficient for the surface is essentially unity. For the bottom assumed to be sand, the density is assumed to be 1900 kg/cubic meter and the speed of sound is assumed to be 1650 m/sec. The result is a coefficient of reflection of 0.5. This would mean that for an initial angle of eleven degrees, a 120 dB source would be reduced to less than 1 dB in 3718 m. Such a reduction would result in the signal being lost in the background noise (1 & 9).

The surface is assumed to be flat for the purpose of ray path calculation. In fact waves are typically present. The work of Chapman and Harris (5) shows that the loss due to back scattering is a function of frequency of the signal, wind speed and incident angle. Back scattering will increase with increasing wind speed and frequency and incident angle.

The cutoff frequency (7) for a shallow water sound duct is given by the relationship:

F = Cw/[4D{1 - (Cw/Cb)^2}^.5]

Where F is the cutoff frequency, Cw is the speed of sound in the water, Cb is the speed of sound in the bottom and D is the depth of the water. This yields a cutoff frequency of 92.4 Hz in winter and 98.7 Hz in summer with wavelengths of 16.1 m and 15.3 m respectively.

The results of the study indicate that use of the inverse method in the lower Chesapeake Bay would have limited value. Although good conjectures can be made about why various areas of the Bay cross section might maintain certain conditions, it is impossible to be sure which conditions are responsible for the general behavior of the ray paths in the lower Chesapeake Bay. This is because of the complicated mixing patterns. As can be seen from figures 1, 2 and 3 relatively deep channels, Thimble Shoals, Chesapeake and Beach Channels, cut through the entrance of the Bay. These bring water from the continental shelf, especially the southern most two channels. The extent of mixing depends on many factors resulting in a variety of unpredictable conditions. Therefore, making specific conjectures about which conditions have changed would be difficult based simply on sound velocity conditions.

During the winter conditions, when horizontal variability is greatest and the vertical sound velocity profile is reversed, it would appear that no sound ray path solution would exist.

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