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Potential Improvements for Underwater Sound Speed Measurement Devices

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Abstract

Modern sonar systems rely on fast and accurate measurements of the speed of sound in water. Plenty of measurement devices currently exist which are used to gather sound speed measurements in water. They specifically require accurate temperature measurements, as temperature is the most influential factor which affects sound wave speed. Previous research on sound speed properties, a few different examples of sound speed measurement devices, and examples of different types of temperature measurement devices was used along with new research on salinity equations and properties of sound, ocean water, and various existing measurement devices to suggest possible improvements for sound speed measurement systems.

Introduction

Various measurement devices currently exist which are used to measure the speed of sound waves in water. For sonar systems to be able to receive sound waves and gather the information they require, the speed of the sound waves must be determined so the equipment can be designed or calibrated to pick them up. The ability to transmit sound waves underwater is important for companies that rely on sonar systems for things such as underwater threat detection and communication between underwater vehicles. As a mechanical engineering student who will be working on submarines' sonar systems in my career, it is of great value to me to know what methods and factors of sonar systems could provide the most accurate sound speed measurements possible.

Previously, I had done research on the factors which affected sound speed measurement and investigated a few examples of different sound speed measurement systems. During this research, I had found that the most influential factors for the speed of sound in water were temperature, pressure, and salinity, with temperature having the largest overall impact. Therefore, further research was conducted on examples of varying types of temperature measurement devices in order to discover which seemed to be the most accurate at measuring temperature.

Methods

The end goal for this research paper was to determine or theorize ways that currently existing sound speed measurement devices could be improved. In order to do this, previous research on the primary factors affecting sound speed measurement, currently existing sound speed measurement devices, and different types of temperature measurement devices was used as a starting point. Considering how the different temperature measurement devices I researched could be implemented into the overall sound speed measurement devices researched could provide possible improvement ideas. The conclusions drawn from my previous research informed the topics I researched further into. Researching other factors affecting sound speed measurement that had not been investigated previously would provide more areas in which improvements could be made. These new considerations from further research done was also combined with the previous conclusions I had made to suggest improvements for numerous types of sound speed measurement devices.

Previous Research Results

One of the first main points of my previous research was understanding the factors that influenced sound speed measurement most. The primary factors are temperature, pressure, and salinity, with temperature being the most influential. Once the main factors affecting sound speed measurement were understood, the next step was to research a few specific sound speed measurement systems which had been used previously. Upon researching the methods which have been used for determining the speed of sound waves in water that have been previously used, I first discovered the most widely used system by many companies, including the Navy. This system is the Expendable Bathythermograph, or XBT, pictured here:

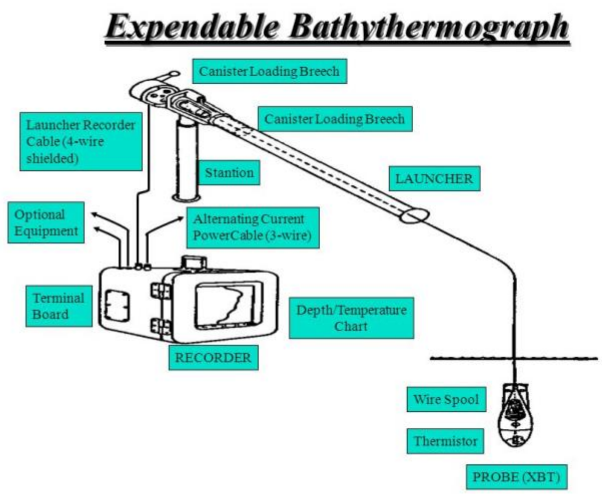

Figure 1- Diagram of an expendable bathythermograph (Speed of Sound in the Sea 2018, Figure 3)

XBT's are launched from submarines or ships on the surface of the water, then sink at a known rate while measuring the temperature as they go and transmitting the information back to the launch platform. The result is a plot of temperature dependent on depth, which is then used to determine sound speeds. (Speed of Sound in the Sea 2018). XBTs, however, neglect salinity completely in favor of only focusing on depth and temperature, since they are the factors which cause the greatest variation in the speed of sound in seawater (Speed of Sound in the Sea 2018). While the fact that they are so widely used implies that they must be proven to give fairly accurate and dependable measurements, the inherit weakness present in XBTs in that they ignore the salinity completely in their measurements means that they are not as accurate as they possibly could be, so a more elaborate and precise system is desired.

Wayne D. Wilson, in his article "Speed of Sound in Distilled Water as a Function of Temperature and Pressure", published in the Journal of the Acoustical Society of America, presents and compares multiple similar methods used by different companies for determining the speed of sound in distilled water. He first explains that the effect of pressure on sound speed has already been explored by multiple scientists, but differences exist between their data, so their methods must not have been the most reliable. He then focuses in on the measurements that were consequently made by the Naval Ordnance Laboratory (NOL) in an attempt to provide more accurate and certain data for sound speeds tested within the temperature range of 0 to 100 degrees Celsius and the pressure range 14.7 to 14000 psia. The system that was selected for use by NOL was similar in principle to another method that was used by two scientists, M. Greenspan and C. Tschiegg, at the National Bureau of Standards (NBS). The general design of both groups' systems can be seen in the following diagram:

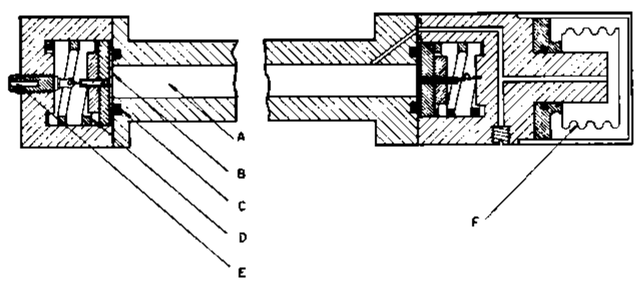

Figure 2- Schematic of NOL's velocimeter; similar to the velocimeter used by NBS (Wilson 1959, Figure 1)

For each system pictured in Figure 2, the water sample is contained in a tubular housing, and each end of the housing is terminated by a quartz crystal which is used for the transmission and reception of pulses of sound. NOL knew the repetition rates of the pulses when echoes are superimposed into the system, which was enough for them to determine the time it took for each sound pulse to travel the entire length of the velocimeter. If the scientists at NOL could then accurately determine the length traveled then it would allow them to compute the velocity of the sound waves (Wilson 1959). Greenspan and Tschiegg would have used the same general procedure to determine the speed of the sound waves, as their apparatus was essentially the same.

While the system's general setup was nearly identical between NOL and NBS, NOL's velocimeter had a few key differences. NOL's velocimeter was 12.7 cm in length as compared to

NBS's, which was 20 cm. NOL used 5-Mc crystals, while NBS used only 3.5-Mc crystals. Finally, the NBS instrument's crystals were wrung to the ends of the tube without electrode plating, while the NOL instrument used gold plated crystals. The gold-plated crystals in the NOL instrument are backed by an insulator and a compression spring which is used to force the crystals against the ends of the tube when the system is fully assembled. A device called an O-ring was placed between each crystal and the walls of the tube to act as a leakage seal and to compress under the force of the spring to allow the crystal to make uniform contact with the ends of the tube. One end cap of the tube contained the electrical leads for the communication of sound pulses between the crystals and the electronic components on the outside of the tube. The other end cap had a bellows attached to transmit the pressure being applied to the water sample inside the tube. The entire velocimeter was placed inside a heat-treated steel pressure vessel capable of withstanding 100,000 psia of pressure (Wilson 1959). All of these additions and modifications to NOL's apparatus as compared to NBS's allowed them to obtain more accurate results, as the apparatus had many of its benefits, such as withstanding higher pressures, having larger crystals to better transmit and receive the sound waves, having the O-rings to prevent leaks in the apparatus, and having an electrical component attached to aid in the measurement of the sound speeds.

One particularly enhanced and unique aspect of NOL's system was the use of the complex electronic instrumentation used to assist in their sound speed measurements. A block diagram of the electronic instrumentation can be seen here:

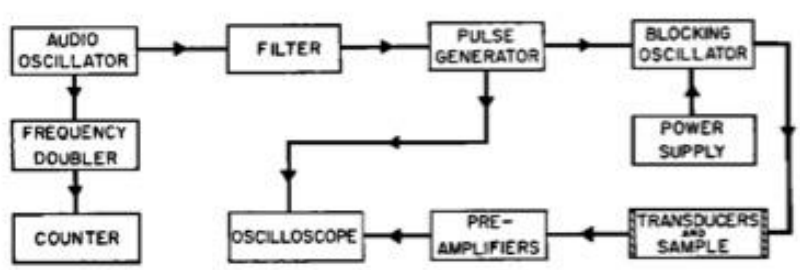

Figure 3- A block diagram of the instrumentation used by NOL for the electronic component of their double-crystal velocimeter (Wilson 1959, Figure 2)

An interpolation oscillator equipped with a fine frequency control was filtered electronically and used to control a pulse generator. The pulse from the generator was shaped by a component called a blocking oscillator, which would send a pulse to one crystal in the velocimeter. The second crystal would receive the pulse after it traversed the wave sample and would then feed it to the preamplifiers. The signal would then be displayed on an oscilloscope. The coincidences of the sound pulses in the velocimeter were adjusted by observing the signal displayed on the oscilloscope while varying the oscillator's frequency. The frequency would determine time required for the wave pulse to traverse the entire length of the velocimeter. The pulse repetition frequency would be doubled and displayed on a frequency counter that was accurate to within one part in 100,000 (Wilson 1959).

The following figure shows the general arrangement of the entire instrumentation used for controlling and monitoring the velocimeter:

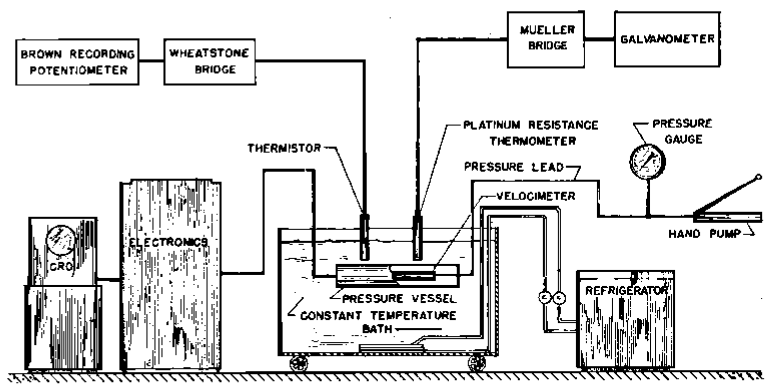

Figure 4- Diagram of the general arrangement of the instrumentation used by the Naval Ordnance Laboratory (Wilson 1959, Figure 3)

The pressure in which the velocimeter was contained was placed into a 110-gallon constant temperature bath which was regulated by a mercury thermometer. Three stirring pumps were used to circulate the water in the bath in order to ensure the constant, uniform temperature required for experimentation. The absolute temperature of the bath was measured by a platinum resistance thermometer to the nearest thousandth of a degree in Celsius. A thermistor was placed in the bath near the pressure vessel to measure temperature variations and temperature gradients. Although in Figure 4 a single meter is shown as the device used to measure pressure, a manganin resistance gauge, a sensitive Heise gauge, and a dead weight tester were used collectively to determine the absolute pressure. It was estimated by NOL that the absolute pressures measured by these three devices combined was known to approximately one part in 20,000 (Wilson 1959).

In order to measure the speeds of the sound waves, the scientists at NOL first adjusted the bath to a particular temperature, and then varied the pressure over the range they were testing. Since it was known that an adiabatic pressure increase in pressure of 2,000 psi would change the temperature inside the velocimeter by nearly a full degree Celsius, it was important for the scientists testing the system to wait until thermal equilibrium was reestablished before their measurements were made. The thermistor that was used to measure the temperature was outside of the pressure vessel and, as a result, was not sensitive to changes inside of the velocimeter. Therefore, the sound speed measurement itself for each trial was used to determine when thermal equilibrium was reached. Once thermal equilibrium had been reached, ten measurements of the pulse repetition frequency were recorded and averaged in order to give the time required by the sound pulse to traverse the entire length of the velocimeter, and thus the speed of the sound waves (Wilson 1959).

Table 1 shows the average results determined by the velocimeter's measurements for the speed of sound waves at various temperatures and pressures:

Pressure psia	Temperature °C										
	0.91°	2.77°	10.20°	19.66°	29.95°	39.42°	49.57°	59.59°	69.66°	78.70°	91.27°
14.7	1407.41	1416.35	1449.05[a]	1481.63	1509.37	1528.36	1542.60	1551.01	1555.02	1554.90	1549.80
2000	1429.25	1438.06	1471.46	1504.34	1532.67	1552.03	1567.11	1576.21	1581.13	1581.83	1578.03
4000	1451.66	1460.83	1494.17	1527.38	1555.87	1575.72	1591.22	1600.96	1606.58	1607.97	1605.31
6000	1475.37	1484.42	1517.28	1550.49	1579.04	1599.16	1614.92	1625.21	1631.44	1633.35	1631.75
8000	1499.72	1508.50	1540.99	1573.79	1602.12	1622.17	1638.22	1648.91	1655.69	1657.95	1657.36
10 000	1524.61	1533.29	1564.78	1596.90	1625.06	1645.14	1661.28	1672.30	1679.34	1682.13	1682.18
12 000	1549.93	1558.09	1588.75	1620.25	1647.88	1667.72	1684.00	1695.13	1702.55	1705.65	1706.39
14 000	1575.22	1583.15	1612.66	1643.41	1670.58	1690.41	1706.51	1717.68	1725.28	1728.69	1730.02

[a] It is believed that this point is in error by +0.6 m/sec.

Table 1- Measurements determined using the double-crystal velocimeter for the speed of sound in water at different pressures and temperature (Wilson 1959, Table 1)

In determining the measurements in Table 1, corrections were made by NOL for the change in the length of the velocimeter itself due to changes in pressure and temperature. Using the results from Table 1, NOL was able to determine an empirical equation that could be used to determine the speed of sound in distilled water:

$$C = a_0 + a_1T + a_2T^2 + a_3T^3 + a_4T^4 \dots \qquad (1)$$

The values of the a coefficients were calculated by summing coefficients notated by the letter b multiplied by various differing pressure values. The coefficients used can be seen in Table 2:

a_i	$(b_i)_{j=0}$	$(b_i)_{j=1}$	$(b_i)_{j=2}$	$(b_i)_{j=3}$
a_0	1402.859	1.050469×10^{-2}	1.633786×10^{-7}	-3.889257×10^{-12}
a_1	5.023859	6.138077×10^{-5}	-1.080177×10^{-8}	2.477679×10^{-13}
a_2	-5.690577×10^{-2}	-1.071154×10^{-6}	2.215786×10^{-10}	-5.088886×10^{-15}
a_3	2.884942×10^{-4}	1.582394×10^{-8}	-2.420956×10^{-12}	5.086237×10^{-17}
a_4	-8.238863×10^{-7}	-6.839540×10^{-11}	9.711687×10^{-15}	-1.845198×10^{-19}

Table 2- Coefficients in the sound velocity equations for distilled water (Wilson 1959, Table 2)

Once the coefficient values were known, NOL used an IBM computer to compute the sound speed from the empirical equations they determined. The resulting values for the speeds of the sound waves are shown in Table 3:

Pressure psia	Temperature °C										
	0.00°	10.00°	20.00°	30.00°	40.00°	50.00°	60.00°	70.00°	80.00°	90.00°	100.00°
14.7	1403.01	1447.85	1482.92	1509.66	1529.30	1542.88	1551.26	1555.06	1554.74	1550.54	1542.51
2000	1424.49	1470.03	1505.66	1532.92	1553.11	1567.34	1576.47	1581.14	1581.77	1578.58	1571.54
4000	1447.24	1492.88	1528.68	1556.21	1576.79	1591.51	1601.25	1606.65	1608.10	1605.80	1599.70
6000	1470.93	1516.15	1551.79	1579.37	1600.17	1615.26	1625.49	1631.47	1633.62	1632.10	1626.88
8000	1495.36	1539.76	1574.97	1602.41	1623.30	1638.63	1649.23	1655.68	1658.40	1657.57	1653.20
10 000	1520.36	1563.60	1598.17	1625.33	1646.19	1661.68	1672.54	1679.36	1682.54	1682.33	1678.78
12 000	1545.72	1587.60	1621.38	1648.15	1668.90	1684.44	1695.48	1702.56	1706.13	1706.47	1703.73
14 000	1571.28	1611.66	1644.56	1670.88	1691.44	1706.96	1718.10	1725.38	1729.26	1730.10	1728.17

[a] Velocity given in m/sec.

Table 3- Sound velocity in distilled water computed from the equation $C=a_0+a_1T+a_2T^2+a_3T^3+a_4T^4$… (Wilson 1959, Table 3)

The sound speeds shift toward higher temperatures at higher pressure, which makes sense and agrees with the calculations of sound speeds performed by numerous other scientists at other companies. NOL actually did test the speeds of sound waves in sea water and determined that pressure has essentially the same effect on the sound speed as for distilled water. However, this behavior is in contrast with that discovered by two other scientists, Kuwahara and Matthews, which show that at all temperatures, the graphs of sound velocity as a function of pressure are concave downward for all temperatures. Kuwahara and Matthews' work was based on an empirical equation developed by a scientist by the name of Ekman; however, Ekman's equation has been shown to provide less accurate results than desirable, as it is only accurate to one part in 500. A scientist by the name of Del Grosso has also called attention to the fact that there is a significant error in Ekman's pressure determinations used to derive his equation. The error results from the fact that he did not measure any pressure values himself, but instead computed them from a formula he made to agree with another scientist's work. Comparisons have been made showing that NOL's sound velocity determinations are remarkably accurate despite the complexity of their system for measuring the speed of sound. Due to the complexity of the velocimeter used by NOL, there are multiple potential sources of error (for which NOL did make corrections before determining their final results). Such errors include molecular scattering, reflections of the waves due to time delays, viscosities, pressure differentials due to the crystals not being able to be held perfectly still against the walls of the velocimeter, and heat conductions. Many of these sources of error turned out to be negligible, however, and, even with all of these sources of error present, NOL was able to determine the speed of sound waves accurately to within a maximum experimental error of 0.093 meters per second (Wilson 1959).

From researching these methods, I had concluded that the sound speed measurement system employed by NOL was the most effective due to the fact that it seemed to be the best at accounting for temperature and pressure effects and due to the accuracy of the results coming with the complexity and specificity of the apparatus. As previously mentioned, temperature was found to be the most impactful factor in determining sound speed. Therefore, the next research paper I wrote focused on different types of temperature measurement devices, with the goal of determining which provided the most accurate results. This was done by finding specific examples of each type of device I chose to investigate, these being thermistors, thermocouples, infrared thermal detectors, and fiber optic sensors. I figured that looking at a specific example for each device and looking into the factors affecting temperature measurement for each would provide me with general information about how each type of device worked and the effectiveness of each.

I first decided to investigate an example of a thermistor. In Robert A. Rasmussen's article "Application of Thermistors to Measurements in Moving Fluids", he describes some of the characteristics and parameters of thermistors and uses of them in moving fluid systems. The general heat transfer equation used to represent the significance of temperature on the behavior of a thermistor is: (Rasmussen 1962)

$$\frac{CdT}{dt} = P - K(T - T_x) \tag{2}$$

In the above equation, P is the power dissipated in the thermistor, which is directly measured, C is the heat capacity of the thermistor, dT/dt is the change in the temperature over time, K is termed the dissipation factor, T is the temperature measured at a particular time, and T_x is the temperature of the fluid surrounding the thermistor. The dissipation (K) itself can be calculated under steady state assumptions, and is itself temperature dependent (Rasmussen 1962):

$$K(v) = \left(\frac{P}{T_x}\right)[\left(\frac{\frac{a_x T_x}{lnR}}{R_x}\right) - 1] \quad (3)$$

In the above equation, the values for a_x are coefficients of resistance, and the values of R and R_x are resistances. The resistances themselves, as well as the coefficients of resistance, are dependent on temperature, further demonstrating the significance of temperature on the behavior of thermistors. A diagram of the apparatus described by Rasmussen can be seen in Figure 5:

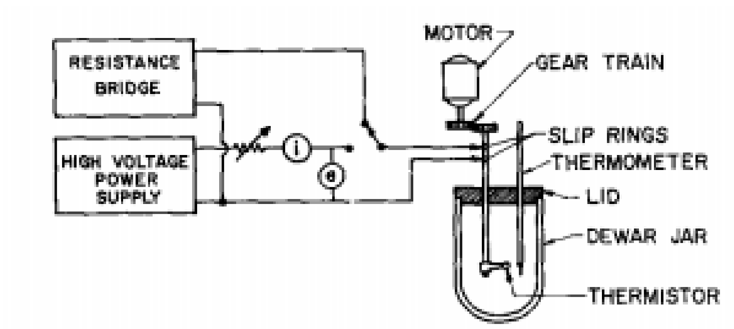

Figure 5 - Apparatus employed to determine the velocity dependence of the dissipation factor (Rasmussen 1962, Figure 1)

The apparatus functions in the following way: "A thermistor extends from the tip of a hollow glass rod which in turn extends perpendicularly from a 15 cm length of rigid plastic tubing having a diameter of approximately 0.5 cm. The plastic tubing passes vertically through a small hole in the cover of a Dewar bottle, its upper end being coupled to a gear train driven by a constant speed motor. Insulated leads from the thermistor traverse the tubing and terminate at a pair of slip rings mounted to its surface. Fluid temperatures are indicated on a mercury thermometer. With the fluid temperature constant, measurements of the thermistor voltage drop e and current i are made at various motor speeds corresponding to linear thermistor speeds of from 0 to 30 in./sec" (Rasmussen 1962). By measuring the voltage drop and current, information about the properties of the fluid around the thermistor are able to be determined, which include the speed of waves travelling through the fluid and against the thermistor. Then, in order to get the actual temperature measurements, various fluid speeds corresponding to particular voltages are measured, allowing the temperature coefficient, and thus, the temperature itself to be calculated. The accuracy of the apparatus and the information it provides can be decreased by a couple of things. For one, if there are any bubbles or material deposits on the thermistor, the heat transfer to the fluid is seriously affected, and will not be read to nearly as accurate a degree. Another would be that in order to make use of Equation 2, one has to make the assumption of steady state conditions, which is very unlikely to actually be the case during the process of operating the thermistor and taking measurements. Also, the thermistor used for the experiment was practically insensitive to speed variations greater than a few inches/second. Such hindrances to accuracy caused significant discrepancies in the temperature measurements compared to what was expected in the experiment discussed by Rasmussen.

The next type of device I chose to investigate an example of was a thermocouple. A common application of thermocouples is in measuring temperature during water cooling. A phenomenon called the Seebeck effect occurs due to the way that thermocouples are set up: “A TC (thermocouple) consists of two dissimilar metallic wires. The measuring junction is the point where the wires are connected to each other and attached or soldered to the surface of the specimen or the plate. The other ends of the wires are referred to as the reference junction. When the two junctions are at different temperatures, e.g., the measuring end is heated, an electromotive force (emf) is intrinsically developed and a continuous electric current will generate and flow in this thermoelectric circuit” (Xu & Gadala 2005). The equation shown below is for calculating the emf developed (Xu & Gadala 2005):

$$eAB = C\alpha * \Delta T \tag{4}$$

The Seebeck voltage produced by the thermocouple depends primarily on two factors: the difference in temperature (ΔT) between the two junctions and the Seebeck coefficient, $C\alpha$. For the purposes of the study conducted by Xu and Gadala for their article “Investigation of Error Sources in Temperature Measurement Using Thermocouples in Water Impingement Cooling”, it was assumed that the Seebeck coefficient was not changing since it is a material constant, meaning the only thing that would practically affect the emf would be the change in temperature. The apparatus used by Xu and Gadala included a separation junction, which is different from a normal thermocouple in the sense that the wires attached to the surface of the specimen are not soldered to each other but have a slight bit of separation between them. A schematic of Xu and Gadala’s apparatus can be seen in Figure 6:

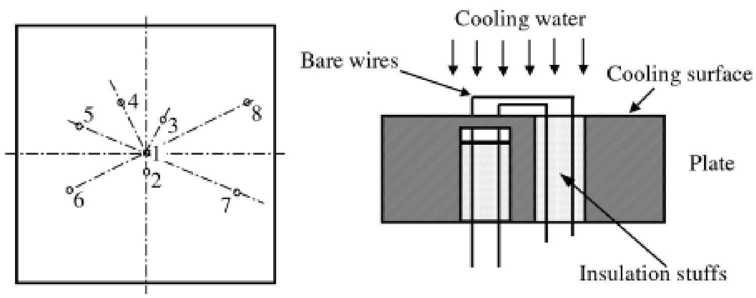

Figure 6 - Schematic installation of TC's used by Xu & Gadala (Xu & Gadala 2005, Figure 3)

The apparatus generates a continuous electric current when the junctions are at different temperatures, and then uses Equation 4 to calculate the difference in the temperature between the two junctions using Equation 4 and the emf generated and measured. From the temperature difference calculated, the actual temperature of the water that needs to be measured can be determined. The possible sources of error present in Xu and Gadala's experiment are the fact that latent heat was not considered in their calculations, the fact that the installation of the thermocouples on the specimen it attaches to will usually cause a deformation of the original temperature field, the fact that steady state is assumed in order to use the equations necessary for the temperature measurement, and the fact that thermal properties of the wire roots were not addressed. Such sources of error were observed in Xu and Gadala's experiments, as they noticed a few significant discrepancies between their calculated and measured temperatures. For example, the combination of the surface temperature recorded being disturbed and changed mid-measurement and the measuring junction not being isothermal leads to a measurement of the temperature that is around 60 degrees Celsius lower than it actually should be, a fairly significant degree of inaccuracy that could carry through to result in a large inaccuracy in a resulting calculation of sound speed.

Another type of device I gathered information on was a thermopile infrared detector. In the article "A Batch-Fabricated Silicon Thermopile Infrared Detector" by G.R. Lahiji and Kensall D. Wise, the two authors describe how thermal detectors function using the device in Figure 7 as an example:

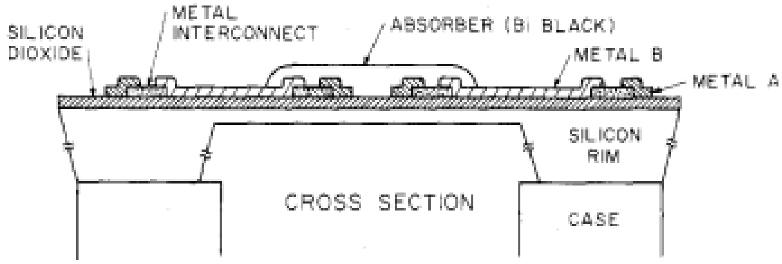

Figure 7 – A monolithic silicon thermopile detector fabricated using integrated circuit technology (Lahiji & Wise 1982, Figure 1)

"In thermal detectors, the radiation is absorbed by the material, generating photons and causing heating of the lattice. This change in the lattice temperature is then converted into a change in the electrical properties of the structure" (Lahiji & Wise 1982). The structure being referred to is essentially a collection of thermocouples arranged in a series and supported by thin silicon membranes. However, due to the fact that the silicon-membrane is a good electrical conductor, there has to be further insulation separating the thermocouple series and the silicon film. Typically, a layer of silicon dioxide (SiO_2), silicon nitride (Si_3N_4), or a combination of the two materials is used as the separating dielectric. Essentially, to get the temperature measurements, an infrared thermal detector measures a change in voltage similarly to how a normal thermocouple does. The change in the electrical properties of the structure measured and the change in temperature can be related by the following equation (Lahiji & Wise 1982):

$$V = N\alpha\Delta T \quad (5)$$

In Equation 5, α is the Seebeck coefficient of the two metals, N is the number of thermocouples in the structure used for the measurement, V is the voltage developed across the thermopile, and ΔT is the temperature difference between the hot and cold junctions of the thermopile. There are numerous advantages to the use of thermal detectors, such as them being easy to operate, having low cost, and not being very sensitive to ambient temperature (the last benefit being a result of the layers of silicon membranes). There are numerous limitations to using a thermal detector as well. It is important that the dielectric layer be low in stress in order to prevent it from deforming while the device is used. Also, the metals used to compile the thermocouples must be compatible with the processing equipment used to measure the temperature difference across the thermopile. If the silicon layers deform or the metals are not compatible with the measuring equipment, the temperature values measured could be highly inaccurate.

The last category of device I researched that has been used to measure temperature changes in hydrological process is a Fiber Brigg Grating. Although a Fiber Brigg Grating is only really valuable for some highly specific applications, it is still a good example to illustrate the overall qualities, positives, and negatives of using a fiber-optic sensor. An image of a general fiber-optic sensor can be seen below:

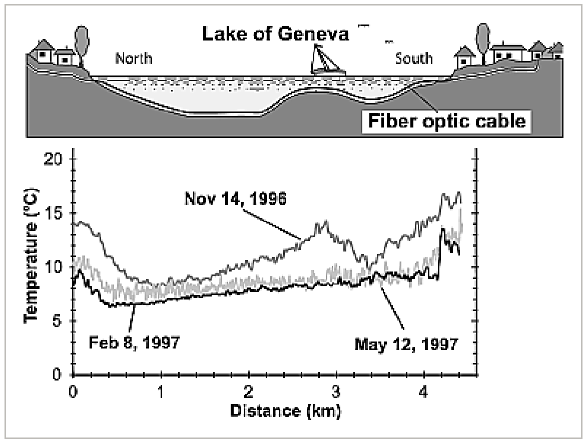

Figure 8 – Temperature transects taken between France (south) and Switzerland (north) using existing communication fibers under Lake Geneva (Selker et. al 2006, Figure 2)

The fiber-optic sensor above identifies a shift in wavelength of scattered light in order to make its measurement. Although a fiber Brigg grating does not identify the shifts in scattered light wavelengths to make its measurements, it functions in a similar way to the fiber optic in Figure 8: "A fiber Bragg grating (often abbreviated as FBG) is a very short (of the order of microns) section of optical fiber on which the outer refractive index barrier has been etched with an optical grating (i.e., a very closely spaced set of 'scratches' on the surface of the fiber) that will filter a very tightly constrained frequency of light, with wavelength specificity of on the order of one nanometer. The 'reading' of each grating consists of measuring the precise frequency of the adsorption band of the grating. If a spectrum of light is transmitted along this fiber, each grating will adsorb light at a very specific range of wavelengths proportional to the spacing of the etching. Since the frequency response of the gratings is a function of the spacing of the lines of the grating, any process that changes this spacing can be monitored. Most prominently, the line spacing may change when the fiber expands and contracts with changes in temperature and mechanical stress on the fiber. As many as 100 such gratings may be distributed along a fiber, with the adsorption peak of each grating identified using a frequency-scanning laser. Each grating acts as a point of measurement. The gratings may be spaced as closely as 0.1 mm, or as widely as allowed by cable attenuation (on the order of 10 km). Using time domain information, it is possible to isolate a series of gratings along a fiber, thus extending the possible number of gratings that can be read, but also increasing the complexity of the measurement instrument" (Selker et. al 2006). A fiber Bragg grating has a significant tradeoff, in that the more gratings that are being read, the greater the accuracy of the temperature reading allowable, but the more complex it is to actually be able to get the reading, introducing more possible sources of error into the measurement. The precision of the measurements can be affected by factors such as how much background noise is being picked up as compared to the actual signal, measurement drift, and cross-sensitivities (Selker et. al 2006). However, even with such factors present, the current technology of such a device allows for measurements of changes in temperature with a precision of 0.1 degrees Celsius. The process of etching out the grating is very technically demanding, so this method of temperature measurement is currently quite expensive. There are other similar methods that are not quite as expensive as fiber Bragg gratings, but they need to take the time of travel into account for the frequencies they measure, which further complicates the measurements and may lead to less accuracy.

From my research of these temperature measurement systems, I had determined that the most effective type of device was a fiber optic device, since the example of one that I researched was able to determine the temperature to a much higher degree of accuracy than any of the other devices researched. Even though I only looked into one specific example for each kind of device, the general information about how each type of device works that I discovered still draws me to the same conclusion.

<u>Discussion/Results</u>

One of the biggest realizations from researching the sound speed measurement systems was that, somewhat surprisingly, none of them seemed to account for salinity. Therefore, I determined that one area where significant improvement was possible was in accounting for salinities in sound speed measurements. The following equation is an approximate equation that has been widely accepted to be an accurate approximation of sound speed measurements and incorporates salinity:

$$c(T,S,P) = 1449.08 + 4.57Te^{-\left[\frac{T}{86.9}+\left(\frac{T}{360}\right)^2\right]} + 1.33(S-35)e^{-T/120} + 0.1522Pe^{\left[\frac{T}{1200}+\frac{S-35}{400}\right]} + 1.46\ x\ 10^{-5}P^2e^{-\left[\frac{T}{20}+\frac{S-35}{10}\right]} \quad (6)$$

In Equation 6, c is the speed of sound in m/s, T is the temperature in degrees Celsius, S is the salinity in parts per thousand (ppt), and P is the gauge pressure in atmospheres (Kinsler et. al 2000). The equation demonstrates that, while its effect on sound speed is not as significant as temperature, salinity still has an impact on sound speed worth considering. Therefore, further research into existing salinity-measuring devices was done.

Kenneth Mackenzie, in his article “Discussion of sea water sound-speed determinations”, sought to conduct an experiment to compare previous scientists’ (Wilson and Del Grosso) sound speed measurement equations. To do so, he performed his own experiments using deep submergence vehicles to simultaneously measure pressure, temperature, salinity, and ultimately sound speed. The measurement equipment was mounted onto a DEEPSTAR-4000 (meaning it has a maximum certified depth of 4000 ft), which can be seen in Figure 9:

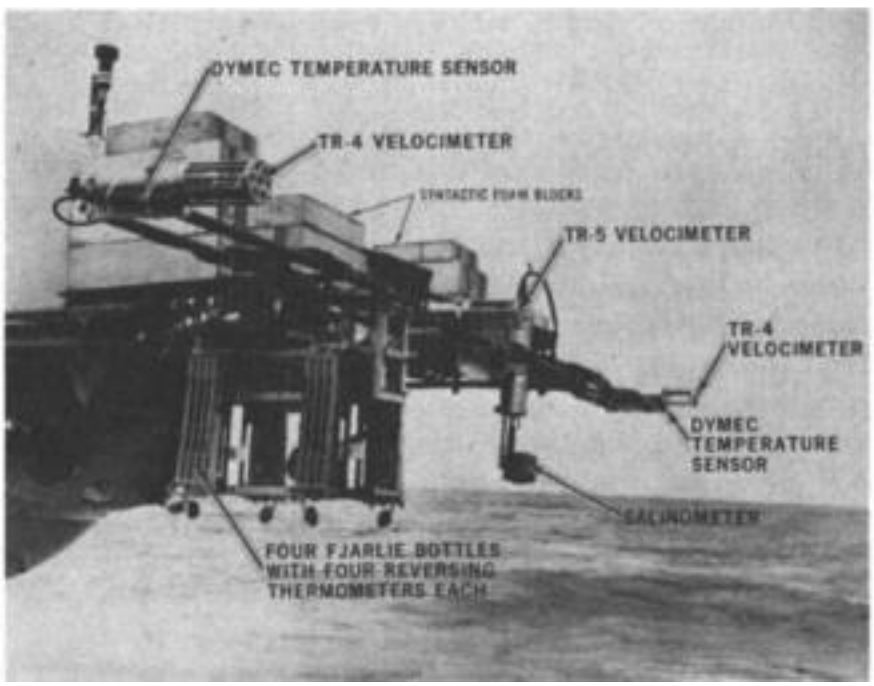

Figure 9 – System used by Mackenzie to collect seawater measurement data (Mackenzie 1981, Figure 3)

Mackenzie described the temperature measuring systems as such: “The two Hewlett-Packard Dymec quartz temperature sensors consisted of two quartz crystal-controlled oscillators operating nominally at 28.2 MHz. A special (LC) cut was used with one crystal to gain a highly linear change of frequency with temperature of about 1000 Hz/°C. The other crystal was temperature insensitive (AT cut). Both crystals were mounted in a $\frac{1}{2}$ -in-diam aluminum can filled with helium for heat transfer. Output frequencies from the two oscillators were heterodyned to provide zero frequency output at 0 °C for one Dymec sensor and -2 °C for the other. Accuracies of 0.004 °C could be realized. Calibrations were conducted with the 1968 ITPS (International Temperature Practical Scale), converted to 1948 ITPS before computing Wilson or Del Grosso sound speeds. Standard reversing thermometers (calibrated with 1948 ITPS) were always utilized for backup" (Mackenzie 1981). The salinity measurement system was described: "Salinities, measured via a Hytec Salinometer Model 6009, were determined by conductivity with a sea water coupled induction coil, and internally compensated for temperature and pressure to yield an output frequency proportional to salinity. Temperature was sensed by a platinum-wire thermometer, and pressure by a strain gauge--both an integral part of the salinometer unit. The salinometer calibration drifted somewhat between dives. Because salinity changed less than 1%/∞ between the surface and the sea floor at 1200 m, the assumption was that the salinometer would afford accurate values throughout the water column, if field-calibrated while suspended near the surface and at the bottom. Output frequencies were counted directly at these equilibrium positions and Fjarlie bottles trapped water samples. Later, salinities were ascertained in the laboratory with a conductivity method, and a simple least-squares fit produced the calibration of the day for each dive" (Mackenzie 1981). The pressure-measuring system was described: "Depth, the most taken-for-granted variable, was subject to uncertainty because stable sensors for pressure measurements accurate to better than 1 part in 1000 were not available. Two Vibrotron pressure transducers (mounted aft of the DEEPSTAR brow) converted pressure to frequency by means of a taut vibrating wire attached to a pressure diaphragm. Despite shortcomings, temperature-compensated Vibrotrons proved more reliable than other methods. Output frequencies ranged from 9000 to 11000 Hz. Vibrotrons with associated oscillators were calibrated at 0° and 20 °C with a deadweight tester for both increasing and decreasing pressures (ocean pressure gradients vary from 1.00 to 1.03 MPa per 100 m). Differences between corrected readings of protected and unprotected reversing thermometers enabled depth to be computed and compared with Vibrotron data, which sometimes differed by 3 m at 1000-m depths. Because of weight constraints an upward-looking sonar, limited to moderate acoustic power, received surface echoes eventually masked by self-noise as depth increased. An upward-looking 23-kHz EDO echo sounder aboard DEEPSTAR-4000 failed to see the surface for depths greater than 800 m during any of the author's dives." (Mackenzie 1981). The overall measurement system used by

Mackenzie contained many separate devices all attached to a larger component, all of which took separate measurements with the most accurate devices Mackenzie had available. The DEEPSTAR-4000 was suspended 6-9 meters below the surface of the water and given 20 minutes to reach equilibrium before any dives were commenced to get measurements. This method of sound speed measurement seems to be quite an effective one, as it could allow for an individual component of the system to be exchanged for a more accurate one if desired. It is also worth mentioning that the salinometer used by Mackenzie did internally compensate for temperature and pressure, meaning that a salinometer, with all of the components making it up, can account for all three measurements in one system.

Mackenzie is not the only scientist found to have been investigating the accuracy of sound speed equations used by various scientists. J. T. Allen, P. W. Keen, J. Gardiner, M. Quartley, and C. Quartley describe the advancements of salinity measurement in sound speed determination and the need for updated equations in their paper "A New Salinity Equation for Sound Speed Instruments": "Recently, there have been significant advances in marine sound speed measurement, clear examples being the commercially available instruments by Valeport Ltd (UK), achieving accuracies better than 0.02 ms^{-1} at sampling rates up to 200 Hz. Such advances in production instruments promises the potential for routine sound speed derivation of salinity and density to around 0.01 psu or kg m^{-3} respectively. Furthermore accuracies far in excess of this, possibly to 0.003 ms^{-1} seem to be an expected target within the next 5–10 yr" (Allen et. al 2017). The previous convention was to derive the seawater's salinity from conductivity measurements (or inductance measurements for some sensors), which are only affected by dissolved ionic solutes present in water. Salinity is, however, defined as the total mass fraction of all dissolved matter in seawater, meaning the conductivity measurements previously employed were an imperfect approximation. This approximation worked when it was still considered that the ratio of dissolved components in seawater was constant everywhere in the sea, but new equations of state for seawater have demonstrated that the ratio of dissolved components in seawater is not constant across the sea, which would affect salinity measurements to the 10^{-2} level or more depending on the body of water. As many scientists continue to seek to test the accuracies of sound speed equations, new discoveries are made as to which will seemingly provide the results with the highest order of accuracy.

"Fundamentals of Acoustics" covered more factors than just the equation generally used to account for salinity in sound speed measurement. One such factor was the refraction of sound waves dependent on differences in temperature, salinity, and pressure throughout the sea: "The most important phenomenon that alters the spherical spreading of sound in the ocean is the refraction that results from spatial variations in the sound speed induced by inhomogeneities in temperature, salinity, and pressure. Variations in salinity are important in regions where waters of differing salinities meet and near the surface where rain and evaporation have maximum effects. Variations in the speed of sound with depth are quite small. The change in pressure over a depth of 100 m (about 10 atm) increases the sound speed by 1.6 m/s, only about 0.1%. By contrast, variations in speed resulting from changes in temperature are quite large and are subject to large fluctuations, especially near the surface. Differences of more than 5°C are common in the first 100 m of the ocean. For temperatures near 15°C, a rise of 5°C increases the speed of sound by 16 m/s, about 1%." (Kinsler et. al 2000). The depth affects all three of the main factors which in turn have varying effects on the sound speed, and when taking measurements, scientists have to be aware of how to account for these differences that present themselves depending on where in the sea measurements are being taken: "Given the dependences of temperature, salinity, and pressure on depth, the variation of c with depth can be calculated from (Equation 6); alternately, the speed of sound can be measured directly as a function of position. Figure (10) gives a representative speed of sound profile for the deep ocean. The most pervasive feature, found at all except the highest latitudes, is a distinct minimum. In the tropics, because of the heat provided by the sun, this minimum tends to lie deep. It rises toward the surface in the higher latitudes, sometimes reaching the surface in polar oceans. The depth at which this minimum occurs is called the deep sound-channel axis. Below this axis, the speed of sound increases until at great depths we find the deep isothermal layer, where the temperature remains a constant, between -1°C and 4°C, for most ocean basins. In this region the sound profile is nearly linear with a nominal positive gradient of about 0.016 (m/s)/m = 0.016 s^{-1}. Above the deep sound-channel axis is the main thermocline. This region possesses negative gradients and responds slightly to seasonal changes but is a relatively stable feature of the profile, with characteristics determined primarily by latitude. Above this is the seasonal thermocline, also negative, which is responsive to seasonal variations. And finally, above this is the surface layer. This layer is quite dependent on the day-to-day, even hour-to-hour, variations in air and surface conditions. If there is sufficient surface-wave activity to mix the water near the surface, this becomes a mixed layer, which is isothermal and has a positive gradient of sound speed about 0.015 s^{-1}." (Kinsler et. al 2000). Figure 10 shows an example sound speed profile for midlatitude ocean water and how sound speeds vary with depth:

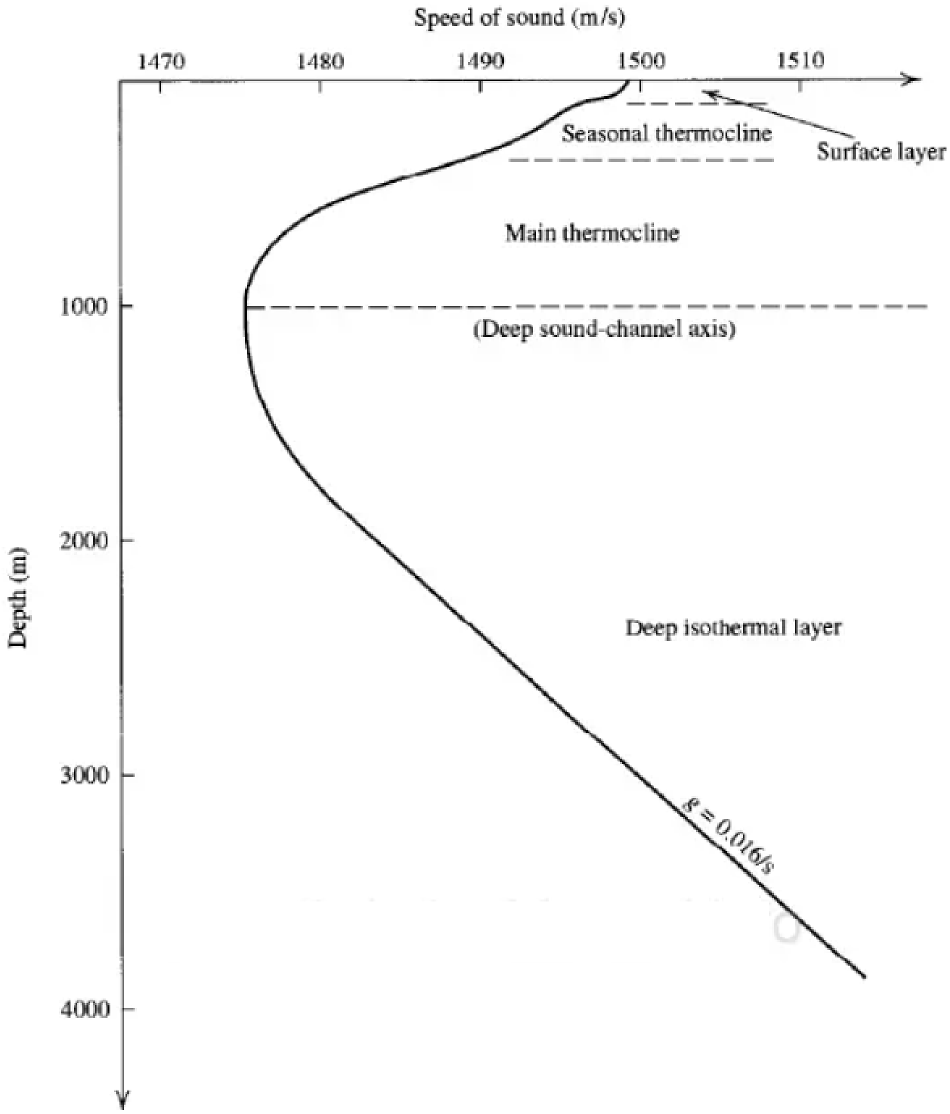

Figure 10 - Representative sound-speed profile for midlatitude deep-ocean water (Kinsler et. al 2000, Figure 15.4.1)

"The actual variations in c are very small compared with its magnitude. The profile of Figure (10) has a maximum variation of about 30 m/s, about 2% of the nominal value" (Kinsler et. al 2000). If sound speed were to be measured as a direct function of position, the variation in properties of each layer has a large impact on the propagation of sound in the ocean. The ray path through a medium in which sound speed varies with depth can be calculated by applying Snell's law:

$$\frac{c}{cos\theta} = c_0 \tag{7}$$

In Equation 7, θ is the angle of depression the ray makes with the horizontal at a depth where the speed of sound is c, and c_0 is the speed at a depth where the ray would become horizontal (or where $\theta_0 = 0°$). Complicated profiles like the one in Figure 10 are often separated into thin layers for the sake of simplification. Each layer is assumed to have a constant sound speed gradient. The advantage of this is that the path of a sound ray through a layer of water with a constant sound-speed gradient is an arc with a center lying at a baseline depth where the sound speed in that layer extrapolates to zero. Once the baseline depth is determined through extrapolation of the isogradient profile in a layer, the ray path can be computed or graphically traced from it. Equations 8 and 9 show the calculations that can be used to determine the changes in range and depth due to refraction of the sound rays:

$$\Delta r = R(sin\theta_1 - sin\theta_2) \tag{8}$$

$$\Delta z = R(cos\theta_2 - cos\theta_1) \tag{9}$$

Essentially there are two ways to account for the inhomogeneities present in ocean water. Using Equation 6 to account for all of the factors is one way. Scientists also tend to divide up the ocean into thin layers based on the sound speed profile shown in Figure 10 and use the qualities of the layer where measurements are taken to measure the sound speed as a function of position, with the refractions of the sound rays as reference. Ultimately, I believe the better method of determining sound speed is to use Equation 6, as regardless of what factors remain constant in a particular layer, Equation 6 will use the reading for it in the sound speed calculation; however, it is still important to be aware of the inhomogeneities present in sea water when it comes to what layer you might be taking measurements in and how temperature, salinity, and pressure are affected by the depth and prescribed qualities of that layer.

In underwater acoustics, it is of critical importance that sonar still be able to detect an acoustic signal in the presence of noise. The performance of sonar can be increased if the detected noise level were to be reduced (Kinsler et. al 2000). This conclusion can be drawn by examining the sonar equation:

$$EL \geq DNL + DT \tag{10}$$

In Equation 10, EL is the echo level, or the level of the signal the system is attempting to detect, DNL is the detected noise level, and DT is the detection threshold, or the value by which the echo level must exceed the detected noise level to give a 50% probability of detection for a specified probability of false alarm. By using knowledge of the frequency spectra of the ambient noise and the target, the bandwidth of the receiving system can be selected in order to effectively reduce the detected noise level. It is essential to consider the Doppler effect, in which sound wave frequencies change relative to an observer. Since the result is that a different frequency will be picked up than the one that originated from the target, the Doppler shift must be accounted for in acoustic receivers: "Assume a source frequency f is traveling with speed v in the water directly toward a receiver, and the receiver is traveling with a speed u in the water toward the source. In a time interval τ the source will send f_τ cycles into the water, and these will fill a distance $(c - v)\tau$ in the direction pointing toward the receiver. The wavelength λ_w of this sound in the water is $(c - v)/f$". (Kinsler et. al 2000) The frequency that would be detected by a stationary observer in the water is found using Equation 11, or Equation 12 after substituting in the formula for λ_w:

$$f_w = c/\lambda_w \tag{11}$$

$$f_w = fc/(c - v) \tag{12}$$

"In the same time interval τ, the receiver intercepts the number of wavelengths $(c + u)\tau/\lambda_w$. This number divided by τ is the number of cycles per second received" (Kinsler et. al 2000). The frequency f' sensed by the receiver can be represented by Equation 13, and substituting in λ_w results in Equation 14, the Doppler shift equation:

$$f' = (c + u)/\lambda_w \tag{13}$$

$$f' = f(c + u)/(c - v) \tag{14}$$

The Doppler shift can be represented by the following equations for both passive (Equation 15) and active (Equation 16) sonar:

$$\Delta f = f_2 - f_1 = \left(\frac{\dot{R}}{c}\right) f_1 \tag{15}$$

$$\Delta f_1 = f'_1 - f_1 = \left(\frac{2\dot{R}}{c}\right) f_1 \tag{16}$$

In Equation 15, Δf is the doppler shift for the passive case, f_1 is the frequency radiated by one of two vessels moving in different directions and with different velocities f_2 is the frequency detected by the second vessel, and $\dot{R} = -dR/dt$ is the range rate, or the speed at which the two vessels are closing range. In Equation 16, f'_1 is the echo vessel 1 receives back from the sonar pulse vessel 2 would reflect back at it, and Δf_1 is the Doppler shift between the received echo and generated sonar pulse f_1. The bandwidth of the receiver must be tuned to account for the Doppler shift: "In passive sonar, the Doppler shift of the frequency of the received signal from that of the source places a lower limit on the bandwidth of the receiver. Given the maximum expected range rate to be encountered, and if both approaching and receding targets are to be detected the bandwidth must be twice the associated Doppler shift" (Kinsler et. al 2000). A passive sonar receiver must have a total bandwidth as shown in Equation 17:

$$w_p = 1.33\dot{R}F \tag{17}$$

In Equation 17, w_p is in Hz, $\dot{R}$ is in m/s, and F is in kHz. By comparing Equations 12 and 13 for the passive and active sonar cases, it can be seen that the active case which has to account for the Doppler targets in both directions and have a total bandwidth w_a twice that of the active case as shown by Equation 18:

$$w_a = 2.67\dot{R}F \tag{18}$$

In Equation 18, w_a is in Hz, $\dot{R}$ is in m/s, and F is in kHz. It is crucial to ensure that sonar systems are tuned to the appropriate bandwidths given the expected target frequencies, so that the Doppler shift does not put the target frequencies out of the range of the sonar's detection capabilities.

Self-noise is another issue to be aware of when designing a sound speed measurement system. It is generated by the device itself and can either travel through the structure of the device or be reflected off the sea surface. Generally, as the speed the device is travelling increases, so too does the self-noise. The noise of the machinery dominates at lower speeds and frequencies, but propeller noise (on a submarine, for example) and flow noise tend to dominate at high frequencies, or at all frequencies when speed is increased past a certain point. At low speeds, self-noise tends to be less important than ambient noise (Kinsler et. al 2000). In order to prevent self-noise interference, there is a sort of tradeoff between speed and what type of self-noise is likely to be experienced: "Self-noise is entered into the sonar equations as an equivalent isotropic noise spectrum level that expresses the masking level of the self-noise in the bandwidth of the receiver in terms of the level of an equivalent amount of ambient noise" (Kinsler et. al 2000). Essentially, self-noise must be factored into the total detected noise level experienced by the acoustic receiver in order to ensure the system will be able to pick up the desired target signal.

Conclusions

With all of the conclusions from my previous research papers and the new information researched in mind, I believe that there are several ways to improve existing sound speed measurement systems. Firstly, adding a salinity-measuring component to the sound speed measurement systems presented that did not account for them, as Mackenzie did, is crucial in improving the accuracy of sound speed measurements, as treating sea water like fresh water as was common to do previously does not allow for measurements with enough accuracy as is desired in newer systems, as stated in “A new salinity equation for sound speed instruments”. Given that in Mackenzie’s system, temperature and pressure were accounted for internally in the salinity measuring device, one option could be to have an overall system that is essentially an expendable bathythermograph, which is itself a salinity measuring device, and implement more accurate methods of temperature and pressure measurements in series within the device itself. As suggested in my previous temperature measurement device research, a temperature measurement device which combines fiber optic sensors with thermopiles could be an effective solution. Inside the XBT salinometer, there could be a series of fiber optic gratings along a cable insulated with silicon membranes much in the same way as the thermocouples inside a thermopile. The temperature would still be able to be measured through detection of wave frequencies by the fiber optic gratings, providing the ability to use the temperature measurement device capable of the highest accuracy while the silicon membrane insulation mitigates ambient temperature disturbances, combining the positives of both systems. Alternatively, a single system which has a salinity measuring component, a temperature measuring component, and a pressure measuring component all separate from each other that all are submerged to roughly the same depth could be an effective choice. This provides the benefit of each individual measurement device being able to focus on providing one of the desired measurements as accurately as possible through specialization. The idea of fiber optic gratings implemented onto a thermopile could still be implemented, and probably more easily modified in accordance with future technological improvements. While a fiber optic temperature sensor would likely be quite expensive to integrate into a sonar system compared to some of the other temperature measurement devices, it is ultimately the most accurate device provided it is able to be correctly implemented.

The velocimeters were able to get sound speed measurements with a greater degree of accuracy than the XBTs, so if you were to implement parts of the complex electronics systems of the NOL velocimeter into one of the widely used XBT's, its performance should be able to increase. In order to do this, components of the NOL velocimeter's electronics could be integrated into the terminal which the XBT connects back to, so as to increase the processing capabilities of the computers used to perform the sound speed calculations. Along the same line as improving the electronics of a system, another way to improve any chosen system is to program in the most accurate equations which account for the most factors and have been tested to provide the most accurate results by scientists. By using equations which account for salinity in the first place and running the measurements gathered for temperature, pressure, and salinity through the most accurate equations, the results will be the most accurate possible. As further developments are made in the equations used to measure salinity, the systems can be updated accordingly to improve their accuracies, provided the cost of doing so would not outweigh the benefits of the accuracy improvement.

Modification of the bandwidth an acoustic receiver is tuned to in order to account for the effects of Doppler shift is yet another way to increase the performance of the system by ensuring it will not be unable to pick up certain desired targets. Perhaps tuning the bandwidths of sonar systems to slightly more than necessary on either side of the computed lower and upper limits could be useful in order to account for any errors from rounding off or slight miscalculations, essentially serving as a margin of error for the system. Adjusting for self-noise by carefully controlling the speed at which the system travels relative to its target in accordance with what types of self-noise tend to dominate the system could help mitigate the detected noise levels and increase the chances that the echo level would greatly exceed them, allowing the system to pick up signals with more certainty. Generally, it would be beneficial to have the system travelling at lower speeds, but there is a balance to the required speed and the type of self-noise experienced that has to be evaluated. Building the system out of materials that tend to produce less self-noise in the form of machinery noise is another way to heighten the chance of the echo level greatly exceeded the detected noise level and detection threshold, especially if the system is modified to move at lower speeds.

Overall, new research involving equations of higher orders of accuracy and testing of new measurement equipment is constantly happening, further increasing the accuracy with which sound speeds can be determined. As technologies such as undersea explosives and other threats continue to evolve, so too must the sound speed measurement technologies used by sonar to detect and combat them, making the improvements of these devices a critical and valuable field of research which always has further to go.

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