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Underwater communication acoustic transducers: a technology review

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ABSTRACT

This paper provides a comprehensive review on transducer technologies for underwater communications. The popularly used communication transducers, such as piezoelectric acoustic transducers, electromagnetic acoustic transducers, and acousto-optic devices are reviewed in detail. The reasons that common air communication technologies are invalid die to the differences between the media of air and water are addresses. Because of the abilities to overcome challenges the complexity of marine environments, piezoelectric acoustic transducers are playing the major underwater communication roles for science, surveillance, and Naval missions. The configuration and material properties of piezoelectric transducers effects on signal output power, beamwidth, amplitude, and other properties are discussed. The methods of code and decode communication information signals into acoustic waves are also presented. Finally, several newly developed piezoelectric transducers are recommended for future studies.

Keywords: underwater communication, acoustic transducers, acousto-optic devices, piezoelectric transducers, information signal, and code and decode.

1. INTRODUCTION

The vast oceans of planet Earth remain mostly unexplored, with scientists estimating only 5% of the oceans have been explored by humans [1]. As such, developing capabilities to communicate in an underwater environment is crucial to opening this unexplored territory. The age of information and technology requires innovative solutions to account for numerous factors, both environmental and synthetic. Communicating in marine environments adds additional complexity to signal transference given the medium through which the signals travel [2-9]. Specialized solutions built and dedicated for naval environments are required for a variety of purposes including small fishing vessels communicating with the coast guard and cruise ships or shipping vessels relaying location information [10-12]. Underwater communication is even more specialized and applies almost entirely to submersibles or submarines, which are used typically for science or surveillance. Several solutions exist to date [10-30]. Piezoelectric transducers, acoustic transducers, and acousto-optic devices have all been considered as technologies that may fill this gap [10-30]. Each type of device is capable of transferring a signal through air and can be modified to send a signal through water. A review of these technologies, how they operate and how they may be applied has been performed to identify the advantages and disadvantages of each option [10-30]. The various device components each lend different qualities of control to the system, thereby further determining the appropriateness of certain devices for this specific use. Piezoelectric transducers are found to be the most versatile, however a true solution may be to combine the various components of each device to produce more desirable results and control the output signal to a more precise degree [10-30].

On the other hand, the U.S. Navy uses hundreds of thousands of various sonar/transducers for warships, submarines and other specialized purposes, as illustrated in Figure 1 [31, 32]. Active arrays for medium range detection usually have a bandwidth of about one octave and operate in the 2–10 kHz region, those for shorter range applications, such as mine or torpedo detection, use frequencies up to 100 kHz, while high resolution applications may go up to 1.5 MHz [33, 34]. Passive naval arrays containing hundreds of hydrophones are designed in many configurations, from those that conform to the ship's hull to line arrays that are towed far astern. Other naval applications include acoustic mines activated by the voltage from a hydrophone sensitive to the low frequency sound radiated by a moving ship. Special projectors and hydrophones are required for acoustic communication between submerged submarines or from a surface ship to a submarine. Sonobuoys are expendable hydrophone/radio transmitter combinations dropped into the water from an aircraft. The radio floats on the surface, with the tethered hydrophone at a suitable depth for detecting submarines. Some types of sonobuoys listen passively, while others echo range; however, both types radio information back to the aircraft.

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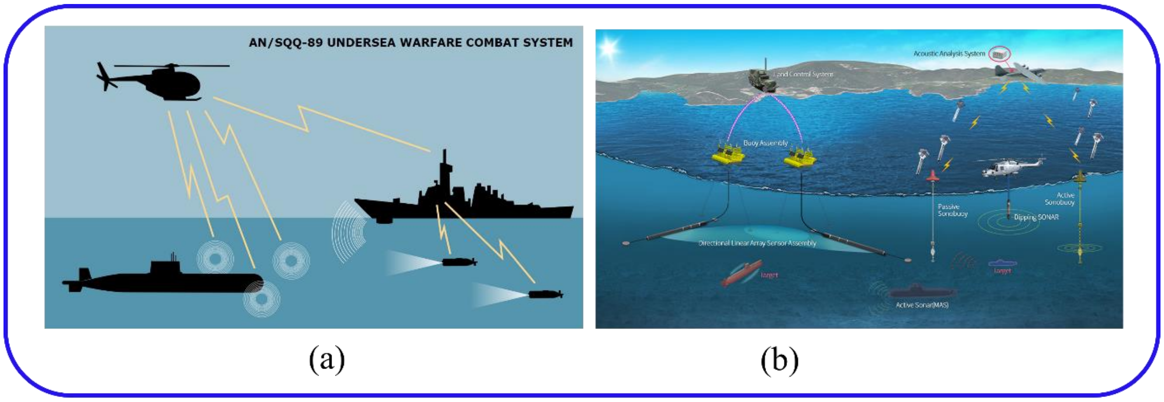

Figure 1. Examples of acoustic transducers for Navy applications. (a) The U.S. Navy's Undersea Warfare Combat System Is Getting an Upgrade [31]. (b) Sonar Systems [32].

The useful spectrum of underwater sound extends from about 1 Hz to over 1 MHz with most applications in large (but sometimes shallow) bodies of water [33]. For example, acoustic communication over thousands of kilometers is possible in the oceans, but frequencies below about 100 Hz are required because the absorption of sound increases rapidly as the frequency increases [35]. On the other hand, depth sounding in water as shallow as 1 m is important for small boats, but it requires short pulses of sound at a few hundred kHz to separate the echo from the transmission. High resolution, short-range active sonar has used frequencies up to 1.5 MHz Applications over this wide frequency range require many different transducer designs.

This paper is divided into four sections. The first section will discuss the electromagnetic and acoustic waves, defining the electromagnetic wave propagation equation and acoustic wave propagation. The second section will cover methods of coding and decoding information, various techniques that are used, their advantages and disadvantages, and how these modulation techniques for communication encoding may behave in an underwater environment. The third section will describe the three types of technologies: piezoelectric acoustic transducers, electromagnetic acoustic transducers, and acousto-optic devices, the how these technologies operate and various advantages and disadvantages. The fourth and final section will provide recommendations to which technology might be the most effective and briefly discuss recommended systems for future study.

2. COMMUNICATING UNDERWATER

Communication through air waves is a field of study that is saturated with various technologies and advancements; from radio communication to satellite communications, infrared sensing and sending coded streams of data to counterparts. The technology for communication is available and viable. Communicating through water, however, introduces many new factors that do not necessarily impact devices above the surface of the water. These factors include the increased viscosity, heat capacity, conductivity, hydrostatic pressure, mass density, and salinity [2-9]. As a result of these various contributors, waves underwater scatter and reflect in ways that may not be easily modeled and controlled [2-9].

2.1 Wave dynamics and propagation

To build a mathematical model of an electromagnetic wave in an underwater environment, the first step is to understand Maxwell's equations in a vacuum. A vacuum environment allows for the neglecting of the medium, regardless of the medium. This includes such environmental factors as ground clutter, weather, or various other barriers.

The following equations make up the fundamental equations of electromagnetism, taking into account the principles derived for electrostatics, magnetostatics, and induction. [2] These equations describe the relationship between the electric and magnetic fields, and the charge and current densities. The electromagnetic wave equation is the derived from these fundamental equations.

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \tag{1}$$

Equation (1) relates to the electromagnetic field, known as the Maxwell-Faraday law, and presents the electromagnetic induction at a local level. That is, this equation applies specifically on a microscopic scale and relates only to the charge and current. Here, E is the electric field, $\vec{\nabla} \times \vec{E}$, the curl of the Electric field, or the measure of rotation of the electric field is defined as the change in magnetic field (∂B) with respect to time (∂t). Equation (2) provides that the divergence of the magnetic field, $\vec{\nabla} \cdot \vec{B}$ equates to 0. That is, the magnetic field is solenoidal, and acts as neither a source nor a sink, thereby nothing is lost and the divergence of the magnetic field is zero.

$$\vec{\nabla} \cdot \vec{B} = 0 \tag{2}$$

Equation (2) is referred to as the Maxwell-flux equation. The next equation considers Ampere's laws on the circulation of the magnetic field. In this case, the flux of the magnetic field over the magnetic permeability is equal to the current displacement through the space plus the dielectric permittivity (a constant in a vacuum) time the change in the electric field with respect to time. This equation mathematically predicts the propagation of electromagnetic waves in space.

$$\vec{\nabla} \times \frac{\vec{B}}{\mu_0} = \vec{J} + \varepsilon_0 \frac{\partial \vec{E}}{\partial t} \tag{3}$$

The final equation, equation (4), the Maxwell-Gauss equation, provides the divergence of the electric field is equivalent to the distribution of electrical charges in a medium [1].

$$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\varepsilon_0} \tag{4}$$

Together, these equations provide the fundamentals of electromagnetics and can be used to determine the electric and magnetic fields of a space. To derive the equations for electromagnetic waves, Maxwell's equations must be solved for the electric field, magnetic field, electrical induction, and magnetic induction (E, B, D, and H, respectively) where:

$$\vec{\mathrm{D}} = \varepsilon \vec{E} \tag{5}$$

$$\vec{\mathrm{H}} = \mu \vec{B} \tag{6}$$

Here, to find the permittivity and magnetic permeability for the specified medium (in this case, ocean water), the following equations are applied, where ε_0 and μ_0 are the constants provided in a vacuum, and ε_r and μ_r are the values based upon the medium in question.

$$\varepsilon = \varepsilon_0 \times \varepsilon_r \tag{7}$$

$$\mu = \mu_0 \times \mu_r \tag{8}$$

Various other characteristics are derived from these values including propagation speed, wavelength and frequency, impedance, and refraction [2-5]. For ocean water, these values will not be constant, as they depend upon such characteristics as temperature and salinity [4,5]. These impacts and the derivations for ocean water will be discussed further in the following sections. The equations for the propagation rate of electromagnetic waves, v, wavelength (λ) and frequency (f), impedance, Z_c, and the refraction index, n, are provided below [4].

$$v = \frac{1}{\sqrt{\varepsilon\mu}} \tag{9}$$

$$\lambda = \frac{v}{f} = \frac{2\pi}{\omega\sqrt{\varepsilon\mu}} \tag{10}$$

$$Z_c = \left(\frac{\mu}{\varepsilon}\right)^{\frac{1}{2}} \tag{11}$$

$$n = \sqrt{\varepsilon_r \mu_r} \tag{12}$$

Note, in the equation for the refraction index, only the permittivity and magnetic permeability of the medium are required.

2.2 Permittivity, Permeability, and Conductivity of Seawater

Permittivity is defined as the ability of a substance to store electrical energy in an electric field, and relies heavily upon the dielectric nature of the medium. Models of freshwater permittivity have been developed for various frequencies. One specific type of mathematical model is the double-Debye model, used to model both freshwater and seawater permittivity [4]. This model for freshwater is provided below in equation (13), and sea water in equation (14).

Here, ε_r remains to be the relative permittivity of the medium (in this case fresh water), ω is the angular frequency of the electric field, T is the temperature of the substance, τ_1 and τ_2 are time-constants referred to as relaxation time based on the inertial properties of orientation polarization and can be written as $\tau=\varepsilon/\sigma$ [5].

$$\varepsilon_r(\omega, T) = \varepsilon_\infty(T) + \frac{\varepsilon_S(T)-\varepsilon_1(T)}{1+j\omega\tau_1(T)} + \frac{1(T)-\varepsilon_\infty(T)}{1+j\omega\tau_2(T)} \tag{13}$$

In this equation and the following equation for seawater, if temperature (T) is treated as a constant, the permittivity found will be considered an instantaneous measurement of the static relative permittivity [4]. A variable equation describing the change in temperature along the intended path of the signal would be more appropriate to utilize for a closer fit of the permittivity along the entire path. However, this would only be a best fit solution and the temperature may or may not follow a linear path. The following equation, a mathematical model describing the permittivity of seawater, becomes more complicated with the addition of salinity, which may or may not follow a linear or relatively linear scale along the path of a signal.

$$\varepsilon_r(\omega, T, S) = \varepsilon_\infty(T, S) + \frac{\varepsilon_S(T,S)-\varepsilon_1(T,S)}{1+j\omega\tau_1(T,S)} + \frac{1(T,S)-\varepsilon_\infty(T,S)}{1+j\omega\tau_2(T,S)} + j\frac{\sigma(T,S)}{\varepsilon_0\omega} \tag{14}$$

Here, as previously mentioned, temperature and salinity are used as terms to define the relative permittivity, static permittivity, and infinite permittivity, as well as the relaxation constant, and the ionic conductivity of the water (σ). Again, the model becomes overly complicated as various non-linear models are installed within this equation.

Alternative models may provide specific boundaries, within which specific constants may be defined and utilized to solve equation (13). For example, the W. Ellison model provides the following constants for a frequency in the range between 3 and 40 GHz, temperature between -2 °C and 30 °C, and salinity between 20 and 40 parts per thousand [5].

$$c_1 = 0.086 + 0.030T - 4.121 \times 10^{-4}T^2 \tag{15}$$

$$c_2 = 0.077 + 0.001T + 1.937 \times 10^{-5}T^2 \tag{16}$$

These constants can then be used to find the conductivity of the water given the same ranges defined above.

$$\sigma(T, S) = c_1(T) + c_2(T)S \tag{17}$$

The modeling of electromagnetic signals becomes more complicated as the various characteristics of water are considered. For perspective, Figure 2 provides the variation in temperatures of the surface of the ocean across the globe [6]. Four images are provided to depict the change in ocean temperatures through various years at various times of the year. While the images may seem similar, there are visible differences that would affect the various characteristics of electromagnetic waves. For example, a signal sent within the Gulf of Mexico would have different static relative permittivity in January compared to July, as the temperatures of the surface of the Gulf are hotter during July. Similarly, a signal sent within the Persian Gulf in April will act different than if it were sent in October.

Figure 3 provides the sea surface salinity in June of 2020 [7]. For the same purpose as Figure 2, Figure 3 depicts the vast variability of the salinity of the ocean at different points. Any equation requiring either salinity or temperature that would need to follow a path from a transmitter to a receiver would need to consider these variations. A static relative measurement would not be sufficient to properly model the signal.

Other various factors that may affect the behavior of electromagnetic waves within the ocean include viscosity and density. Figures 2 and 3 provide variations along the surface of the ocean, however both viscosity and density, as well as temperature and salinity, are variable based upon the depth of the measurement. Figure 4 depicts the variation in temperature, nitrate and oxygen based on the ocean depth in meters [8].

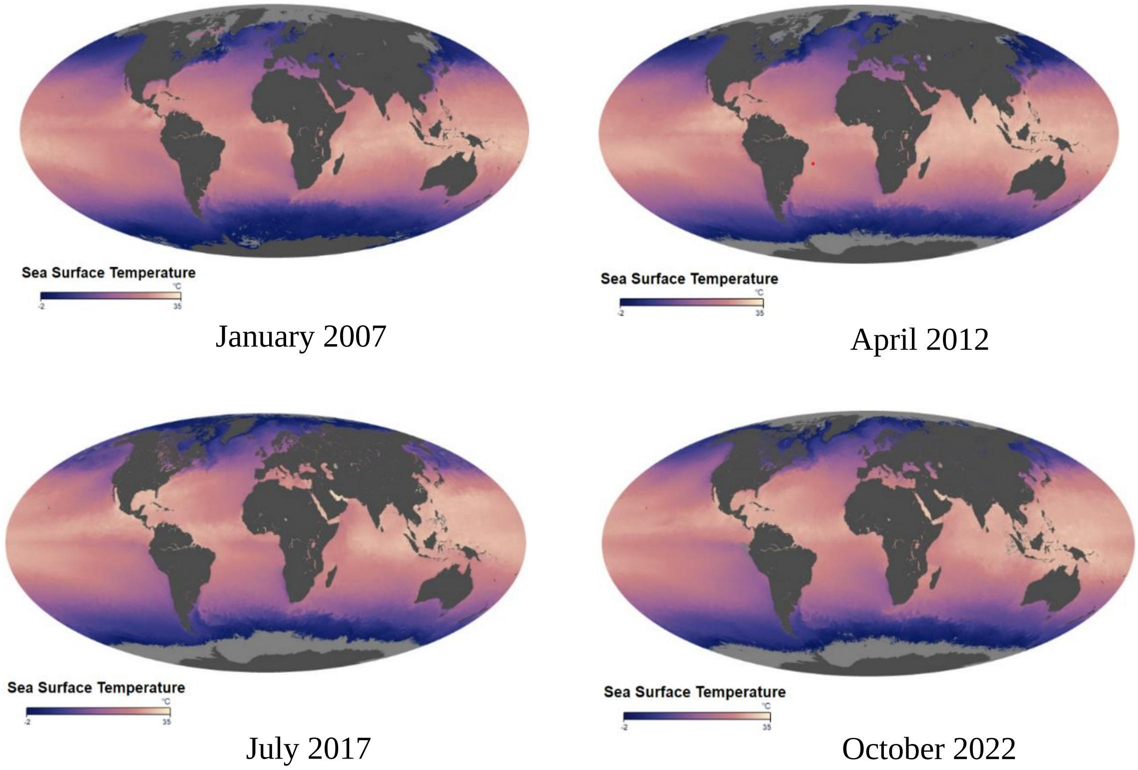

Figure 2. The temperature at the surface of the ocean over 15 years, through four seasons, provided by NASA Earth Observatory [6].

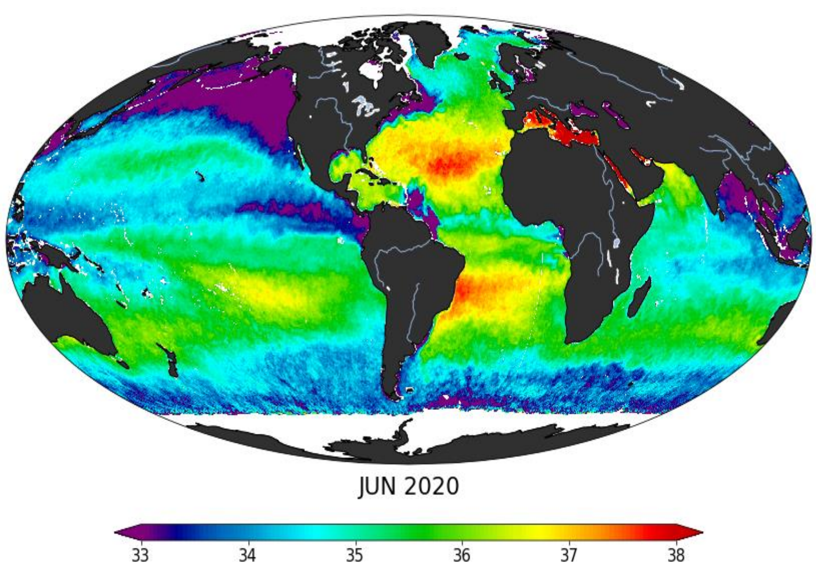

Figure 3. Surface salinity in parts per thousand of the ocean as measured in June of 2020, provided by NASA Earth Observatory [7].

These differences are a result of the exposure to air and light [8] and are expected traits. However, these regions of ocean depth have different values for density, specific heat, and viscosity, because of this exposure to light and air that then affect the ability of electromagnetic waves to propagate. While electromagnetic waves have several advantages such as the wide frequency bands and speed, the medium of water makes this form of communication more difficult to control or predict, which is less than ideal.

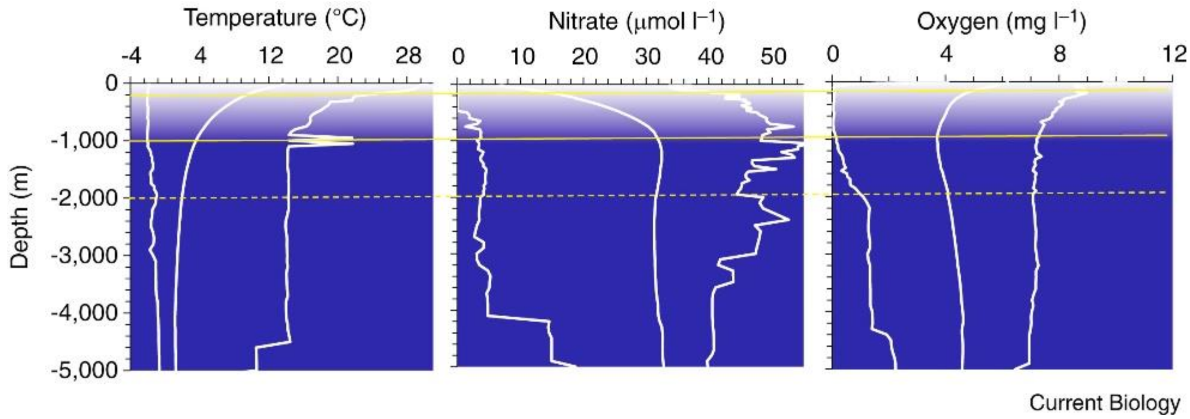

Figure 4. Variation in temperature, nitrate, and oxygen concentrations based on ocean depth. The vertical lines provide the minimum, mean, and maximum values across the oceans, while the yellow horizontal lines describe the transition in ocean boundaries [8].

2.3 Acoustic Wave Propagation

For these reasons, most typical underwater communication is presented through the use of acoustic waves. One of the most well-known devices for this kind of wave transmission and receipt is called SoNaR (Sound Navigation and Ranging, to be scripted as "sonar" herein) [9]. This type of technique has been used for a variety of purposes, from navigating underwater to mapping objects in the ocean [9].

Sonar has two modes: active and passive [9]. In active mode, the marine vehicle sends an acoustic signal out and listens for the return. If a return signal is received, the observation is that an obstruction or object was within the path of the wave, thus reflecting back to the origination point of the signal. In this case, changes to the signal will be measured and evaluated to determine various characteristics of the object in question.

Passive sonar is only comprised of the listening portion of the system. In this case, the system listens for noises (or acoustic waves) from other objects in the ocean. These noises may come from animals like whales or dolphins, or transponders from a fishing vessel, to movement in wave currents that a passing submarine might make [9].

In regards to communication, similar methods to sonar are utilized. Commonly, hydrophones act as the listening system, receiving the acoustic signal and parsing it into understandable data.

It is important to note that acoustic waves are not beams, but rather can be omnidirectional if not carefully controlled. Acoustic pressure would typically follow a spherical path, proceeding outwards uniformly in air from the point source. Cylindrical acoustic waves, being more controlled, are generally preferred. The equation for cylindrical acoustic waves is given by equation (18).

$$\left(\frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{\partial \theta^2} + \frac{\partial^2}{\partial z^2}\right) p = \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} \tag{18}$$

This is the wave equation for cylindrical wave propagation [9], where r is the perpendicular distance from the point source in the z-direction. This equation can be further broken down into three separate differential equations to develop relationships between each of the constants. However, solving for this equation becomes equally as complicated as the electromagnetic wave equations. In this case, the velocity potential and the intensity of the signal must also be considered to provide an accurate expression. This equation also, assumes the medium is homogenous, which has already been deemed false when the medium is seawater. Therefore, further evaluations are made and various nonlinear solutions are derived to fit this mold. A final equation that may describe a complete inhomogeneous lossless wave equation [9] is provided below. This equation accounts for mass injection (when a closed surface experiences a change in volume), body forces (when the source moves while providing tone) turbulence or changes in momentum of the fluid, and gravity.

$$\nabla^2 p - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} + \nabla \cdot (\rho_0 \vec{g} s) = -\frac{\partial G}{\partial t} + \nabla \cdot \vec{F} - \frac{\partial^2(\rho u_i u_j)}{\partial x_i \partial x_j} \tag{19}$$

This equation is still complicated, however the effects of the properties of water are either accounted for or irrelevant to the task at hand. The biggest challenge to utilizing acoustic waves in underwater communication is the small frequency band and the low propagation speeds [36] These are both factors that current research is working to mitigate and circumvent, either through the use of ultrasonics or some marriage between acoustics and another time of charged wave.

3. CODE AND DECODE

Signal coding and data encryption are based on cryptographic algorithms applied to signals and data that can only be decrypted with the correct encryption key. This technology has been applied across various fields, from electronic mail and banking information to radio and communication signals [37]. Data encryption defines the physical codification of documentation prior to sending the data through to the receiver, based on data encryption standards defined and produced by the National Communication System. This type of encryption is applied to the data being sent, and only the proper decryption key may translate the data. Signal coding, however, is based upon the physical waves being transmitted, that is the signal is coded by variations in frequency, flux, or intensity, and various modulation techniques may be used to keep the data secure. Once received by the appropriate listening system, the signal's characteristics: the frequency, voltage level, and/or amplitude, may be converted to the appropriate measures and the final message received.

3.1 Current capabilities

Various methods are utilized to produce one single signal. These methods convert analogue data into optical data, install data modulation, and apply dispersion effects, all to encode and transmit one signal with a packet of data [37]. Various methods of coding signals are in use today, with varying levels of effectiveness and security. These methods primarily include modulation techniques like frequency shift keying (FSK), phase-shift keying (PSK), frequency-hopping spread spectrum (FHSS), direct-sequence spread spectrum (DSSS), frequency pulse-position modulation (FPPM), pulse-position modulation (PPM), multiple frequency-shift keying (MFSK), and orthogonal frequency-division multiplexing (OFDM) [38]. Each of these techniques has benefits and disadvantages when securing acoustic data. This information will be summarized in Table 1.

Frequency shift keying, or FSK is a form of digital modulation. FSK requires the use of two distinct frequencies, to act as bit 1 and bit 0, where the frequencies are offset by equal and opposite amounts from a carrier frequency. These signals will act as a binary code, providing a string to the receiver. This would be considered two-state FSK. Four-state FSK also exists, with each frequency providing a two-bit value (01, 00, 10, 11). The receiver then collects the signal, and decoding is as simple as knowing which frequencies are which bit [39]. Multiple frequency shift keying (MFSK) is a variation of FSK that makes use of more than one carrier frequency.

PSK, phase shift keying, is similar to FSK however, rather than shifting the frequency of the signal, the phase is shifted, or modulated. In this case the carrier wave will vary between sine and cosine inputs. This is a more sophisticated modulation technique than FSK in that PSK modulation can be specialized to the specific circumstances to account for efficiency and suitability for the situation at hand. PSK techniques can range from a simple 2-bit system to continuous shifting, though there are system tradeoffs for each method [39,40].

Frequency-hopping spread spectrum (FHSS) is a modulation technique by which the assigned bandwidth is split into many distinct channels. The transmitted signal is sent while switching between these channels to some predefined algorithm. If the receiving device is not privy to this algorithm, the signal sequence will appear random and indecipherable. With many multiple channels any interference becomes relatively inconsequential [41]. Direct sequence spread spectrum (DSSS) is the IEEE replacement with direct sequencing. The intention is to utilize the signal over a larger bandwidth than needed, thereby increasing the speed of the transmission and installing redundancy where there originally was none, while sacrificing that additional bandwidth efficiency. Each bit is transformed into a longer bit sequence, utilizing many frequencies to send the same message [41 – 43].

Pulse position modulation (PPM) and frequency pulse position modulation (FPPM) are modulation techniques that vary the position of the pulses per amplitude. The PPM signal is time shifted, while FPPM varies the instantaneous frequency.

OFDM or orthogonal frequency division multiplexing is a block transmission scheme that separates information into blocks, with guard intervals between blocks during transmission. This type of encoding both protects the information and is robust against multipath propagation [36].

Table 1. Acoustic data modulation techniques, and the advantages and disadvantages for each option.

Modulation Method	Description	Advantages	Disadvantages
Frequency shift key (FSK)	Using frequencies offset from a carrier frequency as bit values	• Low probability of error • High signal to noise • Simple implementation	**• Large bandwidth requirements** **• Bit error rate worse than other types of modulation**
Phase-shift keying (PSK)	Using a phase shift from the initial carrier phase to present binary data	• Power efficient • High data rates • Versatile implementation	**• Low bandwidth efficiency** **• Complex detection algorithms**
Frequency-hopping spread spectrum (FHSS)	Transmitting a signal across different frequency channels and small bandwidth	• Robust transmission path • Supports multiple access points/ports. • Decryption codes are known only to the transmitter and receiver	**• Low data rates/transfer limits** **• High SNR requirements at receiver** **• No built-in redundancy** **• Obsolete modulation scheme**
Direct sequence spread spectrum (DSSS)	Transmitting a signal across different frequency channels and large bandwidth	• Best anti-jam performance • High coverage range • Simple HW implementation • Discrimination against multi-path signals • Difficult to detect	**• Long acquisition time** **• Wideband channel required.** **• Limit on DSSS users in an area due to interference**
Frequency pulse-position modulation (FPPM)	Instantaneous frequency is varied per pulse	• High SNR • Rejects RF interference.	**• Clock must be synchronized.** **• Sensitive to multipath interference**
Pulse-position modulation (PPM)	Time shifted signal per pulse	• Better noise immunity • Decryption is simple	**• Large bandwidth requirement** **• Transmit and receive must be synchronized.**
Orthogonal frequency-division multiplexing (OFDM)	**Bitstream divided into multiple streams and transmitted in parallel**	**• High spectral efficiency** **• Easily adaptable** **• Low sensitivity to time sync issues** **• Robust against multipath**	**• Sensitive to doppler shift** **• Guard interval causes loss of efficiency**

3.2 Underwater Application

Each of the aforementioned techniques have been used in underwater environments. Table 2 provides a breakdown of the behaviors recording for acoustic signal treated with modulation encoding in an underwater region. Various experiments have been proposed and/or performed to account for these enumerated issues. These experiments are outside of the scope of this paper. Please consult the provided references for more information.

Table 2. Behavior of acoustic signals when treated with various modulation encoding techniques to be utilized as signals underwater.

Modulation Method	Behavior in Water
Frequency shift key (FSK)	Strong reflections at hydrophones may distort signals, confusing the detectors and limiting signal reception.
Phase-shift keying (PSK)	Multipath effects and doppler shift degrade coherent communication [40].
Frequency-hopping spread spectrum (FHSS)	Multipath interference, doppler compression, phase fluctuation interference [42].
Direct sequence spread spectrum (DSSS)	Multipath interference, doppler compression, phase fluctuation interference [43].
Frequency pulse-position modulation (FPPM)	Susceptible to multipath interference
Pulse-position modulation (PPM)	Susceptible to multipath interference
Orthogonal frequency-division multiplexing (OFDM)	Multicarrier modulation allows for the signal to be received with minimal timing delay

4. COMMUNICATION TECHNOLOGIES

Various technologies have been utilized through time to communicate between underwater vessels. Modern interest in underwater communication is generally accepted as beginning in World War II, specifically for military uses. Since then, however, interest in submarine communications has extended to such things as diver communications, exploration and scientific expansion, and identifying geographical markers and fluctuations such as underwater volcanic eruptions or to identify the size of an iceberg. Despite the growing interest, however, as suggested in the previous sections, underwater communication and communication techniques and technologies remains to be one of the more evasive topics of scientific research. Ocean water and water wave dynamics continue to push researchers to more and more innovative ideas and solutions to further our capabilities. Several of these proposed solutions are described below, including piezoelectric acoustic transducers, electromagnetic acoustic transducers, and acousto-optic devices. Each of these devices is a type of underwater acoustic transducer (UAT).

4.1 Piezoelectric Acoustic Transducers

The first technology to be examined is the piezoelectric acoustic transducer. A transducer is a device used to convert energy from one type of input to another. For example, a microphone is a type of transducer that converts audio signals to electrical energy. Piezoelectric transducers are a type of transducer that converts the electrical charges produced by the piezoelectric material. This is a dense field of research today as the need for clean and sustainable power, and with the numerous forms and types of piezoelectric crystals and components the only limitation at the moment is imagination [10]. Piezoelectric acoustic transducers have been in use for over 60 years: the sensors using the piezoelectric material to generate the acoustic wave as well as detect acoustic waves, such as sonar systems do.

Piezoelectric transducers can be made using a variety of different materials, though some materials have crystalline structures that are more conducive to performing certain tasks or may provide better efficiency or energy. These materials can be classified into three major material categories: single crystal materials, thin-film piezoelectric materials, and piezoelectric ceramics.

Traditional single crystal materials include quartz and lithium niobate, though various other types of crystals can be grown that exhibit better piezoelectric performance and can be used in both actuator and transducer mechanisms. These types of grown single crystals include lead magnesium niobate-lead titanate (PMN-PT) and lead indium niobate-lead magnesium niobate-lead titanate (PIN-PMN-PT) [11]. PMN-PT single crystals are considered ideal for small imaging type transducers to be used for biological image testing. PIN-PMN-PT single crystals, on the other hand, have much higher transition phase temperatures than PMN-PT single crystals making them more suited for high-temperature environments. These materials are most commonly used for small biomedical devices such as intravenous imaging devices for diagnostic or therapeutic purposes [11].

The next type of piezoelectric material is thin-film piezoelectric materials. These materials are considered ideal for energy harvesting acoustic vibrations and can be utilized as microelectromechanical system energy harvesters for such things as gyro-sensors or information processing and radio frequency devices on microchips [12, 13]. Some thin-film piezoelectric materials include perovskite materials fabricated through various material treatment processes like annealing, ablation, or sintering [13].

The final category, piezoelectric ceramics are the most common type and are utilized in a wide variety of sensors and transducers including motion sensors, watches, ultrasonic devices, and more. This is mostly as a result of the wide variety of materials and material properties. Some of these so-called piezoceramics include lead zirconate titanate, potassium dihydrogen phosphate, barium titanate.

Table 3 provides typical dielectric and piezoelectric properties for various single-crystal, piezoelectric-based thin films, and piezoelectric ceramic materials.

Table 3. Dielectric and piezoelectric properties for various single-crystal material and thin-film materials [11-13]

Single Crystal Material			
Properties	*LN*	*PMN-PT*	***PIN-PMN-PT***
ρ (kg/m^3)	4700	8060	**8198**
d_{33} (pC/N)	~49	2820	**2742**
κ_t	0.49	0.58	**0.59**
κ_{33}	0.47	0.94	**0.95**
ε_{33}^s	39	680-800	**659**
c_p (m/s)	7340	4610	**4571**
Z_a (MRayl)	34.5	37.1	**37.5**
T_{rt} (°C)	-	60-95	**100-117**
T_c (°C)	1140	130	**~200**
Thin Film Material			
Properties	*PZT*	*PMN-PZT*	***AIN***
Substrate	(001) MgO	(001) MgO	**Sapphire**
Structure	Epi	Epi	**Epi**
$\varepsilon/\varepsilon_0$	200	155	**9.5**
2Ec (kV/cm)	200	230	
2Pr (μC/cm^2)	100	120	
***e_{31} (C/m^2)**	-4.8	-7.7	
e_{31f} (C/m^2)	-6.2	-10.8	**-1.37**
d_{31} (pC/N)		-83	**-2.65**
e_{31f}^2/ε (GPa)	**20.5**	**85**	**22.3**

When deciding upon the specific material to use, there are several characteristic parameters that must be considered as they relate to piezoelectric materials. The characteristics are the piezoelectric coupling factor (κ), mechanical quality factor (Q_m), frequency constant (N_1), and the various piezoelectric constants like the dielectric permittivity and piezoelectric coefficient, and the constant of elasticity. Some of these values can be determined mathematically while others require physical experimentation to determine. For piezoelectric materials in particular, the crystalline structure plays an important role in simplifying many of these property characterizations [14]. Equations 20 through 23 describe how to determine some of these important characteristics.

The first equation provides the effective electromechanical coupling coefficient $\kappa_{eff.}$ This value describes the materials ability to convert energy from one form to another, and will always be a value less than one. Simply, the effective coupling coefficient is the ratio of how much energy was converted to the amount of energy initially input. The equation below, for example, provides κ_{eff} in the case of a circuit where a minimum and maximum frequency for impedance are provided for a circuit.

$$\kappa_{eff}{}^2 \approx \frac{f_{max}{}^2 - f_{min}{}^2}{f_{max}{}^2} \tag{20}$$

This value is related to the parallel and series resonance frequencies as well. For example, $\kappa_{31,}$ the planar coupling coefficient, can be described by a function of Poisson's ratio and the planar coupling coefficient. The resulting equation appears similar to equation 20.

$$\kappa_{31}{}^2 = \frac{1-\nu}{2}\kappa_P{}^2 \tag{21}$$

The next two characteristics are the resonant frequency and the acoustic impedance. Both of these characteristics are inherent to the piezoelectric material and may be determined either through experimentation or mathematics. Knowing these two values is required to manipulate the device [11]. Matching the acoustic impedance to the impedance of the material medium through which the signal travels.

$$\omega_0 = \frac{2\pi c_p}{t} \tag{22}$$

$$Z_a = \rho c_p \tag{23}$$

Equation 22 defines the resonance frequency of the piezoelectric material as a function of the speed of sound inside the piezoelectric material and the thickness of the material. The second equation, also a function of the speed of sound within the piezoelectric, and the density of the material, defines the acoustic impedance. Designing a piezoelectric device to work for specific situations, such as in an underwater environment, or with specific output, will rely heavily on manipulating the system to match the chosen piezoelectric material.

In addition to considering the type of piezoelectric material for the piezoelectric acoustic transducer, the transducer itself can be chosen and tailored to each the designated situation. For example, the composites typically used as the transducers have high values of k for better energy conversion, a value that is also preferred to be as close to 1 as possible for the piezoelectric material as well. In addition to k, the electromechanical coupling coefficient, impedance should also be tailored to match between the two devices to ensure better sensitivity [11-14].

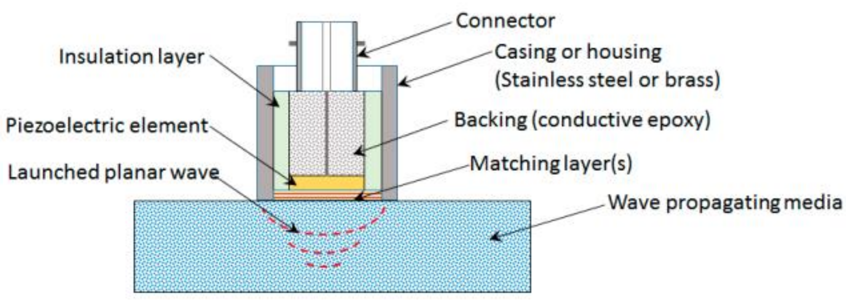

Figure 5. General schematic for the configuration of a piezoelectric (ultrasonic) acoustic transducer [14].

Figure 5 provides a general diagram for piezoelectric acoustic transducers, and includes the most integral elements of the device, including the piezoelectric material and the acoustic matching layer. The acoustic matching layer is designed per device and the intended use in order to match the impedance between piezoelectric element and the propagation medium (in this case water). Additional layers surround the device, the insulation layers and backing, though these are designed to reduce or deny transmission in these directions. The matching layer, as the name suggests, is intended to create a bridge or match the impedance between the piezoelectric and the water and therefore allow high-energy transmissions and reduce lossy interference.

In 1944, piezoelectricity was discovered by A. R. von Hippel in permanently polarized barium titanate ceramics [44]. In 1954 even stronger piezoelectricity was found in polarized lead-zirconate-titanate (PZT) ceramics [45]. The discovery of these materials initiated the modern era of piezoelectric transducers. Today, PZT ceramic compounds are still being used in most underwater sound transducers. However, other similar materials, such as lead manganese niobate (PMN), textured ceramic and relaxor piezoelectric single crystals of lead magnesium niobate-lead titanate (PMN-PT), and lead indium niobate-lead magnesium niobate-lead titanate (PIN-PMN-PT) have been developed which can improve over PZT in some applications [33]. Piezoelectric ceramics and ceramic-elastomer composites can be made in a great variety of shapes and sizes with many variations of composition that provide specific properties of interest. The characteristics of these materials have led to the development and manufacture of innovative, relatively inexpensive transducer designs, as indicated in Figure 6. High output power and efficiency are of paramount importance for any projector of sound, which is difficult to achieve if wideband operation is also required. This leads to designs that have multiple resonances or operation in the mass-controlled region above resonance.

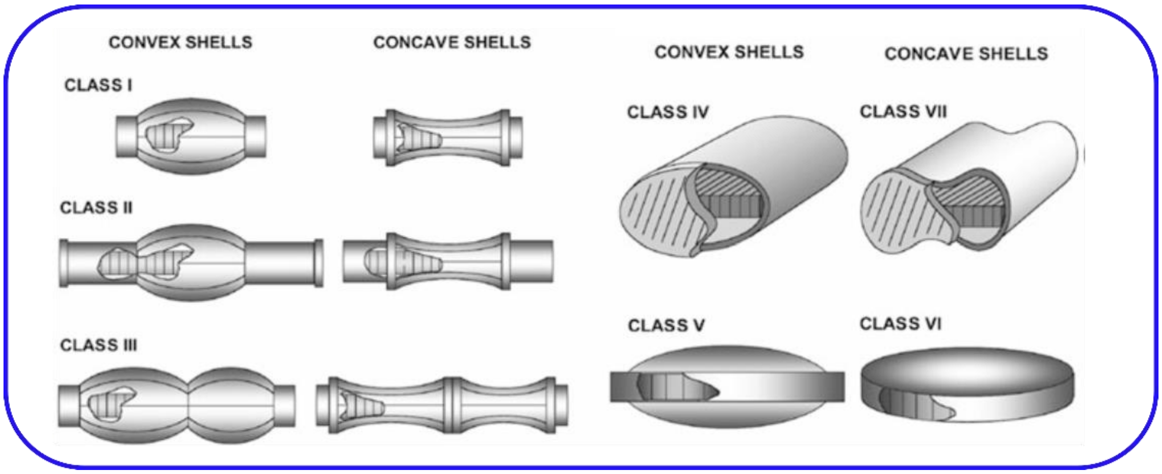

Figure 6. Sketch of various classes of flextensional transducers [33 46].

Depending on source level, bandwidth, and system requirements, projectors can take various geometrical and mechanical forms such as spheres, cylinders, rings, piston radiators, benders, and amplified motion devices such as flextensional transducers [33]. Piezoelectric ceramics are the most commonly used material for generating underwater sound, because of the many geometrical shapes in which they can be fabricated, their excellent electromechanical properties, their low electrical losses, and their ability to generate high forces. The desired performance from a projector is typically high power or intensity, high efficiency and broad bandwidth, usually with limitations on size and weight. The operating frequency band for a particular application has a strong impact on the type of transducer required. If the transducer is to operate at low frequencies, designs which have low resonant frequencies and manageable sizes, such as benders or flextensional transducers, are most suitable. Flextensional transducers also provide amplified motion from a shell attached to the piezoelectric drive section.

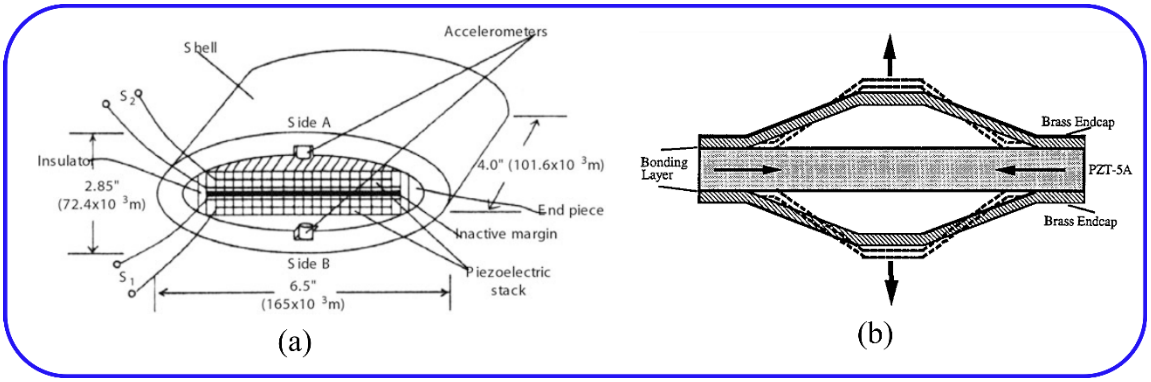

Figure 7. Example diagram of flextensional transducers. (a) IV class and (b) cymbal [33].

The first flextensional transducer has been attributed to Hayes; however, it was the later work and patent of Toulis that led to the Class IV design, which was modeled by Brigham and later encoded for computer design and analysis by Butler [33, 47-55]. Other early flextensional designs by Merchant and Abbott, as well as the modeling by Royster, laid the foundation for more recent designs by Jones and McMahon [56]. Dogan and Newnham [53] developed a very compact design, and Butler [57-62] extended the flextensional concept in several ways. The most common design is a Class IV type as shown in Figure 7(a), which is an oval or elliptical shell driven by a piezoelectric ceramic stack along the major axis of the shell with amplified motion along the direction of the minor axis. Since the inactive shell makes up a significant portion of the transducer stiffness, it causes a significant reduction in the coupling coefficient, resulting in an effective value of $k_e = k_{33}/2$ for a 33-mode driven system. Since flextensional transducers make use of flexural modes of an elastic shell, the analysis and modeling required to determine equivalent circuit parameters is considerably more complicated than the longitudinal mode cases discussed earlier, and it is usually necessary to make simplifying approximations. A new type Class 5 flextensional transducer called Moonie/Cymbal was invented in the later of 1980s [51-55], and made significant improvement on the source level and the transmitting voltage response, which are two major parameters to measure underwater acoustic transducer performance [33, 47].

In the past a couple decade, Xu at. al. invented several advanced transducer concepts and did comprehensive studies on piezoelectric transducers [63-87]. Among of those piezoelectric transducers, the multistage amplification transducers, and hybrid piezoelectric transducers will have advantages for future underwater communications.

4.2 Electromagnetic Acoustic Transducers

Electromagnetic acoustic transducers are another type of transducer that take advantage of the principles of electromagnetic acoustic excitation [19]. Electromagnetic acoustic transducers have the benefit of acting as both a transmitter and a receiver. Typical electromagnetic acoustic transducers are made up of a magnet, spiral coil, and a piece of aluminum [20].

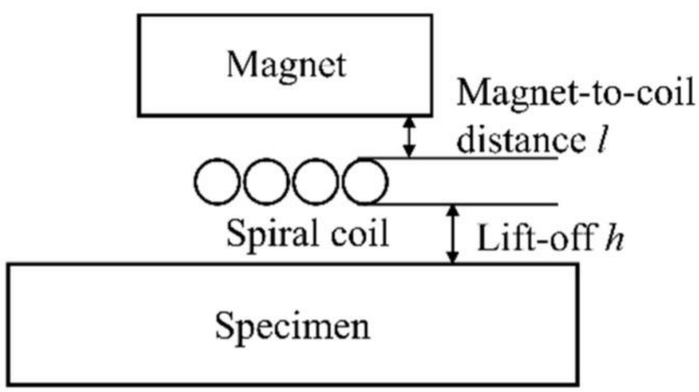

Figure 8. Typical spiral coil electromagnetic device [25].

In figure 8, various key components to an electromagnetic acoustic transducer are indicated, including the spiral coil and the magnet. On a very basic level, a current is passed through the coil and an electric field is inducted. When this electric field interacts with the magnetic field, a Lorentz force will be generated. Lorentz forces are forces exerted on charged particles moving through an electric and magnetic field. The vibrations caused by these Lorentz forces produce ultrasonic waves in the direction perpendicular to the specimen. The following equations define these various properties and fields produced by the system.

$$J_e = -\sigma \frac{\partial A}{\partial t} \tag{24}$$

Equation (24) is the induced current of the electric field, where σ is the electrical conductivity of the specimen and A is the potential magnetic vector. The next equation defines the magnetic flux density, where the permeability in a vacuum, relative permeability, and the magnetic field intensity are taken into account. The intent is to mathematically model the magnetic field, and electric field, to then define the Lorentz force. This Lorentz force is used to then induce the ultrasonic wave[23]. Both a static and dynamic magnetic field is generated on the surface of the specimen [22], which are both accounted for in the equation for magnetic flux density below.

$$B = \mu_0 \mu_r H + B_r \tag{25}$$

The total Lorentz force is defined below.

$$F_L = J_e \times B \tag{26}$$

Changing the composition of the specimen, the coil, and the magnet all play a role in increasing the effectiveness and efficiency of electromagnetic acoustic transducers. The one quality of the system that has not been effectively reported on is the lift-off effect. This quality affects the amplitude of the signal, which may then cause the signal to be covered by noise, thereby ruining the purpose of the system. Lift-off and amplitude share the relationship defined below.

$$A_s = e^{k \cdot h + b} \tag{27}$$

One important concept to consider here is the magnetorestrictive forces. These forces are a dominant transduction mechanism, so the chosen material must be chosen with consideration for the material properties that may affect both the magnetorestrictive force and Lorentz force density. The magnetorestrictive effect is nonlinear, and may be compared analogously to piezoelectric materials.

4.3 Acousto-Optic Devices

Acousto optic devices are derived from the study of the sciences of acoustics and optics. Acousto optic devices take advantage of the change in refraction index of a medium as a result of sound waves in the same space. In essence, the acoustic waves affect the behavior of light, along which the signal may be transferred, based on the change of the refraction index of a medium as a result of sound waves existing in the same space. The magnitude by which the light is affected is dependent upon the medium through which the interaction occurs. As a result, the material utilized in acousto-optical devices tends to be composed of a crystal coupled to a transducer in order to convert the acoustic waves, which is then applied to the optical wave within the medium previously described. The Brillouin theories describing the scattering of light with frequency change have been considered the pinnacle of this science, and many various experiments have been designed and performed in attempts to prove or disprove these theories.

Two of the most important theories in this area are the Raman-Nath theory and the Klein-Cook theory. The Raman-Nath theory is called the phase grating theory and assumes the light being acted upon is only affected in terms of phase, while the amplitude and trajectory are left unchanged. It is important to note the following parameter, the so-called "Raman-Nath parameter."

$$v = \frac{2\pi\mu L}{\lambda} \tag{28}$$

This parameter is dependent upon the thickness of the ultrasonic wave, L, the maximum variation as a result of the ultrasonic injection, μ, and the wavelength of the light being affected, λ. It is important to note that only small values of this parameter apply to the actual Raman-Nath theory. The figure below, Figure 9, provides a graphical representation of the Raman-Nath theory of ultrasonic light diffraction.

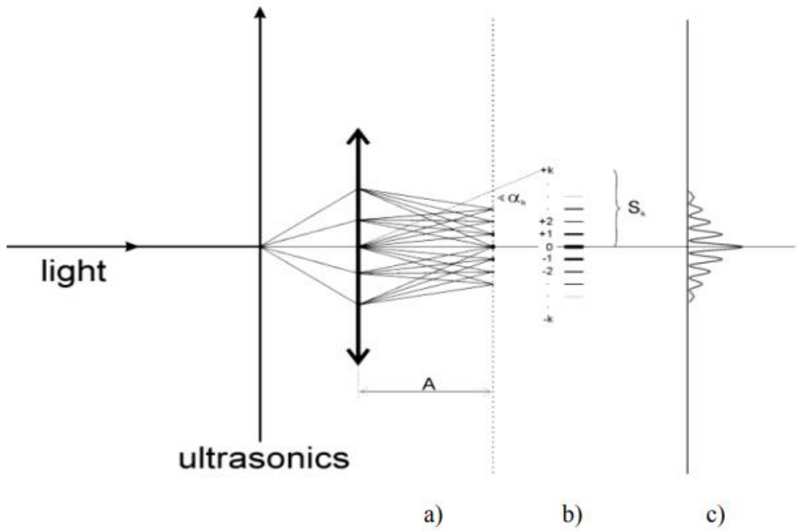

Figure 9. Raman-Nath theory of ultrasonic light diffraction [29].

Figure 9 is split into three categories to more accurately describe the theory. 'A' described ultrasonic light diffraction from an interaction and diffraction scheme, 'B' shows what could be seen through a focus lens during this experiment, and 'C' the intensity distribution of the light when subject to a diffraction pattern of several orders. As is typical with theoretical physics, however, some cases were defined and fit the model perfectly, while other cases seemed anomalous or required an entire rework of the theory [24]. This is where applying Bragg's diffraction law allowed for a more succinct understanding and development of acousto-optical theory.

Bragg's law, and subsequently Bragg's diffraction, is described in the Britannica Encyclopedia as the relationship between "the spacing of atomic planes in crystals and the angles of incidence at which these planes produce the most intense reflections of electromagnetic radiation." This is important to the study of acousto-optics because it allows researchers to better define and predict the behavior of the diffraction of the wave, regardless of the angle of incidence.

Equation (29), the so-called Raman-Nath system of equations, has been derived from their various experiments to more readily define and explain the acousto-optic phenom. This equation takes into account the Raman-Nath theory and Bragg diffraction, as well as another theory, the Klein-Cook theory, which defines the parameter Q, a variable meant to distinguish between which diffraction type, Raman-Nath or Bragg, was utilized during the experiment [24-26].

$$2l\frac{d\psi_n}{\partial z} - v(\psi_{n-1} - \psi_{n+1}) = lnQ(n-\beta)\psi_n,\ \psi_n(0) = \delta_{n,0} \quad (n \in Z) \tag{29}$$

This equation makes use of the previously defined Raman-Nath parameter, $\upsilon = 2\pi\mu_1/\lambda$, and the Klein-Cook parameter, $Q = 2\pi\lambda L/\mu_0\Lambda^2$, where, as expressed earlier, L is the thickness of the ultrasonic wave, λ and Λ are the wavelengths of light and ultrasound respectively, μ_0 is the refractive index of the medium, and μ_1 is the maximum variation of the refraction index as a result of the ultrasonic interference. The additional variables of equation (29) include ψ, the diffracted light amplitudes in the given order n, z, the direction reference perpendicular to the ultrasonic wave, l, the thickness of the optical wave, and β, the actual angle of incidence of light as described by Bragg.

For most cases, solving this equation is an iterative procedure, where the diffraction is neither perfectly defined by Bragg diffraction nor Raman-Nath diffraction, and the solution is only an approximation. However, there are two specific cases where this equation can be fully solved. Recall the Klein-Cook parameter, which defines the type of diffraction the system experiences.

$$Q = \frac{2\pi\lambda L}{\mu_0\Lambda^2} \tag{30}$$

When the Klein-Cook parameter, Q, approaches zero, the corresponding diffraction is Raman-Nath diffraction. When Q approaches infinity, the expectation is Bragg diffraction. In other words, when the value of Q is found to be much greater than one, Raman-Nath diffraction is at play, and when Q is much less than one, Bragg diffraction is taking place. One or the other circumstance may occur when the ratio of the square of the optical wavelength to the ultrasonic wavelength is much less than or much greater than L, the thickness of the ultrasonic wave [26].

Acousto-optic devices make for incredibly controllable and repeatable systems, given the nature of light generation and sound generation. From experimentation several applications were conceptualized. Spatial beam shaping (which can be performed with high efficiency using acousto-optics) has applications in material processing, laser displays, optical communication, and microscopy. Additionally, beam deflectors, tunable filters, signal demodulation, and bistable switches are all acousto-optic technologies. Further still, real-world applications of acousto-optics and the various products utilizing acousto optics include such real-world applications as Electronic Warfare (EW) [28, 29, 30]

Acousto-optics allow for better control in all types of devices where they are utilized, and this control becomes a pattern for every application. Better control results in better precision, and more precision equates to better results.

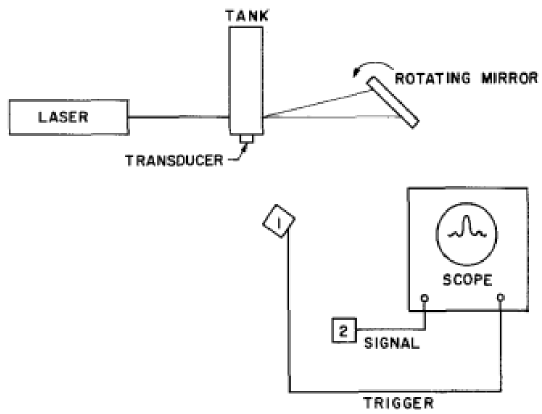

Figure 10. Pierce-Byer acousto-optic experiment setup [30]

Figure 10 provides an experimental setup of an acousto-optic device. The purpose of this experiment was to apply an acoustic beam to the water within the tank and see how the laser light was affected by the specific frequency. A clear acoustic absorber was installed on two of the walls of the tank to allow the laser to pass through the water with minimal interference. Bare electrical leads were used to make contact with the transducer submerged in the tank and a mirror. A rotating mirror was placed perpendicular to the laser origin point on the other side of the so-called windows of the tank to allow for observance of the resulting beam in terms of diameter, intensity, and diffraction [25].

The results of this experiment found that the diffraction efficiency is proportional to the power producing the sound [25]. To further explain this, increasing the sound frequency or the width of the acoustic wave, the resultant diffraction is Bragg diffraction, which is expected based on the theoretical value of Q. The opposite is also true; as the acoustic frequency decreases or the acoustic wave thickness decreases, the expected result would be Raman-Nath diffraction [25]. This experiment successfully proved the theory behind both Bragg and Raman-Nath diffraction, though in real world applications Bragg diffraction would be preferred, hence the turn to ultrasonic acoustic vibrations.

The major area of research and the biggest limitation for these devices today is in the available material and material properties. The crystals originally used in these devices are quartz-based materials. Quartz crystal, which was the crystal used in the experiment performed by Pierce and Byer, is useful for the demonstration of the properties of acousto-optics and can be used in a variety of applications. However, despite the quartz crystalline structure being known enough to control, it is not as efficient or controllable as is needed for some applications.

4.4 Device Comparison

Table 4. Comparison of the advantages and disadvantages of piezoelectric acoustic devices, electromagnetic acoustic transducers, and acousto-optic devices.

Device	Advantages	Disadvantages

Piezoelectric acoustic transducers	• No external power source required. • High-frequency response, parameters shift quickly. • Usable in various fields	• High impedance required. • Temperature and humidity can affect output. • Low output requires external circuit
Electromagnetic acoustic transducers	• Can be used as both transmit and receive. • Multi-mode capability • High temperature application	• Poor conversion energy • High-powered RF drivers and low noise pre-amplifiers required • Limited to metallic/magnetic products
Acousto-optic devices	• Quick response time • Highly controllable output • Various components can be improved upon to improve results.	• Material parameters restrict acoustic attenuation. • Temperature and density of the material may affect the resultant signal

5. CONCLUSION

Various devices exist for similar purposes. This is how science works and how progress is made. That said, progress can become stagnant when scientists choose to focus on one solution over the other. For example, consider the discussion on coding and decoding signals. Various methods exist but the most effective type of signal encryption is an amalgamation of various types of proven encryption methods. Similarly, each of the devices discussed: piezoelectric acoustic transducers, electromagnetic acoustic transducers, and acousto-optic devices, have their own advantages and disadvantages. Acousto-optic devices seem to be the most effective in and of themselves. These devices are very controllable in a variety of ways. The major disadvantages are based very closely on the materials chosen and the medium through which the signal is sent. However, as previously mentioned, combining the different devices may lead to furthering technological capabilities. At this point, quartz crystals make up the vast majority of acousto-optic devices, however, the addition of piezoelectric materials may improve the signal quality. Additionally, adding in the matching layer of the piezoelectric acoustic device to the acousto-optic device may allow for better control of the acoustic waves as they travel from the device into the water. Similarly, the transmit and receive functions of the electromagnetic acoustic devices may be implemented in this same way. There is no one simple answer to underwater communication, as each type of device provides some positive aspects. Creating a new device with various components not only embodies the nature of science but continues the human aspect of growth and improvement.

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