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Underwater Acoustics and its Applications. A Historical Review.

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1. Introduction

Underwater acoustics is one of the fastest growing fields of research in acoustics. The number of publications per year in underwater acoustics is still increasing. The relationship to other fields of importance for science and technology like oceanography, seismology and fishery is becoming more close. Every year billions of dollars are spent on the use of underwater acoustics by the mineral industry (oil and solid mineral exploration in the sea), by the food industry (fishing), by the transportation and recreation industries (navigation and safety devices) and by the worlds navies (undersea warfare). A great number of industrial companies are developing and manufacturing instruments and devices for underwater acoustics, including for instance instruments for inspection and mapping of the seabed, for underwater communication, for control of processes in off-shore activities, for search and recovery missions etc.

This very wide-spread field of underwater acoustic activities started many centuries ago with the humans curiosity about the fundamental nature of sound in the sea. From primitive philosophical and experimental studies of the velocity of sound in the sea the development of military technology for undersea warfare during two world wars accelerated the underwater acoustics studies. Over the last 45 years - strongly supported by the development in computer technology - a fast increase in experimental and theoretical investigations of all aspects of underwater acoustics have taken place and new areas of research like acoustical oceanography and seismo-acoustics have been formed.

2. Studies of underwater acoustics before World War 1

The Greek philosopher, **Aristotle** (384 - 322 B.C.) may have been one of the first to note that sound could be heard in water as well as in air. In 1490 the Italian, **Leonardo da Vinci** (1452 - 1519) wrote in his notebook: "if you cause your ship to stop, and place the head of a long tube in the water and place the other extremity to your ear, you will hear ships at great distances". Of course, the background noise of lakes and seas was much lower in his days than now, when all kinds of ships pollute the seas with noise. About one hundred years later, **Francis Bacon** in Natural History supported the idea, that water is the principal medium by which sounds originating therein reach a human observer standing nearby.

In the 18th and early 19th century, a few scientists became interested in sound transmitted in water. They measured the speed of sound in fresh and salt water, comparing these with the speed of sound in air already well measured by then. Their sound sources included bells, gunpowder, hunting horns and human voices. Their own ears usually served as receivers. In 1743, **J. A. Nollet** conducted a series of experiments in order to prove that water is compressible. With his head under water, he heard a pistol shot, a bell, a whistle and loud shouts. He noted that the intensity of the sound decreased a little with the depth, thus indicating that the loss mostly occurred at the surface. **Alexander Monro**, in 1780, tested his ability to hear sounds underwater. He used a large and a small bell, which he sounded both in air and in water. They could be heard in water, but the pitch sounded lower than in air. He also attempted to compare the speed of sound in air and in water, and concluded that the two sound speeds seemed to be the same.

In September 1826 on the Lake Geneva, when the water temperature was 8 °C, **J.D. Colladon** (1802-93), a Swiss physicist, and **J.K.F. Sturm** (1803-55), a French mathematician, made the first widely-known measurements of the speed of sound in water. A bell hanging down from a boat was used as transmitter and when striking the bell a flash of light was made by igniting some gunpowder. This flash could be seen by Colladon in a boat situated at a distance of about 10 miles from the transmitter. He started his watch when he saw the flash and stopped it when he heard the signal about 10 seconds later. His receiver was a trumpet design with one end in the water and the other in his ear. By means of this rather primitive set-up they measured the speed of sound in water at 8 °C to 1435 m/s, only about 3 m/s less than accepted today.

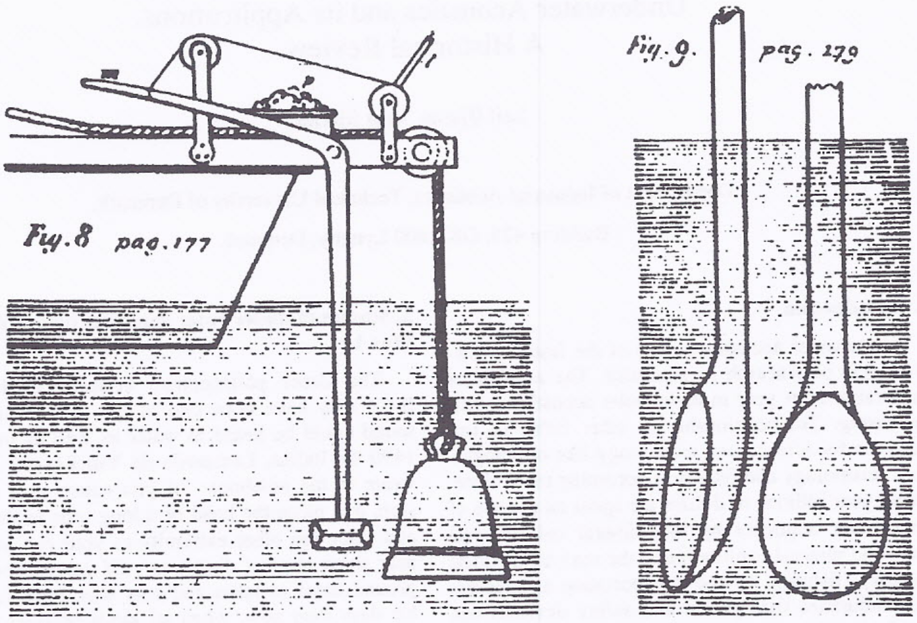
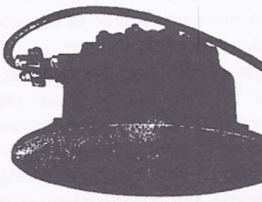


Fig. 1. J.D. Colladon and J.K.F. Sums publication of their first transmission of underwater sound. (Annalen der Physik und Chemie, Leipzig, Vol. 12, 1828)

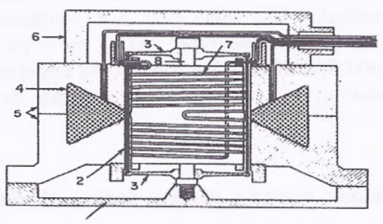
During the years 1830 - 1860 the scientists started thinking over some applications of underwater sound. Questions like: "Can the echo of a sound pulse in water be used for determination of the water depth or the distance between ships?" Or: "Can the communication between ships be improved by underwater transmission of sound?" The frustration in relation to the use of underwater sound for depth measurements comes to the surface in chapter 12 of **M.F. Maury**'s 'Physical Geography of the Sea', 6th Ed., 1859, in which he says: "Attempts to fathom the ocean, by both sound and pressure, had been made, but out in 'blue water' every trial was only a failure repeated. The most ingenious and beautiful contrivances for deep-sea sounding were resorted to. By exploding petards, or ringing bells in the deep sea, when the winds were hushed and all was still, the echo or reverberation from the bottom might, it be held, be heard, and the depth determined from the rate at which sound travels through water. But, though the concussion took place many feet below the surface, echo was silent, and no answer was received from the bottom..."

During the last half of the 19th century, when the world changed from sail to engine driven ships, concern was expressed about the safety of navigation in fog and the danger of collision with other ships or with icebergs. **John Tyndall** in the UK and **Joseph Henry** in the USA - in spite of the fact that they both in separate investigations found sound in the air to be unreliable - recommended in 1876 to the lighthouse authorities in both countries, that they should adopt high-power siren warning installations for use in air for all major lighthouses. This blow to underwater acoustics did not have any serious consequences. The possible advantages of signalling by sound in water were taken up again in the late 1880s by **Lucian Blake** and by **Thomas Alva Edison** in the USA. Edison invented an underwater device for communication between ships, but for some unknown reasons the US Government lost the interest in his work.

Reginald Fessenden



The Fessenden oscillator, circa 1913.



A cross section of the working parts of the Fessenden oscillator:

Fig. 2. Reginald Fessenden and his oscilloscope.

Submerged bells on lightships were introduced to a large extent during the last years of the l9th century. The noise from these bells could be detected at a great distance through a stethoscope or by means of simple microphones mounted on a ship's hull. Moreover, when the ship was outfitted with two detecting devices, one on each side of the hull, it became possible to determine the approximate bearing of the lightship by transmitting the sounds separately to the right and the left ears of the observer. **Elisha Gray**, working with Edison on improving the telephone, recognised that the carbon-button microphone in a suitable water-proof container could be used as a hydrophone to receive underwater bell signals. In 1899, Gray and **A.J. Mundy** were granted a patent for an electrically operated bell for underwater signalling. The commercial market now started to motivate the efforts. The work by Gray and Mundy led in 1901 to the establishment of the Submarine Signal Company in Boston (now part of the Raytheon Comp.), but the rapid development in radio communication and direction finding threatened the commercial market of undersea acoustic navigation devices.

In 1912, the Submarine Signal Company hired the Canadian, **R.A. Fessenden** to develop a sound source more efficient than the pneumatically or electrically operated bell. Fessenden designed and build a moving coil transducer for the emission and reception of underwater sound. The Fessenden oscillator, which was designed somewhat like an electro-dynamic loudspeaker, allowed ships to both communicate with each other by use of the Morse Code and to detect echoes from underwater objects. The power level in water was around 2 kW at the resonance frequency of 540 Hz. By 1914, the echo location process, known as echo ranging, was far enough developed to locate an iceberg at a distance of 3.2 Km. This development, unfortunately, came too late to avoid the Titanic disaster.

3. Underwater acoustic studies during World War I.

The outbreak of World War I and the later introduced unrestricted submarine warfare from the Germans side, were the impetus for the development of a number of military applications of underwater sound. In France the Russian electrical engineer, **Constantin Chilowsky** collaborated with **Paul Langevin** on a project involving a condenser (electrostatic) projector and a carbon-button microphone situated at the focus of a concave acoustic mirror. In 1916 they filed an application on a patent comprising the principle of their method and their equipment. The same year they had been able to signal underwater for a distance of 3 Km and to detect echoes by reflection from an iron plate at a distance of 100 m. As Chilowsky left the project after the filing of the patent, Paul Langevin in 1917 turned his interest to the piezoelectric effect - originally discovered by Jacques and Pierre Curie in 1880 - in order to develop transmitters and receivers for undersea use. The newly developed vacuum tube amplifier was used by Langevin for his quartz receiver and in 1918 he completed the development of his steel-quartz-steel transmitter. By means of this transmitter the range for one-way transmission was increased to more than 8 Km, and clear submarine echoes were heard.

A slap of the quartz was sent to **Robert W. Boyle** in the UK who in 1916 had organised a research group to study underwater ultrasonics. His experiments with the quartz receiver were as successful as Langevin's. The name "ASDIC" for the underwater detection system was formed during these days.

In the USA, **Dr. Harvey Hayes** had gathered a group of specialists at the Naval Experimental Station, New London, with the term of reference: "To devise as quickly as possible the best of available technology to defeat a U-boat". Hayes and his group developed the towed hydrophone assembly called the "Eel", and a passive sonar installation using 48 hydrophones - hull mounted and towed - were tested. This installation was the most advanced passive sonar system produced during World War I.

In Germany, **Heinrich Hecht** in Kiel developed an electromagnetic membrane transmitter which during the war was build into several hundred surface ships and submarines and **H. Lichte** performed rather extensive underwater acoustic studies in which he correctly deduced the effects of temperature, salinity and pressure on the speed of sound and he predicted in 1919 that in deep water the upward refraction produced by pressure should produce extraordinarily long sound listening ranges. This fact was verified only many years later.

4. Underwater acoustic studies 1918 - 1940.

During the period 1918 - 1940, three uses of underwater acoustics based on wartime experiences were developing extensively, but slowly; namely, **echo sounding, sound ranging in the ocean and seismic prospecting.** A great practical impetus was received from advances in electronics which made available new devices for amplification, processing and displaying of received underwater signals. **M. Marti** had in 1919 patented a recorder to be used for echo sounding. This recorder - which turned out to be of extreme importance to ocean science - consisted of a sheet of paper constrained to move slowly beneath a pen writing on the paper, while traversing the paper from one side to the other in a direction perpendicular to the motion of the paper. The pen was driven laterally to its own motion by an electric signal representing the output from the underwater sound receiver. Viewing side-by-side the successive echoes, with passage of time, a profile of the seabed could be produced. In 1922 the first long echo-sounding profiles were made while exploring a cable route between France and Algeria.

The need for improved and more rugged high-power transducers instead of the transducers based on quarts or Rochelle salt, led **G.W. Pierce** in the USA, in 1925, to develop a magnetostrictive oscillator operating at 25 kHz with a power level of a few kW, without the danger of fracture of the oscillating element as found by the crystal based transducers.

During the same period the US Coast and Geodetic Survey in their attempts to establish geodetic control by horizontal sound ranging was experiencing a strong variability in sound intensity and speed in the sea. Also the Naval Research Laboratory (NRL) seeking to improve submarine hunting, working at 20 - 30 kHz, found the same variability. Some of this variability appeared to show a diurnal cycle, where the equipment in the morning was working according to the specifications while it in the afternoon did not produce any echoes from submarines, except at very short ranges. This effect was found in several regions of the ocean. **Dr. Harvey Hayes** and scientists from the young oceanographic institution at Woods Hole, including the institution head, **Columbus Iselin**, decided to study these phenomena in more depth.

It soon became clear that the upper parts of the oceans were heated during the day by the sun leaving a layer, 4.5 - 9 meter thick, with a temperature of 1 - 2 °C warmer than the temperature of the more uniform water layer beneath and with a gradual decrease in temperature from the surface of the sea. As the appearance of the temperature layer coincided with the deterioration of the signal reception, the scientists concluded that the warm layer caused sound entering to bend downward, thus producing an acoustic shadow zone in which a submarine could hide. This discovery in 1937 through the co-operation between acousticians and oceanographers led to the start of the new field of research called, **acoustical oceanography.** The same year **A.F. Spilhaus** build the first bathythermograph, and by the beginning of World War II all US naval vessels engaged in antisubmarine work was equipped with that device.

5. Underwater acoustic studies during World War II.

The outbreak of the war launched a great activity in underwater acoustics research in Europe as well as in the USA. The hunt for submarines received high priority. The combination of convoys, aircraft patrols and the ASDIC gear effectively held off conventional daylight attacks by the small number of German submarines. However, the Germans soon learned to launch night attacks on convoys, using so-called wolf-pack techniques. The development of the airborne radar, and in particular the Allied's monopoly on the 10 cm radar, became a great help in hunting down the German submarines, of which Germany during the war lost 781.

The development in Germany of the listening equipment - in German "Gruppenhorchgeräte (GHG)" - with which the cruiser 'Prinz Eugen' for instance was equipped, gave the Germans some advantages for their surface ships. The crew of 'Prinz Eugen' later told, that they were able to track the British super-dreadnought 'Hood' over the horizon on their passive GHG device 20 miles away for a long distance and that they had a good range, bearing and course on it. They also claimed that they, and not the 'Bismarck', fired the "lucky shot" which blew-up the 'Hood'. At any rate, the passive sonar played a very important fundamental part in one of the great sea battles of World War II.

Apart from the development of underwater arms like the acoustic homing torpedo, the acoustic mine and the scanning sonar, a much better understanding of underwater factors influencing sonar performance was established. Concepts like target strength, self-noise of ships, reverberation of the underwater environment etc. were established. Sound propagation under influence of vertical variation in sound speed was studied, for instance using the 'ray theory', borrowed from theory of light, which permitted calculations of sound propagation at elevated frequencies. Most of the achievements in underwater acoustics during World War II were published just after the War in 23 reports called 'National Defense Research Committee Division 6, Summary Technical Reports'. One of these reports - entitled 'Physics of Sound in the Sea' - comprises chapters on deep- and shallow-water acoustic transmission, on intensity fluctuations and on the explosion as a source of underwater sound.

6. Underwater acoustic studies after World War II.

Maurice Ewing, professor of physics at Lehigh University in Pennsylvania, was convinced that it would be possible to propagate sound over hundreds - possibly thousands - of kilometres through the ocean if both source and receiver were appropriately placed. World War II had prevented him from testing his theory, but in 1945 he propagated sound from small explosions over a distance of more than 3000 Km from Eleuthera in the Bahamas to Dakar in West Africa.

The propagation took place in a ubiquitous permanent sound channel of the deep ocean. The channel was by Ewing called the 'SOFAR' channel, i.e. the SOund Fixing And Ranging channel. The first application of this discovery was aimed at providing a rescue system for downed-at-sea airmen. From his inflated rubber boat, the airman should drop small cartridges over the side, set to explode on the axis of the SOFAR channel some 1200 m deep in the North Atlantic. Sound from the explosion would be refracted back to the channel axis and the propagation would only be influenced by cylindrical spreading. Receiving hydrophones positioned on the channel axis at various positions off the continental shelves would contribute to the pinpointing of the source. It should be noted that also Russian scientists were studying the undersea sound channel, and in the late 40ties **L.M. Brekhovskikh** discovered the sound channel in the Pacific Ocean.

Ewing together with **J.L. Worzel** and several other colleagues at Woods Hole also studied long-distance sound propagation in shallow water. Based on their data, **Chaim Pekeris** constructed his normal mode propagation theory. This concept of elastic wave propagation has allowed underwater acousticians to model and to understand the complex acoustics of shallow water. Ewings and Worzels experiences also formed the basis of a series of sea-bed geologic structure studies performed mostly in shallow water off the East Coast of the USA. The co-operation between Ewings group at Columbia University and the scientist at Woods Hole turned out to become very fruitful for underwater seismology studies. The 'refraction method' and the 'Continuous Seismic Profiler' were developed.

A group around **C. F. Eyring** in San Diego had observed that diffuse echoes were received from the volume of the water. These echoes were arranged roughly in horizontal layers whose depths were of the order of 400 meter at noon, but they migrated to the surface during twilight and the early evening. At dawn, they migrated downward to complete a daily cycle. Due to help from marine biologists it was possible to show, that the responsible scatters were small planktonic fish having a swim bladder and living in the deep water regions of the oceans. The research in the 'deep scattering layers' peaked during the period 1949 - 1957. Important contributions to marine bio-acoustics were produced during the subsequent years.

The fast development in computer technology permitted a great step forward to be taken in underwater acoustic modelling. The ray, the normal mode and the parabolic equation methods for underwater sound propagation modelling were refined and a great number of computer codes - range independent and range dependent - were developed. Environmental models quantifying the boundary conditions (surface and bottom) and the volumetric effects of the ocean environment, and ambient noise and reverberation models have been developed. The development in acoustical modelling now seems to accelerate the model development in fields like oceanography, seismology and global meteorology.

It is an impossible task in a few lines to give credit to all the important aspects of underwater acoustics developed during the last 40 years. However, the most important achievements are reported in several books treating Acoustical Oceanography published more recently. The list of references comprises some of the most essential publications on the history of underwater acoustics and its applications and on the recent developments in acoustical oceanography.

7. Conclusions.

The development over more than 2000 years in underwater acoustics and its applications has been briefly discussed. The importance of the impact of underwater warfare and military applications on the development in underwater acoustics has been emphasized. This close relationship has frequently given underwater acoustics a heavy military element, which sometimes have overshadowed the many important civil applications of underwater acoustic research results. The termination of 'the cold war' nearly 10 years ago has, however, given basis for a more peaceful, world-wide co-operation between scientists interested in some of the aspects of great potential in underwater acoustics as for instance an inverse method like large scale acoustical tomography, which may bring us information on long term variations in the sea. The sea, which has prepared so many surprises for us and which is so important to us, still carries enough secrets to keep underwater acousticians busy for many, many years.

References.

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