Underwater Acoustics: A Brief Historical Overview Through World War II

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Research, discovery, and engineering rise to challenges in times of great peril.

Background

Man's involvement with sound in the ocean has been motivated by intellectual curiosity, as well as by necessity, in response to threat. These have included navigational hazards, catastrophes, and world events including shipwrecks and many problem areas associated with naval warfare. Around the turn of the 20th century, a number of inventors addressed the problem of navigational hazards, leading to the use of underwater bells to create warning signals. Naval warfare and the threats it poses have been the greatest motivation for underwater acoustics, starting with World War I (WWI) and reaching remarkable levels of achievement during and after World War II (WWII). These efforts led to basic discoveries in oceanography and acoustic science and engineering, including sonar and geophysical exploration.

The history of underwater acoustics over the first half of the 20th century includes its initial development, followed by a myriad of accomplishments through two world wars. This is a very broad and voluminous topic, for which only highlights can be given in this brief sketch. The material covered is largely derived from three special sessions on the topic, chaired by the authors at the 169th meeting of the Acoustical Society of America (ASA) held in Pittsburgh, PA.[1] The authors give full credit to presenters at these special sessions: Thomas Howarth, Michael Pestorius, Karim Sabra, Frederick Erskine, Michael Buckingham, William Kuperman, James Lynch, Arthur Newhall, and David Feit, as well as others who discussed topics after WWII. Coverage is restricted to underwater acoustic development in the United States and her allies France and the United Kingdom. The history of the topic in the Union of Soviet Socialist Republics (USSR) has been well covered elsewhere (Godin and Palmer, 2008).

First 20th Century Efforts and the Pioneers of Underwater Acoustics

The ASA awards a silver medal honoring five Pioneers of Underwater Acoustics: H. J. W. Fay, Reginald A. Fessenden, G. W. Pierce, Paul Langevin, and Harvey C. Hayes (**Figure 1**). Here is an outline of the pioneers' contributions.

Harold J. W. Fay was long associated with the Submarine Signal Company (SSC), which was founded in 1901 to develop commercial products in submarine signaling pertinent to ship navigation for avoiding hazards. Fay became SSC president in 1942 and led it through its merger with the Raytheon Company in 1946. He made creative strides, including a very early system whereby two carbon-button hydrophones in water-filled "sea chests," one on each side of the vessel, could be used

1 The papers were given at three special sessions chaired by the authors: "Historical Perspectives on the Origins of Underwater Acoustics I, II, and III," and are in The Journal of the Acoustical Society of America 137, 2273, 2274, 2275 (I), 2306, 2307, 2308 (II), and 2331, 2332 (III), April 2015.

Figure 1. Acoustical Society of America (ASA) Pioneers of Underwater Acoustics Medal.

to steer the ship toward a bell (Fay, 1912; Reynhout, 2002; Howarth, 2015). He is credited with leadership in underwater acoustics over almost 50 years.

Reginald Fessenden joined SSC as a consultant a few months after the April 1912 loss of the *Titanic* (Fessenden, 1940). At SSC, he began development of active sonar with a device called the Fessenden oscillator (Fessenden, 1916, 1940; Seitz, 1999; Howarth, 2015). Although a transducer and not an oscillator, it utilized a vibrating faceplate exposed on one side to seawater and driven by a voltage applied to an electromagnetic coil that moved in an induced magnetic field (much like a modern loudspeaker). This created underwater acoustic signals in the form of tone bursts, and it also received echoes. Sea trials began in 1914, demonstrating underwater communications and iceberg detection. Experiments on submarine detection were done in 1917, and the US Navy began installing Fessenden oscillators for communication on new submarines in 1918. Commercial "Fessenden fathometers" came into use in 1924.

The pioneering electronic efforts of **George Washington Pierce** greatly supported advances in underwater acoustics. Pierce served at the Naval Experimental Station in New London, CT, during WWI and developed sonar circuitry, including phase-delay "compensators," to enable a binaural listener to determine the bearing of a signal from two or more external sensors on one's own ship. He later capitalized on vacuum tube technology and developed many profitable ideas, including the famous Pierce oscillator, which remains significant to this day. He was also a pioneer in magnetostrictive transducers. These devices utilize the sound-generating expansion and contraction of certain metals when exposed to alternating electromagnetic fields, a process that also permits signal reception (Pestorius and Blackstock, 2015).

The early 20th century was a time of great advances in the physical sciences, including the development of relativity and revolutionary discoveries in atomic physics. The great French physicist **Paul Langevin** was at the center of these exciting developments. His professor (Pierre Curie) had codiscovered piezoelectricity, which is the ability of certain crystals, such as quartz, to expand and contract in an electric field and to generate an electric charge when acoustically excited. WWI motivated Langevin to utilize this effect to develop ultrasonic sonar. Quartz crystals, mass loaded on both sides to lower their resonance frequencies, were used to develop high-resolution, narrow-beam sonars. The war ended before they saw service, but Langevin was able to demonstrate ultrasonic echo ranging for submarine detection and depth finding (Centre National de la Researche Scientifique [C.N.R.S.], 1950; Zimmerman, 2002; Sabra, 2015).

Harvey Hayes was the first Director of the US Navy Torpedo Station in New London, CT, during WWI. He became the first Superintendent of the Acoustics Division of the Naval Research Laboratory (NRL) in Washington, DC, on its founding in 1923. For the next 25 years, he supervised a huge variety of benchmark research projects, establishing this organization as a world leader in underwater sound. This successful laboratory became a model for the development of subsequent underwater acoustics laboratories worldwide, and more will be said about it below. Hayes was also the first recipient of the ASA Pioneers in Underwater Acoustics Medal in 1959 (Erskine, 2013, 2015).

WWI

The onset of WWI saw the allies ill-prepared for antisubmarine warfare (ASW), and only easily developed, primitive systems were fielded. Examples include the use of Thomas Edison's carbon-granule microphone in a waterproof design, which was deployed on a vertical column and used by British fishing boats in the war effort (Lasky, 1977; **Figure 2**). The resulting hydrophone was baffled against backward excitation, and its "cardioid" directivity was used to roughly sense a target's presence and direction against noise. This device gave way to another quick solution consisting of a simple binaural pneumatic system. It utilized rubber bulbs at each end of a steerable vertical column, with sonic tubes brought into the submarine or ship to a stethoscope, enabling a trained operator to scan the horizontal azimuth for noise radiating targets in the 500- to 1,500-Hz band (Klein, 1968). Passive listening systems such as these were the main systems deployed by the allies. Sonar research by Langevin and others was successful but did not produce fleet systems before the war's end.

Several turning-point events in underwater acoustics research were initiated during WWI. The US Navy had largely depended on SSC up until the United States entered the war in 1917, and this quickly changed with the establishment of the Naval Experimental Station in New London, CT, for technology development (Lasky, 1977). This marks a trend toward creation and reliance on in-house Navy laboratories for independent research, development, and advice independent of the profit motive.

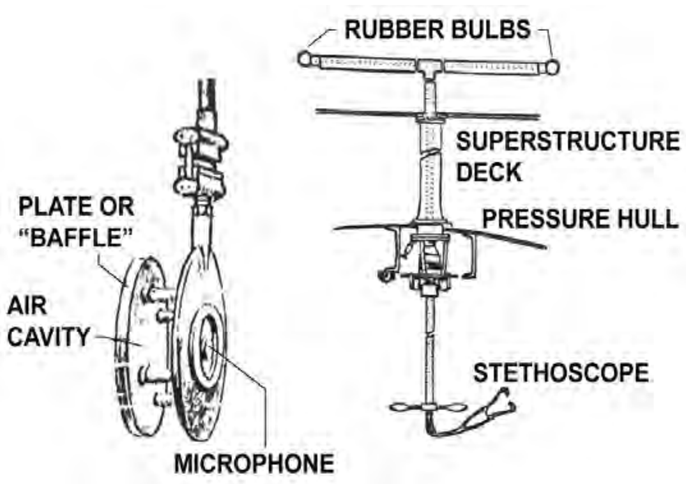

Figure 2. *World War I carbon button and pneumatic hydrophones.*

British involvement in WWI was much larger than that of the United States. A young **Albert Beaumont Wood** (**Figure 3**) had come into underwater acoustics in 1915. He and Robert W. Boyle worked with Langevin in France but developed their own piezoquartz transducer ideas for their early sonars, which were called "asdics" in the United Kingdom, a code word meaning "antisubmarine-division-ics," with the "ics" at the end as in physics. At the start of WWII, Wood was awarded the Order of the British Empire in recognition of his work on dismantling an enemy magnetic mine. A. B. Wood became an international figure in underwater acoustics, doing groundbreaking research, serving as Deputy Superintendent of the Admiralty Research Laboratory, and writing a classic acoustics book (Buckingham, 2015). He was awarded the ASA Pioneers of Underwater Acoustics Medal in 1961. A medal of the (British) Institute of Acoustics for achievements by young researchers is named in his honor and is given to North Americans in alternate years. His professional achievements and interesting accounts of his own war experiences are documented in the *Journal of the Royal Naval Scientific Service* (Wood, 1965).

Figure 3. *A. B. Wood.*

Post-WWI Efforts

After WWI, many American, British, and French scientists and engineers were busy developing the ideas born during the conflict. The first research efforts involved transduction. It was shown that Langevin's transducers could be made to work as highly directional echo-ranging devices. G. W. Pierce developed magnetostrictive transduction for depth sounding. US transducer efforts also focused on piezoelectric crystals of Rochelle salt. The NRL extended these technologies to submarine detection and developed an electroacoustic system for binaural listening (Klein, 1968).

This era saw industrial concerns develop an inventory of "searchlight sonars" for both surface ship and submarine use (**Figure 4**). The US sonars operated at frequencies of 24-30 kHz, above the frequency range of human hearing, which reduced intercept detection. They were also above the frequencies of most shipboard machinery noise sources as well as above the range of most wind driven sea-surface noise. These sonars worked by transmitting a short tone burst or "ping," typically 20-200 ms long, within a fairly directive "conical" beam, typically around 10° wide at the half-power points. Echoes were received from targets before the next ping was transmitted (National Defense Research Committee [NDRC], 1946a).

An important hydroacoustic problem was solved in 1937 by Elias Klein and others at the NRL who determined that the blunt edges on propellers led to cavitation, excited resonances in the propellers, and caused noisy vibrations aboard

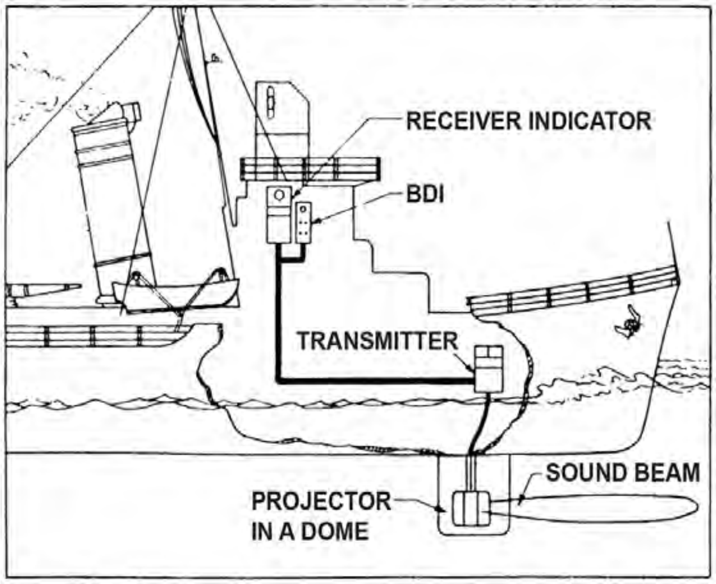

Figure 4. *Searchlight sonar concept. A sonar transducer is housed in a dome beneath the hull and is mechanically steered to search for targets. BDI, bearing deviation indicator (developed later during WWII).*

ship. Sharpening the blades led to quieter ships with more propeller thrust. The late 1930s also saw the NRL developing harbor defense technology, including an anchored acoustic buoy system called "Herald" (**Figure 5**) that was interconnected to provide alerts and track and locate stealth craft that could enter the port facility or area (Klein, 1968).

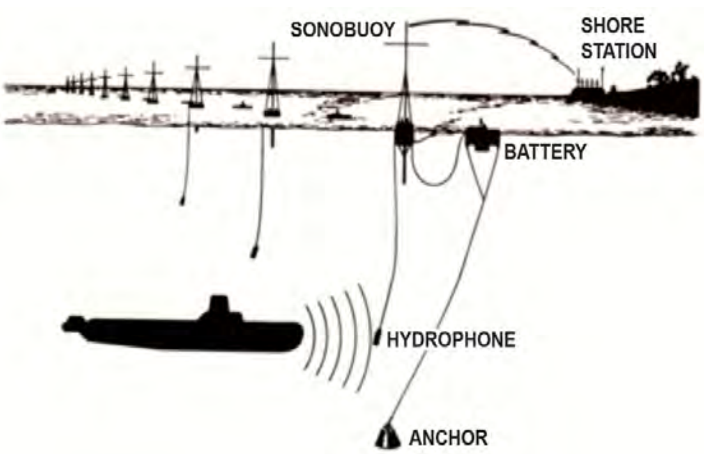

Figure 5. *Naval Research Laboratory's "Herald" system for port and perimeter security. A line of radio-coupled hydrophones senses the presence of an intruder.*

WWII

In the period leading up to WWII, several farsighted scientists in the United States became justifiably concerned with the poor state of US preparations for war. Led by Vannevar Bush, a plan was submitted to President Franklin Roosevelt in June 1940 to form a National Defense Research Committee (NDRC), with subsurface warfare becoming an action area for accelerated research and development (Lasky, 1977). It was soon recognized that the US Navy's existing underwater acoustic systems needed to be improved and new systems needed to be developed.

Three universities (Columbia, Harvard, and the University of California, San Diego) were tasked to develop staff and facilities to accomplish results in specific underwater acoustic areas, far beyond their normal academic scope, as well as the Woods Hole Oceanographic Institution (WHOI) and the Massachusetts Institute of Technology (MIT). The Navy laboratories and many American industrial concerns were heavily involved. The list is too long to contemplate here but includes major organizations shown on the simplified organizational diagram of **Figure 6** (Lasky, 1977).

The Columbia University Division of War Research (CUDWR) was established in 1941, with headquarters in New York, NY, and a sound laboratory at the US Coast Guard Station on the legendary Revolutionary War site, Fort Trumbull in New London, CT (CUDWR NLL). This laboratory undertook many projects, including research and development

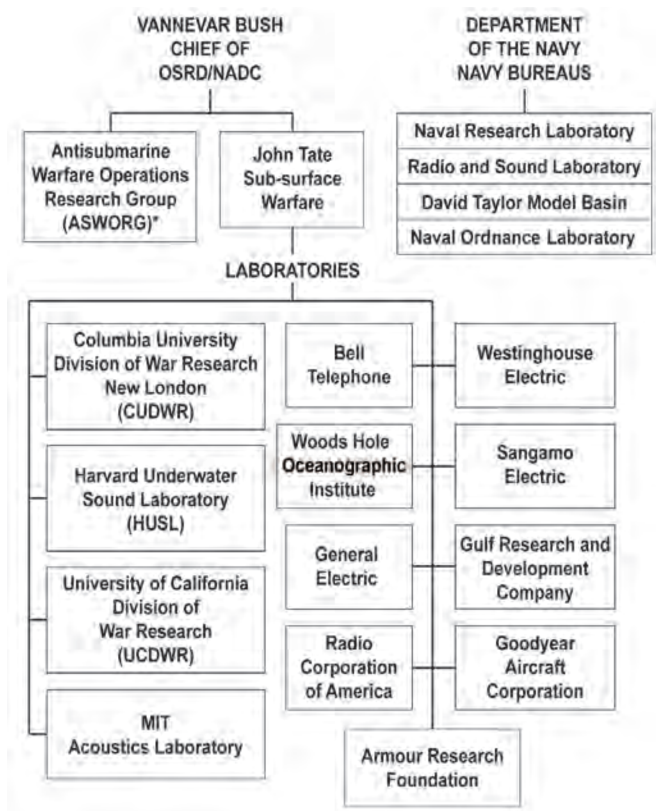

Figure 6. *World WarII research and development organizational chart. OSRD, Office of Research and Development; NDRC, National Defense Research Committee. From Lasky (1977).*

on passive listening sonar for US submarines and quieting of their radiated noise or ship signature (Lasky, 1977). An example of their work was the JP directional hydrophone system, shown in **Figure 7**, mounted on a submarine. This enabled submerged US submarines as well as patrol boats to get bearings on surface ships from their signatures in the audio band (NDRC, 1946b). This system provided much needed sensing in the audio band, enabling US submarines to sense and measure the direction of enemy ships. CUDWR NLL became the US Navy Underwater Sound Laboratory after the war (Knobles et al., 2015)

In 1942, CUDWR was also tasked to operate an Underwater Sound Reference Laboratory (USRL), under the direction of Robert S. Shankland, to be in charge of developing and providing an inventory of wideband underwater acoustic standard transducers (NDRC, 1946c; Brown and Paolero, 2015). A test facility was established in Orlando, FL, while

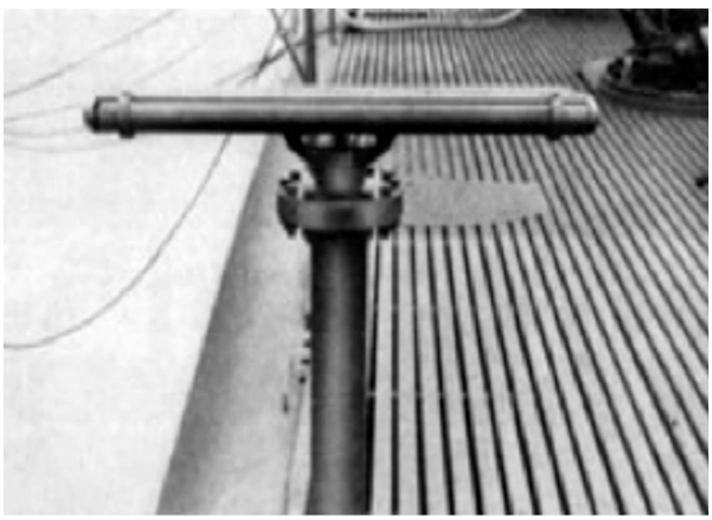

Figure 7. *JP directional hydrophone, the fleet's first wideband surveillance system in the audio band.*

the engineering work was done at CUDWR headquarters in New York. These transducers were calibrated by first principle means (i.e., reciprocity) and were utilized by a variety of clients working on the war effort.

The Harvard Underwater Sound Laboratory (HUSL) was established in June 1941 with Frederick V. (Ted) Hunt (**Figure 8**) as its director. Hunt went on to become an ASA President (1951-1952). He received the ASA Pioneers of Underwater Acoustics Medal (1965) and the Gold Medal (1969). HUSL operated for four years, making important contributions on

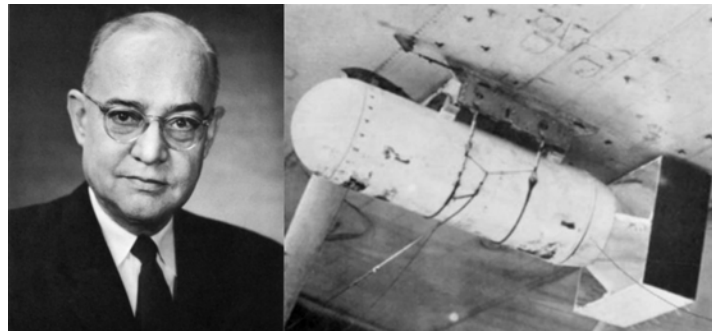

Figure 8. *Frederick (Ted) Hunt and Mk 24 torpedo "Fido."*

using sound to detect submarines by (1) improving current equipment, (2) developing new devices, and (3) developing acoustic homing torpedoes (Hunt, 1946; Pestorius and Blackstock, 2015).

Improvements to the existing fleet ASW sonar included (1) a system to determine target bearing with a single, split sonar beam, called the bearing deviation indicator (BDI), (2) a time-varying Gain (TVG) system to compensate for transmission losses, and (3) an own-ship Doppler nullification (ODN) system to increase the detection of Doppler shift in target signals. These were incorporated in an improved sonar display console. The new sonar architecture HUSL developed (cylindrical array of transducer elements, electrical capacitive, and electronic modulation scanning) set the pace for modern sonars (Pestorius and Blackstock, 2015).

A classic HUSL development was the Mk 24 torpedo (for secrecy purposes, designated a mine called "Fido") that was developed by this laboratory in record time. It was an air-dropped, battery-electric propulsion device, guided by an autonomous sonar system installed ahead of the warhead (**Figure 8**) and was developed and tested in December 1942, put in production by Western Electric, and successfully utilized in 1944 operations in the Atlantic.

The University of California Division of War Research (UCDWR) was established by the NDRC in April 1941 to capitalize on the scientific expertise of the University of California system, the Scripps Institute of Oceanography (SIO), and to provide a research and development presence on the West Coast. The Navy Radio and Sound Laboratory (NRSL) was already in existence at San Diego's Point Loma. The UCDWR was contracted to administer the NSRL for the Navy and provided most of the scientists, engineers, and technical staff while the NSRL provided the facilities and support. The first director (1941) was Vernon Knudsen, a cofounder of the ASA, a former ASA president (1933-1935), and later an ASA Gold Medalist (1967). Knudsen was succeeded in 1942 by Gaylord Harnwell, who received the Medal of Merit for his service to the NSRL and went on to become president of the University of Pennsylvania. Carl Eckart was NSRL's preeminent theoretical physicist and went on to win the ASA Pioneers of Underwater Acoustics Medal in 1973 (all shown in **Figure 9**).

The UCDWR's San Diego laboratory carried out research and experiments on a long list of oceanographic and ocean acoustic effects, including currents, water temperature, salinity, bathymetry, and other ocean variables as well as sound propagation, scattering, target strengths, reverberation, and ambient noise. The basic knowledge needed to improve sonar and the use of Navy systems was developed as were adjunct sonar devices. The UCDWR also ran an extensive training program for naval personnel and staff scientists deployed with the fleet to support equipment testing and use, and to advise on acoustics issues (Kuperman, 2015; Rees, 2015).

Figure 9. *Vernon Knudsen, Gaylord Harnwell, and Carl Eckart (left to right).*

Experts were widely recruited from unique backgrounds for tasks such as precision sound recording. Among these was Arthur Roshon, who came from Walt Disney Studios in Hollywood, to lead a major accomplishment on the development of a high-frequency continuous transmission frequency-modulated (CTFM) sonar system, designated the QLA, which was installed on 45 US submarines and proved extremely useful in mine avoidance in operations in heavily mined inland seas (NDRC, 1946d). Another major project was the development of decoys designed to simulate submarines, and over 4,000 of these saw service in the fleet (NDRC, 1946e).

WHOI was founded in 1930 at the instigation of the National Academy of Sciences and a grant from the Rockefeller Foundation and was guided by visionaries such as Henry Bigelow and Frank Lille. Beginning in 1935, geophysics professor Maurice Ewing of Lehigh University began participating in summer research cruises aboard WHOI's *R/V Atlantis* with his students, including J. Lamar (Joe) Worzel, who was to be associated with Ewing for a professional lifetime (**Figure 10**). In 1940, Ewing and his students came to WHOI for the duration of the war, bringing underwater acoustics to the institution. They included Alan Vine, Brackett Hersey, and Frank Press, who went on to become president of the National Academy of Sciences (Lynch et al., 2015).

Figure 10. *Maurice Ewing, J. Lamar Worzell, and Chaim L. Pekeris (left to right).*

Underwater acoustic experiments were done with explosive shot sources, hydrophones in the water column, and geophones on the shallow seafloor. Acoustic experiments were enhanced by the measurement of ocean parameters such as bathythermograph logging of the ocean temperature-depth profile. Worzell and Ewing (1948) made shallow-water measurements along the East Coast and studied sediment and water column propagation to discover and describe dispersive features of broadband acoustic pulses. The data sets were analyzed by Chaim Pekeris (1948; **Figure 10**) of the Columbia University Mathematical Physics Group. He carefully studied the measurement results and developed the first theoretical shallow-water, normal-mode model, which bears his name and continues to this day as a benchmark.

Ewing is credited with first predicting and then making the first measurements on the sound fixing and ranging ("SOFAR") sound channel, created by decreasing temperature and increasing pressure with depth in the deep ocean, thus creating a minimum in the sound speed-depth profile (Ewing and Worzel, 1948). This effect enables long-range propagation within a deep horizontal zone. Leonid Brekhovshikh independently found this result through the study of experimental data in the Soviet Union (Brekhovskikh, 1949; Godin and Palmer, 2008; Godin, 2015). The SOFAR channel enabled downed pilots to signal for help with a small explosive charge.

The NRL missions in WWII were in solving a myriad of problems, including remedial engineering of existing sonar for tactical ASW applications in actual warfare. One of these was to redesign the soundhead tilt mechanism so that the fleet surface ship sonar could "look downward" at steep angles to maintain echo location on submarine targets. Application of research discoveries made elsewhere were reduced to naval practice and made available to the fleet. Unique devices involving countermeasures and weapons systems were also developed to overcome wartime problems (Lasky, 1977; Erskine, 2013).

NRL field assets were also established for research and testing. The Navy's first acoustic test range was developed in Key West, FL, and the NRL's Leo Treitel developed instrumentation to test the sonars of warships passing through a test track to test the proper operation of their sonar systems.

The David Taylor Model Basin (DTMB) was named after Rear Admiral David W. Taylor, who constructed the first US facility for hydrodynamics research on ships at the Washington Naval Yard in 1898 and was a world-renowned naval architect. The DTMB facility was built in 1939 and today is part of the Naval Surface Weapons Center Division at Carderock, MD. Although largely a hydrodynamic research facility, the DTMB has been a center for underwater acoustics because there is a strong relationship between hydrodynamic flow and self as well as radiated ship signature noise, which is detected by passive (listening) sonar.

In the early days of WWII, a young physicist named Murray Strasberg (**Figure 11**) joined a DTMB group involved in submarine noise problems, headed by William Sette. They made measurements on cavitation noise bubbles generated by model propellers in the DTMB water tunnels and studied the inception of cavitation bubbles as a function of ambient pressure. Strasberg was the first to notice that the onset of cavitation noise occurred before it could be visually observed and identified an additional noise-generating cavitation effect originating from the propeller tips (NDRC, 1946b). He made the first sea trials on three Guppy class (SS 212) submarines, measuring propeller cavitation with specially installed outboard hydrophones. He went on to develop new propeller design principles, which utilized different shapes and number of blades. Murray Strasberg was later to publish in *The Journal of the Acoustical Society of America* (Strasberg, 1956), and he became a key ASA leader, serving as president (1974-1975) and receiving the Gold Medal in 2000.[2]

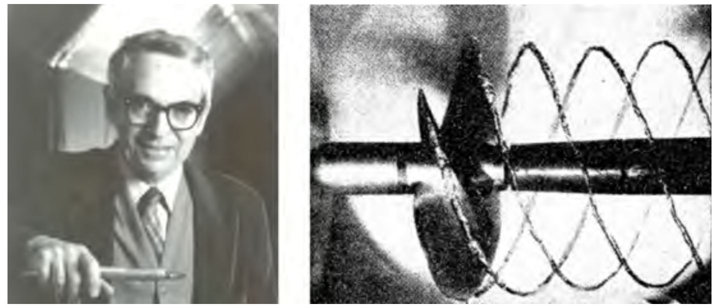

Figure 11. *Murray Strasberg and the propeller tip cavitation.*

A number of organizations conducting WWII research with those mentioned above were quite active and were not described here due to space limitations. One of these was the MIT Underwater Sound Laboratory, which did work on underwater noisemakers used to confuse enemy weapons systems (NDRC, 1946e). Perhaps the greatest MIT contributor to the war effort was Philip Morse. Vannevar Bush selected him to head the ASW Operations Research Group, which had the responsibility to guide the fleet on the effective use of their sonar, radar, and weapons systems to maximize their impact (NDRC, 1946f). His knowledge of physics and acoustics served him well in this endeavor. Morse went on to write acoustics textbooks, become president of the ASA (1951-1952), and receive its Gold Medal (1973).

Perspective

Some brief highlights of underwater acoustics in the eras sketched here have focused on noteworthy people, places, and examples of developments that were involved. Some truly significant features of ocean acoustics were discovered in these eras, for which we have only been able to give qualitative mention. Many of these efforts simply had to be done, mostly in times of war, but they became scientific and engineering achievements in their own right. Acousticians from all disciplines were involved, whereas others from completely different disciplines were also engaged. It is interesting that many of the basic and applied research discoveries made in both WWI and WWII could not be utilized before the wars ended. These achievements have since been further explored and now appear in modern texts as well as in the acoustics literature. The history of WWII shows the significant role underwater acoustics played in its outcome, and much credit is due to those members of the ASA who contributed.

[2] *David Feit presented a paper, "Underwater Acoustics Research at the David Taylor Model Basin," during a panel discussion at the special session "Historical Perspectives on the Origins of Underwater Acoustics II" at the 169th meeting of the Acoustical Society of America held in Pittsburgh, PA, 2014.*

Biosketches

Thomas G. Muir is the Director's Fellow at the Applied Research Laboratories, The University of Texas (UT) at Austin. He studied physics and mechanical engineering at UT Austin, earning a PhD in 1971. He has long been a scientist at the Applied Research Laboratories as well as a scientist at NATO's Supreme Allied Commander Atlantic (SACLANT) Antisubmarine Warfare (ASW) Research Centre in La Spezia, Italy (1986-1989); a Professor of Physics and Chair Professor of Mine Warfare at the US Naval Postgraduate School (1997-2003); and a Principal Scientist at the National Center for Physical Acoustics (2003-2010). He is an Acoustical Society of America Fellow. His research interests are in underwater acoustics, seismic acoustics, and infrasound.

David L. Bradley received a PhD in mechanical engineering from The Catholic University of America. His work career includes US Navy-supported research; Laboratory Directorship at the NATO Undersea Research Centre, La Spezia, Italy; and research/academic activity at Pennsylvania State University's Applied Research Laboratory. A Professor of Acoustics, he is funded by the Office of Naval Research. He has served on review panels for the National Academy of Sciences and has been the editor of the *U.S. Navy Journal of Underwater Acoustics* since 2011. A Fellow of the Acoustical Society of America, he has chaired Society committees and served as President.

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NEWS *from the* Acoustical Society Foundation Fund

Elizabeth L. and Russell F. Hallberg

The Acoustical Society Foundation Fund is pleased to announce the creation of the Frank and Virginia Winker Memorial Scholarship Fund. The fund was established with an initial endowment of $100,000 by the Elizabeth L. and Russell F. Hallberg (pictured) Foundation through Douglas F. Winker, individual trustee of the Hallberg Foundation, in honor of his parents. The annual scholarship is available to eligible graduate students in architectural acoustics, noise control, or engineering acoustics.

Dr. Winker explains that "this scholarship was established in honor of my parents and in recognition of their lifelong dedication to education. I was fortunate to receive their motivation, support, and guidance for my educational endeavors. It is my intention that their spirit and support of education lives on through this scholarship."

The scholarship fund was established so that additional contributions to the Acoustical Society Foundation Fund that are consistent with the goals of this scholarship can be directed to the Frank and Virginia Winker Memorial Scholarship Fund.

A scholarship subcommittee will be established to coordinate the disbursement of the scholarship on an annual basis.

Carl Rosenberg
Chair, Acoustical Society Foundation Board
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Mission of the Acoustical Society Foundation Board:
To support the mission of the ASA by developing financial resources for strategic initiatives and special purposes.

ASFF *For more information, contact: Carl Rosenberg at crosenberg@acentech.com*