Walter H. Munk: Seventy-Five Years of Exploring the Seas

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During a career spanning 75 years, Walter Munk has made seminal contributions to acoustical oceanography, underwater acoustics, physical oceanography, and geophysics.

Some people think there is more than one Walter Munk and with good reason. Acousticians know the Walter Munk who is one of the inventors of ocean acoustic tomography and ocean acoustic thermometry, or the Walter Munk who quantified the effects of ocean internal waves on acoustic propagation, or the Walter Munk of the canonical Munk sound-speed profile. Oceanographers know the Walter Munk who, with Christopher Garrett, devised the Garrett and Munk formulation of the ocean internal wave spectrum (Garrett and Munk, 1972), or the Walter Munk who did pioneering research on ocean tides, tsunamis, and surface waves. Geophysicists know the Walter Munk who studied the Earth's wobble and spin and who, with Gordon McDonald, produced a classic monograph on the subject (Munk and MacDonald, 1960), or they know the Walter Munk who was one of the initiators of the 1962 MOHOLE project to drill into the Earth's mantle.

Walter did not begin to work on underwater sound until the early 1970s after he had made seminal contributions in many other fields. When he was in China in 1978 as the chairman of the first US Oceanographic Delegation, he was asked if it was his father who had worked on ocean waves, or did he have a relative with the same name who worked on tides? When he tried to assure them that both were his early work, they were hard pressed to believe him because, they said, the Walter Munk they knew worked on acoustics! More than one person who has met him has thought that *he*, Walter Munk, was the son of *the* Walter Munk. One of us (RS) was a victim of the delusion. RS had used Walter's elegant work (with Chip Cox) on the slope of ocean waves, estimated by observing the sun's glint off the water (Cox and Munk, 1954), in his doctoral research. Like many students reading papers by famous authors, he naturally assumed that the author had long ago passed on. So when RS first met Walter in the mid 1970s he thought he was meeting Walter Munk's son!

Walter H. Munk was born on October 19, 1917, in Vienna, Austria, a country with no coastline, far from the ocean, yet he has spent much of his life in, on, and studying the sea. He was sent to the United States at age 14 to finish high school at an upstate New York preparatory academy. After graduation, he was apprenticed to a financial firm that his grandfather had founded. Apparently, to our good fortune, economics was neither Walter's love nor his forte. He left the firm after three years, and it collapsed a year after that. Then, in his own words: "Somehow I talked my way into Cal Tech and graduated in 1939 in Applied Physics." Because the girl he was seeing at the time vacationed in La Jolla, he took a summer job at the Scripps Institution of Oceanography. Although the romance ended, it was here that his life long passion for the sea was born and ultimately his interest in ocean acoustics. Scripps is where he has spent his entire career.

Figure 1. *Walter (left) with Harald Sverdrup, Director of Scripps, in the George H. Scripps Memorial Marine Biological Laboratory building at Scripps Institution of Oceanography (circa 1940). Harald was working on his epic* The Oceans. *Photo from Scripps Institution of Oceanography Archives.*

Scripps was then a small institution with a staff of about 15 led by Harald Sverdrup, the distinguished Norwegian Arctic explorer. Following the summer job, Walter returned to Cal Tech for a Master's Degree, and then the next summer, back at Scripps, he convinced Sverdrup to take him on as a PhD student (**Figure 1**).

According to Walter, for a time he constituted Scripps' entire student body. He applied for US citizenship when Nazi Germany invaded Austria. Anticipating the outbreak of war, he interrupted his studies, enlisted in the US Army, and spent the next year and a half in the Field Artillery and, because he was an avid and expert skier, in the Ski Troops. One gathers from stories he tells of those eighteen months that neither he nor the army were unhappy when he was excused from military service in order to pursue defense research at the University of California Division of War Research (UCDWR) with offices at the US Navy Radio and Sound Laboratory in San Diego. Walter says that he was so ineffective as a private that he was promoted to corporal, and he was so good at that that he was promoted back to private.

For the next six years, Walter and colleagues from Scripps at the UCDWR worked primarily on issues related to amphibious landings, starting with developing a forecast system for wave conditions to be expected during the planned Allied landing on the northwest coast of Africa. In winter the coast is subject to a northwesterly swell that produces breakers exceeding six feet on two out of three days. Because the LCVP (Landing Craft, Vehicle, Personnel) tended to broach in seas exceeding six feet, the problem of predicting the right day for the landing was critical to its success. Based almost entirely on empirical data, Sverdrup and Munk developed an analytic representation for a storm-generated, sea-surface spectrum based on wind speed and fetch and then calculated how it would be attenuated beyond the area of the storm and how it would be transformed in shallow areas. The ultimate prediction for the Normandy invasion based on their work was correct—the seas would be rough but would permit landings. This work was published in the now classic H.O. 601 (Sverdrup and Munk, 1947), and the method was used to predict sea conditions for amphibious landings in both the Pacific and Atlantic theaters. A prescient aspect of this work (aside from the fact that it yielded very good predictions!) was that it produced what amounted to a sea-surface spectrum years before an analytic spectral description of sea state was introduced.

In many ways this early work illustrates Walter's *modus operandi.* Pick a difficult problem with a big payoff, develop physical insight before equations, rely on data and observation, collaborate with colleagues, both scientists and engineers, knit it all together with great mathematical facility, and explain it simply and clearly. When working with colleagues, he always shoulders far more than his share, and even though he does more of the work than anybody, he takes less of the credit. He is particularly insistent that young people, especially students, be recognized for their contributions.

Walter has a self-professed, unique, personal philosophy. He says he chooses not to spend time polishing lectures because students learn more if they participate in halting derivations and have the joy of pointing out blunders. Yet anyone who has heard Walter's clear, concise, organized, and often humorous talks, speeches, and lectures might justly wonder about the truth of this assertion. His colleague Christopher Garrett has accused him of not letting the truth get in the way of a good seminar.

Walter has said, "I do not like to read." It may be true, but he obviously reads voraciously. One of the great joys of his writing is the wonderful way he puts things into historical perspective with his virtually photographic memory of facts and figures that can go back to Devonian times when the year had 400 days! We think Walter's philosophy is like his sense of humor—mischievous, with tongue in cheek.

Walter has modestly written about himself: "During my career I have worked on rather too many topics to have done a thorough job on any one of them; most of my papers have been superseded by subsequent work. But 'definitive papers' are usually written when a subject is no longer interesting. If one wishes to have a maximum impact on the *rate* of learning, then one needs to stick out one's neck at an earlier time. Surely those who first pose a pertinent problem should be given some credit, not just criticized for having failed to provide a final answer."

The work on waves conducted during the war years was followed by theoretical studies of wind-driven ocean gyres and then on Earth's wobble and spin in the 1950s. Irregularities in the Earth's rotation are an elegant remote sensing tool from which one can infer information about Earth's core, its air and water masses, and global winds. The notion of remote sensing has been fundamental to Walter's science, and it is no surprise that remote sensing is the basis for Walter's major contributions to ocean acoustics—the use of underwater sound to measure physical ocean parameters such as tides, currents, and heat content (Munk, 2006).

Walter spent a decade working on ocean swell (1955-65) and another (1965-75) on ocean tides. His work on swell is reminiscent of his later work on ocean acoustics in that both are of global dimensions, both involved global instrument arrays, and both involved close collaboration with engineers. Aerial photographs taken off the California coast during the war had revealed regular swells that Walter calculated (taking into account the change of direction caused by wave refraction in shallow water) were coming from the south-southwest (SSW) and, incredibly (at that time), must have been the result of winter storms in the southwest Pacific. Furthermore, it appeared that the waves were coming from a source either in or beyond the window between Antarctica and New Zealand, some 5,000 miles away. He and Frank Snodgrass, a talented engineer with whom Walter collaborated for 25 years, installed a global array of six wave stations between New Zealand and Alaska to track the waves. The data confirmed that waves off the California coast can indeed originate in Southern Ocean storms and that some may even start in the Indian Ocean some 10,000 miles distant, halfway around the world.

In the mid-1970s, as a result of serving on the JASON committee (an independent scientific advisory group to the Department of Defense named after a hero in Greek mythology), which was working an anti-submarine warfare problems, it was our luck that Walter was lured into the world of underwater sound. The Navy was concerned about the stability of underwater sound transmissions, which exhibited fluctuations in amplitude and phase that negatively affected the performance of sonar systems. Walter's work on the effects of internal waves on ocean microprocesses naturally led to considering their effect on fluctuations in the speed of sound. It was perfect for Walter—a new problem, an important one, and one that no one had tackled before.

Characteristically, Walter entered what some had thought was a mature field—after all, ocean acoustics had been studied to death since WWII—turned it upside down, completely upsetting much conventional wisdom (perhaps because he doesn't like to read and wasn't encumbered by prevailing ideas?), and generated an excitement that persists today. Through two major books (Flatté et al., 1979; Munk et al., 1995), numerous publications in the *Journal of the Acoustical Society of America (JASA)* and other journals, invited lectures worldwide, and the education of a generation of students, Walter has fundamentally changed the field by the rigorous introduction of oceanography into underwater acoustics. More than anyone, he has revolutionized our understanding of the intrinsic role oceanography plays in ocean acoustics. His name is associated with the invention of ocean acoustic tomography and ocean acoustic thermometry, with the eponymous Munk sound-speed profile, and with the Garrett and Munk internal wave spectrum.

In 1976, as part of a forerunner experiment to ocean acoustic tomography, one of us (PW), then Walter's graduate student, deployed two acoustic transceivers about 25 km apart and measured the differential travel time of acoustic pulses transmitted in opposite directions, thus providing a measure of the average current between the instruments (Worcester, 1977). In this case, transmission in one direction is aided by the current; in the opposite direction it is opposed by the current. This led Walter, together with Carl Wunsch of MIT, to propose the idea of ocean acoustic tomography (**Figure 2**) wherein acoustic transmissions between multiple acoustic sources and receivers, or transceivers, would effectively produce a tomographic cross-section of the enclosed ocean volume (Munk and Wunsch, 1979).

The spatial distribution of sources and receivers provides horizontal resolution, while the up-down cycling of sound paths in the sea provides vertical resolution. The initial idea was to measure the ocean mesoscale, features of roughly 100 km dimension that account for most of the kinetic energy

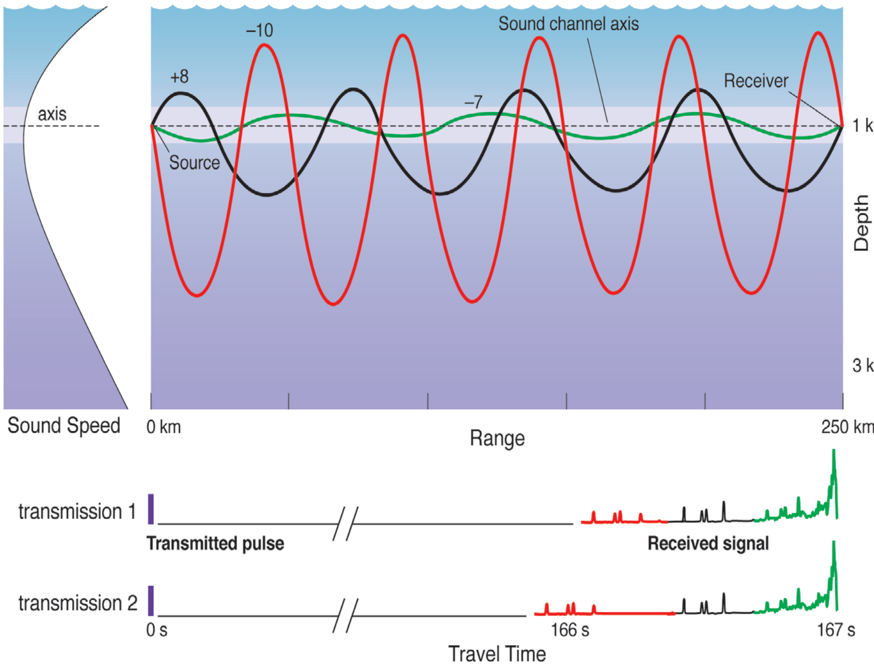


Figure 2. *Cartoon of the Ocean Acoustic Tomography method. The minimum in sound speed provides an axis for an acoustic waveguide. The time sequence of ray arrivals is from steep (red) to moderate (black) to flat (green) launch angles (flat, axial rays cannot generally be resolved). A representative ray for each of the three classes is shown in the upper panel. Transmission 2 (relative to 1) shows earlier arrivals of steep rays but no change otherwise. This is consistent with a warming of the upper ocean (or, less likely, a warming of the abyssal ocean) with intermediary and axial depths unchanged. Modified from Worcester et al. (2005).*

Figure 3. *Top Right, Greenland Sea Tomography Experiment. Walter is on the deck of the* R/V Knorr *during the Greenland Sea mooring deployment cruise, September–October 1988. Photo from Peter Worcester.*

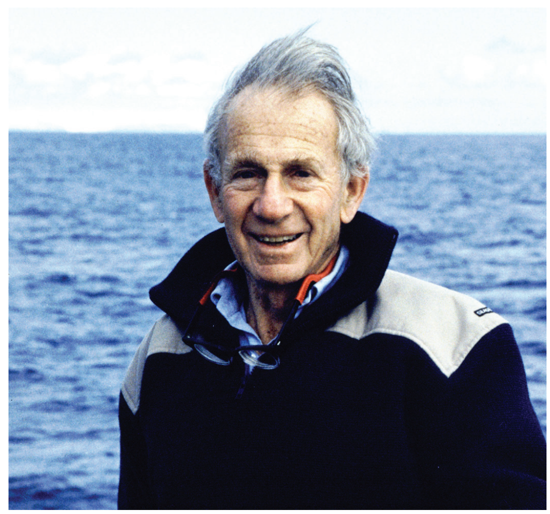


Figure 4. Bottom Right, Walter on board the R/V Cory Chouest *arriving at Heard Island on Australia Day (January 26, 1991) during the Heard Island Feasibility Test. Photo from Jeff Cordia.*

associated with ocean circulation. The mesoscale plays a prominent role in ocean mixing and has unique effects on underwater sound propagation. The first 300 km × 300 km ocean tomography experiment was conducted in 1981 in the Atlantic (Ocean Acoustic Tomography Group, see Behringer et al., 1982). The concept caught on quickly and has resulted in three decades of tomographic experiments by US, Japanese, French, and Norwegian scientists, in the Pacific and Arctic Oceans and the Norwegian, Greenland, Mediterranean, Barents, and Philippine Seas (**Figure 3**).

Never one to settle for 300-km experiments, not with an entire globe beckoning, Walter proposed using ocean acoustic transmissions to measure global ocean warming (Munk and Forbes, 1989). The idea is that sound speed in the ocean increases 4–5 m/s per °C. Thus, for example, taking a typical estimate of 5 m°C/yr warming at the sound channel axis over a 10-megameter (Mm) path, the travel time would change by −0.1 s/yr. Walter convinced the US Navy to assist in a feasibility experiment. In 1991 an array of Navy HLF-4 hydroacoustic transducers was lowered from the R/V *Cory Chouest* (with Walter on board, **Figure 4**) in the vicinity of Heard Island in the Southern Indian Ocean, an almost unique spot that permits ensonification of both the Pacific and Atlantic Oceans. It is also at a high-latitude location where the sound channel axis is shallow, which accommodated the 300 m depth limitation of the HLF-4s.

Transmissions at 57 Hz (to avoid electrical machinery noise at 50 and 60 Hz) with a source level of 221 dB re 1 μPa at 1 m RMS were received at locations throughout both oceans by teams from the US, Canada, South Africa, Australia, India, New Zealand, Japan, France, and Russia (**Figure 5**) (Munk et al., 1994).

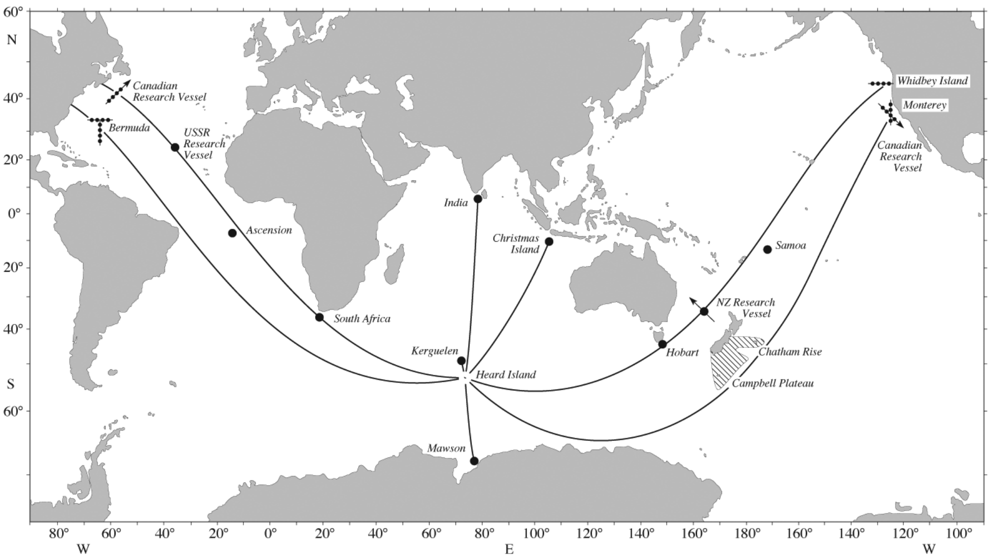


Figure 5. *Heard Island Feasibility Test. The sources were suspended from the center well of the* R/V Cory Chouest *50 km southeast of Heard Island. Black circles indicate receiver sites. Horizontal lines represent horizontal receiver arrays off the American West Coast and off Bermuda. Vertical lines designate vertical arrays off Monterey and Bermuda. Lines with arrows off California and Newfoundland indicate Canadian towed arrays. Ray paths from the source to receivers are along refracted geodesics, which would be great circles but for the Earth's non-spherical shape and the ocean's horizontal sound-speed gradients. Signals were received at all sites except the vertical array at Bermuda, which sank, and the Japanese station off Samoa. Reproduced from Munk et al. (1994).*

The Heard Island Feasibility Test (HIFT) was followed by the Acoustic Thermometry of Ocean Climate (ATOC) series of experiments during the 1990s in which acoustic sources off the coast of central California and the northern coast of Kauai transmitted to multiple receivers in the North Pacific, producing nearly nine years of time series. A summary of HIFT and ATOC is provided in Worcester et al. (2005). The HIFT was the first underwater acoustics experiment to draw attention to the possible harmful effects of anthropogenic (man-made) underwater sound on marine life, albeit unintentionally. Therefore, Walter has even contributed to biological oceanography as the most prominent instigator of today's vigorous research into the effects of underwater sound on marine mammals.

Walter has said, "I also regret that I am so poor at building and repairing gear (I was sheltered from this as a boy)." Yet he has a deep appreciation for sophisticated measurement techniques, and throughout his career he has partnered with engineers and technicians who were able to build instruments and plan and execute experiments suggested by his theories and speculations. Frank Snodgrass was followed by Walter's graduate student, Peter Worcester, with whom he has worked for over 45 productive years. He also collaborated with Robert Spindel, beginning with the first 3-D ocean acoustic tomography experiment and continuing through the Heard Island and Acoustic Thermometry of Ocean Climate Experiments during the 1980s and 1990s. Walter collaborated with Doug Webb, Woods Hole Oceanographic Institution, on the development of underwater, low-frequency, wideband acoustic sources.

An amusing story comes to mind. We (RS and PW) were at sea. Walter was doing what Walter does at sea, which is to wedge himself into a snug crevice with pad and pencil to work continuously with interruptions only for meals. He was hard at work trying to determine how to instantaneously change the frequency of an acoustic source so as to produce a wideband signal needed for high resolution tomographic measurements. He started with the idea of a vibrating string. What force could be applied to the end of the string to instantaneously stop it from vibrating, thus preparing it for the application of a second force to cause it to vibrate in another mode? There were many equations on lots of paper. People on the ship wanted to know what he was doing. He told them he was trying to figure out how to stop a string from vibrating and demonstrated by tying one end of a string to a bulkhead and moving the other up and down so as to create a standing wave. One of the crew shrugged and said he knew how to do it. He took the string and moved it up and down as Walter had, and then without solving any equations, without putting pencil to paper, he let go of the string. It stopped vibrating, to be sure, but it wasn't the solution that Walter was seeking!

Walter loves going to sea and insists on participating in experiments. Although he's a wonderful shipmate, by his own admission—and our many observations—he is not the most useful fellow on deck. On one expedition Peter Worcester and Walter were conducting an experiment that required dropping SUS charges (small, bomblike explosive devices that are a convenient wideband acoustic source). Spindel's experiment on the same ship called for deploying hydrophone listening devices (sonobuoys), and when he was about to heave one over the side, from up above came the voice of Walter frantically shouting, "Not yet. Not yet, we're not supposed to drop the SUS charges until next Wednesday." He was right about the day but wrong about the device. How could one not know the difference between a bomb and a hydrophone? Ever since, we've been wary about letting Walter near anything other than pencils and paper.

As well known as Walter was, his wife Judith was known nearly as well. They were an extraordinary, inseparable team until her death in 2006, after 53 years of marriage. Wherever Walter went, Judy went, too. Whether abroad or in the U.S., whether for a lecture or a scientific meeting, if Walter was there, so was Judy. She opened their beautiful home in La Jolla to friends, colleagues, and students. A highlight of a Scripps visit was dinner at the Munks, always enriched with good cheer and lively conversation. As Charles Kennel, a former director of Scripps described it, "An evening in her living room was renowned as the quintessential Scripps experience for students, scientists, and legions of friends from around the world." Walter and Judith have two lovely daughters, Edie and Kendall, and three grandchildren. In 2011, Walter married Mary Coakley, and she is carrying on the tradition of La Jolla hospitality. On the occasion of Walter's 65th birthday, Roger Revelle, a former Scripps director and President of the American Association for the Advancement of Science said, "Even if Walter Munk had never done any great scientific work, his life as a husband, father, and friend would still be an inspiration for the rest of us."

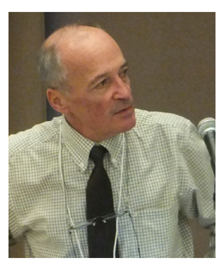
For Walter, work is an avocation. At 98 he still rises early every morning excited to tackle the problem de jour. For the last few years he has been working on the generation of low-frequency ocean ambient noise by surface waves. Walter still participates in JASON studies and takes a pro-active interest in the affairs of the US Navy research establishment through his Secretary of the Navy Chair. He has received every conceivable honor, from the National Medal of Science to the Kyoto Prize. He is an Honorary Fellow of the ASA. The United States Navy and The Oceanography Society established the Walter Munk Award for Distinguished Research in Oceanography Related to Sound and the Sea in his honor (**Figure 6**).

Figure 6. *The front of the medal for the Walter Munk Award for Distinguished Research in Oceanography Related to Sound and the Sea, granted jointly by the United States Navy and The Oceanography Society. Walter's wife, Judith, designed the medal.*

We and Walter's many other colleagues have been fortunate to have had the opportunity to know and work with him. We take pride in knowing that Walter, a quintessential gentleman, a wonderful story teller, a brilliant scientist, and a wise and generous human being and colleague, who has often claimed to have changed fields every decade, has found acoustics to be so exciting and so compelling that he has stayed with us for more than four!

Epilogue: von Storch and Hasselmann (2010) provide a fascinating account of Walter's life and work that resulted from a prolonged weekend discussion with him.

Biosketches



Robert C. Spindel is the Emeritus Director of the Applied Physics Laboratory of the University of Washington and Professor Emeritus of Electrical Engineering. He received his bachelor's degree from The Cooper Union, New York, in 1965 and his PhD degree from Yale University in 1971. He was a scientist at the Woods Hole Oceanographic Institution from 1972 until 1987 when he joined the University of Washington, where he served as the APL's director until 2003. His research interests are underwater acoustics, acoustic signal processing, and acoustical oceanography. He received the Acoustical Society of America's Silver Medal in Acoustical Oceanography in 2009.

Peter F. Worcester received a BS in engineering physics from the University of Illinois (1968), a MS in physics from Stanford University (1969), and a PhD in oceanography from Scripps Institution of Oceanography, University of California, San Diego (1977). He has been a Research Oceanographer at Scripps since receiving his PhD. His primary research interests are acoustical oceanography and underwater acoustics. Dr. Worcester is the recipient of the 2006 Walter Munk Award for Distinguished Research in Oceanography Related to Sound and the Sea. He is a Fellow of the Acoustical Society of America and the Institute of Electrical and Electronics Engineers.

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