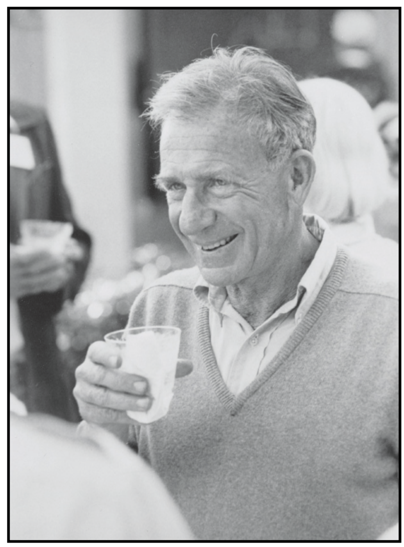
WALTER HEINRICH MUNK



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Walter Heinrich Munk was a brilliant scholar and scientist who was considered one of the greatest oceanographers of his time. He was born in Vienna, Austria in 1917 as the Austro-Hungarian Empire was declining and just before the death of one of its great artists, Gustav Klimt. Hedwig Eva Maria Kiesler, who later changed her name to Hedy Lamarr to accommodate her film career, was one of Walter's childhood friends.[1] Walter's mother, Rega Brunner,[2] the daughter of a wealthy Jewish banker, divorced Walter's father in 1927 and married Dr. Rudolf Engelsberg in 1928. By age 14, Walter apparently had not distinguished himself in his school studies and announced that he intended to become a ski instructor. Walter later claimed that it was this that caused his mother to send him to work at a family bank in New York. The validity of this claim should be tempered by the political turmoil in Germany and its proximity to Austria. In any case, Walter left Vienna in 1932.

In New York, he attended Silver Bay Preparatory School for Boys on Lake George and then became a lowly employee in the Cassel Bank, which was associated with the family's Brunner Bank in New York. In the meantime, Walter restarted his education at Columbia's Extension School. He greatly disliked the work at the bank and apparently made a number of mistakes, which didn't endear him to the owners of the Cassel Bank. Walter appealed to his mother to be released from the banking business. His mother agreed and gave him $10,000—almost $190,000 in today's dollars.

Walter purchased a luxurious DeSoto Phaeton and drove across the United States to Pasadena. He called on Robert Millikan (APS 1914; Nobel Prize 1923), the first president of the California Institute of Technology (Caltech), to accept him as an undergraduate at the Junior (third year) level based on his work at Columbia. Somehow this worked, and he threw himself into his studies. Courses in mathematics, physics, and Earth sciences were of particular interest. While there, he became well acquainted with the early seismologists Charles Richter, Hugo Benioff, and Beno Gutenburg. Upon his graduation, Walter followed a romantic interest to La Jolla. At the same time, he found employment at what became the Scripps Institution of Oceanography; his original gift from his mother had been entirely depleted. Harald Sverdrup (APS 1944) was Director of Scripps at the time, and the Second World War threatened. Sverdrup agreed that Walter could

1 Hedy Lamarr later invented the spread spectrum technology that is now in broad use in communications (e.g., Bluetooth and WiFi), and the U.S. Navy used her patent in the 1950s for sonobuoys for detecting submarines.

2 Rega Brunner's undergraduate tutor at Newnham College, Cambridge, was Harold Jeffreys, a famous physicist and mathematician who made major contributions in geophysics.

study physical oceanography for a Ph.D., which would be awarded by the University of California, Berkeley.

After a very short time with the U.S. Army in a ski battalion, Walter returned to Scripps to work with Sverdrup and Roger Revelle (APS 1960) at the University of California's Division of War Research. The study topics included ocean acoustics and anti-submarine warfare. The study of greatest interest to Walter and Sverdrup was the prediction of waves and wind near the shore. Walter was able to obtain a secret clearance by becoming an assistant oceanographer in the Army Air Force Directorate of Weather, based at the Pentagon. Walter and Sverdrup quickly developed an empirical methodology for wave prediction based on observations of wave height and frequency as a function of the distance over which the wind blew (fetch) and the length of time available to build the observed waves. They developed an idea of "significant wave height" to express the height estimated by a "trained observer." The height was formally the mean wave height of the highest third of the waves measured over time.

Walter was able to observe practice landings at a Navy base in Virginia. Experienced officers knew that landing craft would likely sink if the significant wave height exceeded somewhere in the range of 1.5–2 meters. The technique was first applied in Operation Torch in North Africa and later in Sicily. The seas in the Mediterranean were relatively calm so the early challenges were modest in terms of getting landing craft safely to the beach. Walter and Sverdrup were able to teach the method to more than 200 military and naval officers on Point Loma. The landings in Normandy were quite a different obstacle, where seas were more challenging given the latitude and the large North Atlantic Ocean. The landings were to be made on June 5, 1944. Given the poor weather at the time, the landing was postponed for 24 hours. The delayed landing was a success and, while hundreds of lives were lost, the success of the landing provided a model for collaboration of university faculty with armed forces into the future. Many years later, in 1963, when I was a Naval Academy midshipman, I spent a month in Virginia at the same base practicing landings in the same style of boats used on D-Day. I now recall that the manual for these landings included a great deal of material that came originally from Walter and Sverdrup.

Following the war, Walter's breadth of study exploded. The Navy continued to seek him out for help and advice. The Cold War followed, as did the competition between the United States and the Soviet Union. In 1946, Walter was asked to measure the flushing rate at Bikini Atoll, and a series of nuclear tests ensued. There was also concern that the larger tests might trigger a landslide and an associated tsunami. In the first tests he agreed to ride a float comprising a large tractor tire covered with a sheet of plywood, while tethered to the seafloor by piano wire. No tsunami was observed, but the *R/V Horizon* (a Scripps ship) was exposed to fallout after picking up Walter.

In the late 1940s, Walter married Martha Chapin in La Jolla. The marriage was not a happy one, and they divorced in 1953. Walter married Judith Horton on June 20, 1953. The Hortons were a well-known family in San Diego and had much to do with the development of San Diego as a city. Judith's uncle, Edward Everett Horton, was a well-known actor in Los Angeles and was in many movies, including *Little Big Shot* with Shirley Temple. Walter and Judith were married in his garden in Encino. Judith had earlier contracted polio just as she was to start her education in architecture at Harvard. She spent time in an iron lung and was able to walk with a cane, eventually two canes, and finally a wheelchair. She traveled everywhere with Walter, including a road trip in a Land Rover from the north of Finland to the Adriatic. Judith enjoyed telling a story about her recovery from polio that involved her desire to own a red Cadillac convertible. None were available in Los Angeles or San Diego, but apparently Ronald Reagan learned of this as he was to take ownership and transferred it to Judith.

Following the launch of Sputnik 1 in 1957, the U.S. government became very concerned about the apparent lead that the Soviet Union had opened over the United States in science and technology. There were many discussions on how to boost university education in both science and engineering to catch up. Several scientists including John Wheeler (APS 1951), Herb York, Murph Goldberger (APS 1980), Keith Brueckner, Charles Townes (APS 1960), Kenneth Watson—who would become the director of the Marine Physical Laboratory (1981–1991)—Gordon MacDonald (APS 1963), and Ed Frieman (APS 1990)—who later became the Scripps director (1986–1996)—were recruited to work in a highly classified environment, called JASON, to provide advice to the president on the state of American science and engineering (starting in 1961 with President Kennedy). While Walter had earlier consulted with the Navy on the Sound Surveillance System (SOSUS), he was not a member of the initial group. He did become a member in short order to address issues related to the oceans and acoustics. Not long after JASON had been formed, they undertook a long series of summer studies that continue today. Walter later convinced the group to meet first at the Bishop's School in La Jolla and then at General Atomics near the University of California, San Diego (UCSD).

During President Clinton's term, Vice President Al Gore (APS 2008) was instrumental in forming the MEDEA group to exploit highly classified technologies and knowledge in understanding the rapidly changing Earth environment.[3] MacDonald headed the organization with assistance from Jim Baker (APS 2003), who was the head of the National Oceanic and Atmospheric Administration (NOAA) at the time. MacDonald had previously coauthored *Rotation of the Earth* with Walter and had been a member of the faculty at the Institute of Geophysics and Planetary Physics (IGPP). Walter and Frieman joined the group, and I was asked to participate as well. MEDEA was disbanded by President George W. Bush, but returned under President Obama (APS 2017). Walter served in the last study for the Navy that I chaired, which examined the impact of climate change on naval operations and was published in 2011 (*Changing Oceans and National Security: Potential U.S. Navy Contributions to Understanding the Challenges of Global Climate Change—Unclassified*).

Following the end of the Second World War, Walter's attention soon turned to unraveling some of the complexity of large-scale ocean circulation in both the Atlantic and Pacific Oceans. He spent a sabbatical with Sverdrup in Oslo studying the large-scale circulation of the oceans. Walter's work, in conjunction with Henry Stommel (at Woods Hole) and Sverdrup at Oslo, explained the presence of the Gulf Stream on the west side of the Atlantic and the huge amount of water transported between the equator and the northern ocean.[4] Walter's 1950 paper "On the Wind-driven Ocean Circulation" (*Journal of Meteorology,* 7(2), 79–93) is regarded as a classic in oceanography and set the stage for his scientific career.

The Southern Ocean offshore Antarctica, with no continental boundaries in the E–W direction, drew Walter's interest. In collaboration with the Finnish oceanographer Erik Palmén, who was visiting Scripps, he realized that a very different force balance must apply in determining the Antarctic Circumpolar flow in the absence of continents. They discussed the importance of the irregular seafloor as a potential means of controlling the flow in the absence of intervening continents. Walter remained interested in wind-driven circulation and the role of turbulent mixing and wrote many insightful papers that built on this foundation. In 1966, he wrote a paper with the unusual title "Abyssal Recipes." The paper postulated that very cold Antarctic Circumpolar water would continuously sink to the seafloor and then spread through the world's oceans. The water would have to descend at a rate of approximately one meter each year. In the absence of

3 In Greek mythology, Jason found the golden fleece with great difficulty, while his lover Medea got Jason out of trouble many times in his adventures.

4 Interestingly, Benjamin Franklin, the founder of the American Philosophical Society, conducted the first scientific studies of the Gulf Stream while traveling back and forth to England and Portugal.

downward mixing of heat from the surface, the ocean would be filled with very cold water. He introduced a simple model in which a balance is struck between the proposed upward motion of cold water and the downward diffusion of heat. This simple observation led to great interest in ocean mixing and especially the role of internal tides that eventually became observable through modern satellite altimetry.

Walter's scientific training at Caltech was largely in solid Earth studies, and this interest brought him to support a proposal named "Project Mohole." The Moho was discovered by the Croatian geophysicist Mohorovičić and is generally regarded as the boundary between Earth's upper mantle and the overlying, complex crust. A collection of Earth scientists, including Walter, sought to balance the modern fascination in the space program with a romantic idea of exploring the outer ranges of the solid Earth. The proponents formed a new organization, which they named the American Miscellaneous Society. The project was funded through the National Science Foundation, and an initial effort was made offshore Baja, California from a barge named *CUSS-1*.

The platform was outfitted with a drilling rig and used outboard motors to hold the vehicle in place rather than tethering the system to the seafloor. Acoustics were used to determine the barge's position, and a watch was set to operate the system to hold station. Rocks were retrieved from the seafloor, although the bit drilled through only the veneer of the 5-kilometer-thick ocean crust. John Steinbeck spent some time on *CUSS-1* and wrote a cover story for *Life* magazine with the intention of emphasizing the scientific value of the program vis-à-vis the much-better-funded space program.

The idea of *acoustic tethering* to the seafloor eventually became an important contribution to commercial ocean drilling for petroleum. Walter's brother-in-law, Ed Horton, developed and operated the acoustic station-keeping device and later had great success in building large spar buoys for extracting oil and gas from great depths. Several years later, the Deep Sea Drilling Project (DSDP) and the Ocean Drilling Program (ODP) became major international projects, which contributed greatly to scientific programs in understanding the structure of the ocean crust, the biological history of marine sediments, and the details of plate tectonics. Walter considered this to be his largest failure, but history refutes this. The micropaleontology developed by the program has been critical in discovery of ocean and gas resources and drilling demonstrated the validity of plate tectonics.

Walter's scientific interests brought him to insightful measurements of the length of day on a rotating solid Earth and complexities associated with connections to the oceans. The "Chandler wobble" deals with the movement of the rotation axis within the Earth. Harold Jeffreys (Walter's mother's tutor at Cambridge) had suggested that the noise in the motion was somehow related to geophysical processes. A wide variety of phenomena included the large-scale behavior of the atmosphere, the ocean currents, earthquakes, ice sheet growth and decay, the response of the solid Earth, and its fluid outer core. With a young Gordon MacDonald, Walter published the book *The Rotation of the Earth: A Geophysical Discussion* in 1960. The most recent version of the book bears a date of 2009. Walter returned time and again to the complex relationship between the solid and fluid Earth in understanding the secular change in the length of day. He encountered a problem in reconciling the observed phenomena of tide gauge and temperature data with the secular change in Earth's rotation. It appears that the problem has been resolved by recent work on the interaction between the solid mantle and the underlying liquid core.

In the early 1950s, Walter obtained the brief use of an Air Force B-17, the Flying Fortress, for making observations of sun glitter as a function of wind speed. With no wind and no waves, the result is straightforward. However, as wind speed increases and waves form, the glitter resulting from segments of the waves becomes complex. He was able to demonstrate that a previous result associated with wave frequency doubling at the seafloor extended to very small waves including capillary waves. Walter returned to this problem several times over his lifetime, but he was unable to understand the relationship. He continued to work on this intensely as his lifetime passed the century mark. In the end, the problem remains unsolved.

Walter was joined at Scripps by Frank Snodgrass in 1953. Walter had no qualms in admitting that he had little skill at working at sea. Snodgrass was the polar opposite, and their collaboration lasted for decades. One of their first experiments was to build capsules that could measure changes in pressure at the seafloor. In some of the first measurements near Guadalupe Island off Mexico, they found that the recorded surface waves indicated that the swell had a distant source—in this case from the southern Indian Ocean that traveled to Guadalupe Island via New Zealand. This gave rise to a number of experiments that were documented in the movie *Waves across the Pacific*. Walter, Judith, and their two daughters (Edie and Kendall) manned an observatory on Samoa, shown in the movie, to verify the proposed global propagation and evolution of ocean swell.

Immediately following the Second World War, the University of California, and in particular the University of California, Los Angeles (UCLA), began an effort to merge geology and physics in what came to be geophysics. UCLA was now the parent of the Scripps Institution of

Oceanography. Scripps itself was originally a biological field station with parentage at Berkeley. The geology department was not convinced that such a marriage should be pursued. In order to explore the issue more formally, an "Institute of Geophysics" was formed at UCLA.

Harald Sverdrup was very active in the formation of the Institute of Geophysics and, as early as 1945, was asked to be the director. The nomination was also strongly supported by UC President Sproul. Sverdrup, however, felt he had his hands full as Scripps Director and its modernization and acquisition of capable research ships. Both Walter and Sverdrup were two of the earliest faculty appointed at the Institute. Two later faculty appointments were Barry Block and Robert (Bob) Moore, both at the time on the staff at the Princeton Physics Department working with Robert Dicke (APS 1978).

In the late 1950s, Walter's research had gained much attention and he had offers for faculty positions at both Harvard University and the Massachusetts Institute of Technology (MIT). He seriously considered moving to one of the two institutions. Revelle, the Director of Scripps by then, pointed out that he could have anything at Scripps that he might find at either of the institutions in Boston. Walter was eventually convinced to stay at Scripps, and the UCLA Institute of Geophysics and Scripps provided the funds needed to establish a new branch of the Institute of Geophysics at Scripps. The construction of a new building to house the new branch was part of the offer to Walter.

Cecil Green, originally an early exploration geophysicist with extended experience in the Near East, was the president of Texas Instruments and became involved in the extensive fundraising effort. The funds were eventually collected, and a new building was completed at the end of 1963. Lloyd Ruocco was chosen as the architect. Ruocco felt that "Good architecture should call for the minimum use of materials for the most interesting and functional enclosure of space." Years later, Fred Leibhardt, who apprenticed with Lloyd, was the architect for an addition, the "Revelle Laboratory" across the street.

Walter's wife, Judith, had earlier studied architecture at Harvard before contracting polio. The original lab became the Munk Lab of the Cecil H. and Ida M. Green Institute of Geophysics and Planetary Physics. Judith insisted on being a "good customer" by being closely involved in the review of plans as they were transformed into construction blueprints.

When the original Institute of Geophysics at Scripps was formed, the directions were broad: "Geophysics is used here in its broadest meaning as a term to comprise the sciences of meteorology, including the general physics of the atmosphere; physical oceanography; hydrology; seismology; volcanology, and certain aspects of geology."

Walter greatly disliked the use of room numbers and decided that photographs of scientists that had made major contributions to geophysics would be used to identify the rooms. It's telling that the portrait on his door was Henry Stommel, who spent his career at Woods Hole pursuing deep circulation in the World Ocean.

During the 1950s, Revelle began planning for a new campus of the University of California, La Jolla (UCLJ). Several of the new faculty at UCLJ were lodged at the Institute of Geophysics as construction proceeded on the mesa above. Two of these new faculty members were Geoffrey and Margaret Burbidge (APS 1980) from Great Britain. Their residence in the new building prompted the change in name to the Institute of Geophysics and Planetary Physics (IGPP). Geoffrey ran the Kitt Peak National Observatory and died in 2010. In 1972, Margaret became the Director of the Royal Greenwich Observatory (RGO) near London. Generally, the position of Astronomer Royal came with the directorship, but not in the case of the first female director. She left the RGO after 15 months over a dispute about moving the Isaac Newton Telescope from the RGO to the Canary Islands. She returned to La Jolla and built several instruments for the Hubble Space Telescope.

Other photographs on the doors of IGPP include Edwin Hubble (APS 1929), Sir Fred Hoyle (APS 1980), and William Fowler (APS 1962). All of these astronomers were interested in nucleosynthesis of elements heavier than iron in stars. A famous paper in astrophysics became known as "B^2FH" after Burbidge, Burbidge, Fowler, and Hoyle. Subrahmanyan Chandrasekhar (APS 1945) and Fowler shared the Nobel Prize in 1983 through the extension of B^2FH to elements denser than iron. Chandrasekhar's photograph is on a door; he was IGPP's George Backus's Ph.D. advisor at the University of Chicago. Backus brought general relativity and the formal structure of tensor calculus with him. This became invaluable in the continuum mechanics of a solid Earth.

John von Neumann's (APS 1938) photo also appears on a door at IGPP with a pineapple on his head. He had worked on the Manhattan Project during the war, but also on the UNIVAC (Universal Automatic Computer) at the University of Pennsylvania. Toward the end of the war, the Office of Naval Research (ONR) agreed to build a new version of the UNIVAC, which von Neumann named the MANIAC (Mathematical Analyzer Numerical Integrator and Computer Model). The installation was conducted at the Institute for Advanced Studies (IAS) at Princeton, and the contract monitor for the project was Navy Commander Roger Revelle. In 1951, UCLA Dean Paul Dodd offered von Neumann a special interdisciplinary professorship with as much time at the Scripps Institution of Oceanography as he wished. Because the IAS had not warmly accepted the idea of an electronic computer in the Institute, von Neumann accepted. Von Neumann was a polymath of great breadth. His studies and works included linear programming, Monte Carlo solutions to inverse problems, functional analysis, quantum statistical mechanics, climate geoengineering, and computer architecture. He invented the use of the "kiloton" in gauging the size of nuclear explosions. To explain the pineapple, his wife Klara noted that he could ". . . count anything, but calories." He enjoyed good food and even better wine. Unfortunately, von Neumann died in early 1957 of a cancer he fought for a year while at the Eisenhower Wing of the Walter Reed Hospital. He never had an opportunity to spend an extended time at IGPP. His wife Clara later married Scripps' Director Carl Eckart. Certainly, IGPP's early adoption of computers had been influenced by von Neumann as well as Walter Munk and Freeman Gilbert.

In his studies of tides and surface waves on the ocean's surface in the 1950s, Walter became interested in spectral analyses and the related field of time series analysis. The idea of a periodogram arose in the 19th century with Sir Arthur Schuster (APS 1913) but became of great interest during the Second World War at MIT. Walter worked with John Tukey (APS 1962) at Bell Labs, who had become famous for investigations in spectral analysis and invented the term *bit*. He also invented the fast Fourier transform (FFT). At Walter's 65th birthday party, Tukey asserted that "Walter Munk may well be the most effective practitioner of the spectrum analysis the world has seen." Several people at IGPP wrote a users' manual for practical spectral analysis that was named BOMM after Sir Edward (Teddy) Bullard (APS 1969), Francis Oglebay, Walter Munk, and Gaylord Riggs Miller.

In the 1960s, the collection of geophysical data was being transformed from notes in lab books, and analog and FM recordings, to machine digitization of observables. In the case of Walter's newer instruments, such as his seafloor tide capsules, he punched pressure data on paper tape, a common practice at the time. A large, sunlit room at IGPP included three long rows of cedar tables along which the punched tapes could be stretched for reading and quality control. The data, when ready, were then analyzed using the BOMM software, including the FFT. The computers, at the time, were also quite rudimentary, but this changed rapidly. In the 1980s, the room was no longer used and was converted to student offices and a computer room for the students' use.

BOMM, however, continued to have an impact. Robert Parker built on geophysical inverse theory through a series of papers and classes that depended on the manipulation of large matrices. One student, Loren Shure, completed her Ph.D. in 1982 and moved to

Woods Hole as a postdoc. While there, she decided to accept a position at a small company in Boston—Mathworks. She was the third employee at the company, and the now-commercial software is known as MATLAB. The software is widely used in education, scientific research, and business for solving large programs in linear algebra and the relatively new field of artificial intelligence (AI). Walter's BOMM has come a long way.

The presence of astronomers at IGPP in its earliest days had a significant impact on increasingly close contacts with Cambridge. Fred Hoyle spent time at IGPP with the Burbidges working on nucleogenesis. When he returned to Cambridge, Hoyle constructed a new Institute of Astronomy that was modeled after the IGPP architecture. Today, the building would likely be called the "Institute of Astrophysics." Lord Martin Rees (APS 1993), also a frequent visitor to Scripps, wrote Hoyle's obituary and commented that the building didn't look over the Pacific, but over the cows across the road. The small pasture is bounded by the Institute of Astronomy and the Bullard Lab (geophysics) on Madingley Rise. Generations of IGPP geophysicists have moved back and forth over the years for their educations and sabbaticals.

Sir Edward (Teddy) Bullard was a frequent visitor at IGPP starting in the 1960s. Bullard studied at Cambridge under Ernest Rutherford (APS 1904) at the Cavendish Lab and received his Ph.D. in nuclear physics. Because of the global depression, he elected to become a geophysicist with practical relationships to petroleum prospecting. During the Second World War, he worked on degaussing ships to avoid magnetic mines. After the war, he became a major figure in the development of the theory of plate tectonics and invented the measurement of heat flow in seafloor sediments. Bullard spent large amounts of time at Scripps and IGPP and moved there permanently in 1980. He was a founding member of Churchill College near Madingley Rise, the college that adopted Walter on his many sabbatical visits. A very practical invention came from Bullard's work on heat flow, the "O-Ring." This was a critical invention in making observations at great depth. The rubber or synthetic ring sat between an instrument housing (often a long tube) and the cap that sealed the ends of the tube. At shallow depths, the flexible O-Ring kept water out. As the pressure increased, the soft ring compressed allowing the metal endcap and cylinder to form a metal-to-metal watertight seal. This was a revolutionary and critical invention (possibly the most important invention in ocean observations in history), and Walter made great use of it in all the work he and his students did over the years.

While not generally appreciated, Princeton and the Physics Department in particular had a major impact on the research done at IGPP in the early years, and Walter played a major role in the subsequent research. Robert Dicke and John Wheeler were interested in the Theory of General Relativity. Wheeler was a great theorist, while Dicke was an extremely capable experimentalist. Dicke was generally dismayed that few useful experiments in gravity were being pursued and challenged Wheeler about the obvious value of the experimental verification of General Relativity. Wheeler received a Nobel Prize in 1965, and Dicke formed a very successful business (Princeton Applied Research). (I used one of Dicke's "Lock-In Amplifiers" in my Senior Trident Scholar project in 1966 at the Naval Academy.) Dicke proposed a project he called the "Naissance of Experimental Gravity"; he emphasized that this was not a "renaissance" since there had been very few critical observations in the past. I noted earlier that two of the original appointments to IGPP were Bob Moore and Barry Block from Princeton. Dicke had noted, "There are two experiments being started now. One is an improved measurement of g [little g or the local acceleration of gravity] to detect possible annual vibrations. This is coming nicely, and I think we can improve earlier work by a factor of ten. This is done by using a very short pendulum, without knife edges, just suspended by a quart fiber, oscillating at a high rate of around 30 cycles/sec. instead of the long slow pendulum." In fact, this was work done by his students who had come to IGPP under Walter's Directorship. Dicke had also noted that the normal modes of a spherical Earth had never been measured—the work by Block and Moore initiated these measurements, and the first measurements of normal modes were made at IGPP.

Freeman Gilbert, Jon Berger, and Bill Farrell, with support from Cecil Green, started Project IDA (International Deployment of Accelerometers; Ida was Cecil Green's wife). The instrumentation has been greatly enhanced over the years and forms the academic component of the Global Seismic Network. The formal relationship between Cecil Green and IGPP was cemented in the late 1960s by Walter Munk and Cecil Green with the formation of the IGPP Green Foundation. It continues to this day and supports visitors, postdocs, and new instrumentation. The Green Foundation is unique in the whole of the University of California.

The breadth of Walter's scientific interests has resulted in a faculty, research staff, and engineering capability that is unusual in oceanographic institutions. The demands of new experiments have led to interesting new engineering challenges that are translated into hardware by very capable machine shops. In the not-distant past, physics departments all had major shops; few do today. Nevertheless, the Scripps machine shop is unparalleled in its capabilities in constructing ocean-going instruments. The Marine Physical Laboratory (MPL) has another fine shop with decades of experience. IGPP continues to operate its own shop, but major work is generally done at the Scripps or MPL shops today. In 2019, Scripps opened its own "Maker Shop" that allows students, postdocs, and faculty to experiment with scale models of new systems, including the software to allow them to operate. In terms of the faculty and research staff, the long history of integrating computing, methodologies associated with tensor calculus, geophysical inverse theory, geodesy both traditional and space-based, arctic studies, time series analysis, and applied mathematics has led to advances in many fields in the oceans, in space, and on land. One example over the past 20 years is ocean acoustic thermometry. Solid Earth tomography, using earthquake sources, has led to a major advance of understanding of the three-dimensional structure of Earth's interior. Seafloor instrumentation is contributing to this work.

The ocean itself is heterogeneous at all scales, and sampling in detail in a rapidly changing environment is impossible. In the 1990s, Walter, Carl Wunsch (MIT; APS 2003), and Peter Worcester began to study the application of seismic tomography to the oceans—ocean acoustic tomography (OAT). The applied mathematics for tomography was largely developed by seismologists working from land with targets in deep Earth. Nevertheless, the methodologies were in place to image the time-varying properties of the global oceans. Because the major changes in ocean sound speed result from changes in water temperature, the work became known as Acoustic Tomography of Ocean Climate (ATOC) or Ocean Thermometry. Walter played the leading role in developing new methods for tracking long-term changes in climate associated with global warming as part of the ATOC project.

Starting in the early 1970s at the Cecil and Ida Green Piñon Flat Observatory in the high desert above Palm Springs, Jon Berger and Ralph Lovberg began the construction of a 3-axis laser interferometer to measure small motions in the Earth. The system exploited approximately 1-kilometer-long evacuated tubes with a laser interferometer for measuring motions. The ostensible purpose of the strain meter was to measure possible motions in the Earth prior to an earthquake. After some period of operation, "optical anchors" were used to measure the position of the long granite piers in order to enhance the fidelity of the measurements. One day in the early 1980s as LIGO (Laser Interferometer Gravitational-Wave Observatory) was being planned at Caltech and MIT, Berger and Frank Wyatt were installing optical anchors. They were visited by Professor Ronald Drever from Caltech. He was interested in the long legs of the interferometers and the use of the interferometers for making lateral measurements of motion. Drever was an investigator of a new National Science Foundation project entitled "Laser Interferometer Gravitational-Wave Observatory," or LIGO. The goals were vastly different, but the technologies were closely allied. IGPP wanted to measure details of Earth motion with great fidelity, while LIGO hoped to isolate Earth motions to measure waves in space-time. Drever was experimenting with the use of large tractor tires at Caltech to isolate the interferometer from the Earth, and IGPP was working on the opposite problem. Of course, the tire idea was a small step in the right direction, but they succeeded in making the first measurement with LIGO of the interactions of two black holes in 2016. The tractor tires had disappeared years ago, and the system now uses seismometers identical to those in many of the global and ocean seismic networks to provide feedback signals to quiet the related motions of the interferometer. Dicke's Naissance had come full circle, and Walter was alive to see it.

Judith Munk died of pneumonia in 2006, shortly after returning from a trip with Walter. In 2011, Walter married Mary Coakley, a leader in the La Jolla community. Walter and Mary traveled extensively, including a honeymoon in Venice. At the end of his career, Walter was Research Professor of Geophysics, Emeritus, at the Scripps Institution of Oceanography. He received numerous honors for his work, which are listed below, and remained active in scientific projects throughout his life. He died in 2019 at the age of 101.

Elected 1965

John Orcutt
Distinguished Professor of Geophysics
Cecil and Ida Green Institute of Geophysics and Planetary Physics
University of California, San Diego

Honors and Awards

1948	Guggenheim Fellow, Oslo University
1955	Guggenheim Fellow, Cambridge University
1962	Guggenheim Fellow, Cambridge University
1965	Arthur L. Day Medal, American Geological Society
1966	Harald Sverdrup Gold Medal, American Meteorological Society
1966	Alumni Distinguished Service Award, California Institute of Technology
1968	Gold Medal, Royal Astronomical Society
1969	California Scientist of the Year, California Museum of Sciences and Industry
1970	Josiah Willard Gibbs Lecturer, American Mathematical Society
1970	Lockheed Martin Award
1975	Doctor Philosophiae *Honoris Causa*, University of Bergen, Norway
1976	Agassiz Medal, National Academy of Sciences
1976	Maurice Ewing Medal, American Geophysical Union and U.S. Navy
1978	Senior Queen's Fellow, Australia
1978	The Captain Robert Dexter Conrad Award, Department of the Navy
1978	UCSD Alumnus of the Year
1981	Fulbright Fellow, U.K.
1985	National Medal of Science
1986	Doctor Philosophical *Honoris Causa*, University of Cambridge, England
1989	William Bowie Medal, American Geophysical Union
1992	UCSD Alumnus of the Year
1993	Walter Munk Award, Office of Naval Research & The Oceanography Society
1993	Vetlesen Prize, Columbia University
1993	Presidential Award of the New York Academy of Sciences
1996	Doctor Philosophical *Honoris Causa*, University Crete, Greece
1997	Rolex Lifetime Achievement Award, Singapore
1999	Kyoto Prize, Inamori Foundation, Japan
2001	Albert A. Michelson Award, Navy League of the United States
2001	Prince Albert I Medal, International Association for the Physical Sciences of the Oceans (IAPSO)
2007	Lifetime Achievement Award, The American Society of Mechanical Engineers
2007	Spirit of Surfing Award, The Groundswell Society
2010	Crafoord Prize, The Royal Swedish Academy of Sciences

2010	*Österreichisches Ehrenzeichen für Wissenschaft und Kunst* (Austrian Decoration for Science and Art)
2013	Aquarium of the Pacific Conservation Award
2013	Roger Revelle Medal, UCSD 2014 Explorers Club Medal
2014	Medal of Honour of the French Navy
2015	American Polar Society Medal 2017 Doctor of Humane Letters, UCSD
2018	*Chevalier, Légion d'honneur*, France