1 Background

1.1 Some History

As a child you probably played the swimming pool game of tag where you close your eyes and then repeatedly call out “Marco” with the response “Polo” each time from the other players by which you’re supposed to locate them and tag someone who is then it. Biurnal hearing allowed you to tell which direction to lunge, and you could guesstimate who was nearby and who was farther away. The game is a little trickier to play at indoor pools because the acoustic scattering from walls and such can be confounding.

Marco Polo may or may not have traveled from Venice to China, although he did spend a couple of decades travelling and trading along the Silk Road, where he would certainly have picked up a lot of information, such as how to make power smoothies, and trade goods like yak hair [1]. He mistook rhinos for chubby unicorns, which is now a meme. In his book, he also claimed to have been besties with the emperor Kublai Khan. Christopher Columbus brought a copy of that book along with him on his 1492 trip to the Orient, but it turned out to be unhelpful. Navigating the world based on maps pieced together from stories of other travelers is always going to be a bit iffy. Fortunately, over the last century or so there has been a rapid development of navigation technologies.

The Submarine Signal Company, established in 1901 in Boston, was the first commercial enterprise organized to conduct underwater sound research and to develop equipment to be used for increasing the safety of navigation [2]. “Our invention relates to a method of ringing or sounding a bell and also to a system and apparatus for transmitting intelligence between ships at sea and between the shore and any ship by means of sound-signals made in the water at the transmitting-station by electrical means. These sounds are picked up from the water at the receiving-station by means of electrical or mechanical devices.” The initial product line included underwater bells for shore-based stations, buoys, and lightships as well as encased microphones for sound detection on the ships [3, 4].

1.1.1 The Titanic Disaster

In 1912, the unsinkable Titanic struck an iceberg and sank [5]. Not long after, Sir Hiram Maxim self-published a short book and submitted a letter to Scientific American [6] in which he asked, “Has Science reached the end of its tether? Is there no possible means of avoiding such a deplorable loss of life and property? Thousands of ships have been lost by running ashore in a fog, hundreds by collisions with other ships or with icebergs, nearly all resulting in great loss of life and property.” Maxim noted that collisions often take place in a fog at night when a searchlight is worse than

A Data Engineering Approach to Wave Scattering Analysis: with Applications in Radar, Sonar, Medical Diagnostics, Structural Flaw Detection and Intelligent Robotics, First Edition. Mark K. Hinders.

useless because it just illuminates the haze. It was (becoming) known that bats used some form of sound that was outside the range of human hearing in order to echolocate and feed, but he thought it was infrasound rather than ultrasound [7, 8]. Maxim described a concept for a very low-frequency directional steam whistle or siren that could be used to (echo)locate icebergs during foggy nights when collisions were most likely to occur. Whether Maxim's patented apparatus would have been effective at preventing collisions at sea is a question that's a little like whether Da Vinci's contraptions would have flown. He got the general idea right, and can be credited with stimulating the imaginations of those who subsequently worked out all the engineering details.

His sketch, reproduced as Figure 1.1, is quite remarkable. The key idea is that the time delay of the echoes determines distance because the speed of sound is known, but more importantly, the shape of the echoes gives information about the object that is returning those echoes. Analysis of those echo waveforms can, in principle, tell the difference between a ship and an iceberg, and even differentiate large and small icebergs. He even illustrates how clutter affects the echoes differently from backscattering targets. Science has not, in fact, reached the end of its tether, even after a century of further development. This is exactly how radar, sonar, and ultrasound work [9, 10].

Maxim's suggested apparatus embodies a modified form of "siren," through which high-pressure steam can be made to flow in order to produce sound-waves with about 14–15 vibrations per second, and consequently not coming within the range of the human ear. These waves, it is asserted, would be capable of traveling great distances, and if they struck against a body ahead of the ship, they would be reflected toward their source, "echo waves" being formed [11]. This self-published pamphlet was discussed in [12].

1.1.2 Das Unterseeboot

The first submarine to successfully dive, cruise below the water surface, and emerge to the surface again on its own was the Sub Marine Explorer of the German American engineer Julius H. Kroehl, which already comprised many technologies that are still essential to modern submarines [13]. The first submarine built in Germany, the three-man Brandtaucher, sank to the bottom of Kiel harbor on 1 February 1851 during a test dive [14]. The Confederate States of America fielded several human-powered submarines, including CSS H. L. Hunley. The first Confederate submarine was the 30-foot-long Pioneer, which sank a target schooner using a towed mine during tests on Lake Pontchartrain, but it was not used in combat. It was scuttled after New Orleans was captured and in 1868 was sold for scrap, but the similar Bayou St. John submarine is preserved in the Louisiana State Museum. CSS Hunley was intended for attacking Union ships that were blockading Confederate seaports. The submarine had a long pole with an explosive charge in the bow called a spar torpedo. The sub had to approach an enemy vessel, attach the explosive, move away, and then detonate it. It was extremely hazardous to operate, and had no air supply other than what was contained inside the main compartment. On two occasions, the sub sank; on the first occasion, half the crew died, and on the second, the entire eight-man crew (including Hunley himself) drowned. On 17 February 1864, CSS Hunley sank USS Housatonic off the Charleston Harbor, the first time a submarine successfully sank another ship, although it sank in the same engagement shortly after signaling its success. Submarines did not have a major impact on the outcome of the American War Between the States,[1] but did portend their coming importance to naval warfare and increased interest in their use in naval warfare.[2]

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1 A more accurate name is War of the Rebellion. As we reevaluate our history, monuments, and heroes, naming things properly is important [15].

2 See, for example, https://en.wikipedia.org/wiki/History_of_submarines.

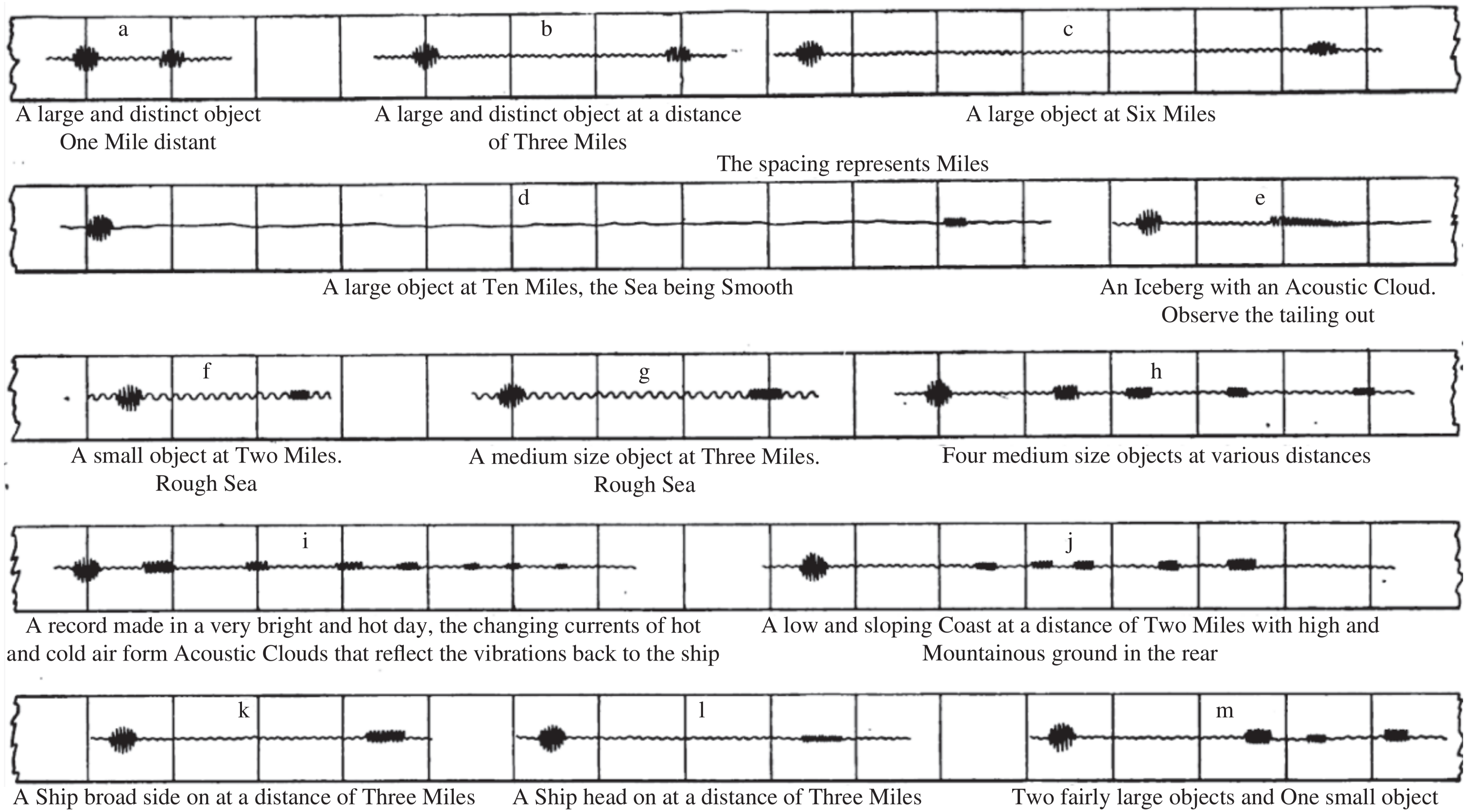

Figure 1.1 The infrasonic echo waves would be recorded by a stretched membrane that the infrasound waves would vibrate, and those membrane vibrations could jingle attached bells or wiggle pens tracing lines on paper as Maxim illustrated. Maxim's concept was discussed in Nature, a leading scientific journal yet today.

You almost certainly know Captain Nemo's submarine Nautilus from Jules Verne's *Twenty Thousand Leagues Under the Sea* (1870), but you may not have read *The Mysterious Island* (1874) or know that Nemo's fictional craft was named after Robert Fulton's real-life submarine Nautilus (1800). Verne was inspired by the French Navy submarine Plongeur, a model of which he saw at the 1867 Exposition Universelle. The fictional Nautilus was battery powered, not nuclear like today's boomers that can travel way more than 20,000 leagues (not quite three laps around the earth) under the sea, sneaking around for six months at a time just in case they need to destroy the world because reasons.

The Battle of Hampton Roads was the most important naval battle of the American Civil War. It was fought over two days in March 1862, where the Elizabeth and Nansemond rivers meet the James River just before it enters the Chesapeake Bay adjacent to the city of Norfolk, Virginia. The battle was a part of the effort of the Confederacy to break the Union blockade, which had cut off Virginia's largest cities and major industrial centers, Norfolk and Richmond, from international trade. The battle was the first meeting in combat of ironclad warships: USS Monitor and CSS Virginia. USS Monitor was a semisubmersed, iron-hulled steamship and was the first ironclad warship commissioned by the Union Navy. Her remains were found upside down 16 miles off Cape Hatteras in 1973 at a depth of about 240 ft. In 1987, the site was declared a National Marine Sanctuary, the first shipwreck to receive this distinction. Because of Monitor's advanced state of deterioration, recovery of any remaining significant artifacts and ship components was quite urgent. Numerous fragile artifacts, including the innovative turret and its two Dahlgren guns, an anchor, steam engine, and propeller, were recovered. They were transported to the Mariners' Museum in Newport News, where a full-scale copy of USS Monitor, the original recovered turret, and a variety of artifacts and related items are on display.[3] Also in Newport News is the largest military shipbuilder in the United States and sole designer, builder, and refueler of nuclear-powered aircraft carriers. HII is responsible for building more current aircraft carriers than the rest of the world's navies put together. Virginia would be a superpower if they seceded today.

Most consider French physicist Pierre Curie's discovery of piezoelectricity in 1877 to be the moment that sonar was conceived. Thirty-five years later, also inspired by the sinking of the Titanic, Physicist Paul Langevin was commissioned to invent a device that detected objects at the bottom of the sea. Langevin invented a hydrophone –what the World Congress of Ultrasound in Medical Education refers to as the "first transducer" in 1915. Langevin built an echo-ranging system using quartz crystals placed between two steel plates to generate sound. In 1918, for the first time, echoes were received from a submarine at distances as great as 1500 m. WWI came to an end, however, before underwater echo ranging could meet the German U-boat threat (See http://rsnr.royalsocietypublishing.org/content/66/2/141, https://phys.org/news/2008-02-inventor-sonar-history.html and http://journals.sagepub.com/doi/pdf/10.1177/0968344516651308).

1.1.3 Aircraft Detection

Acoustic location was used until the early years of WW2 for detection of aircraft by picking up the noise of their engines (Marco!), which was then analyzed to determine the direction of the aircraft (Polo!). Horns give both acoustic gain and directionality; the increased interhorn spacing compared with human ears increases the listener's ability to localize the direction of a sound. Acoustic techniques had the advantage that they could "see" around corners and over hills, due to sound refraction. The technology, shown in Figure 1.2, was rendered obsolete by the introduction of radar,

3 See, for example, https://en.wikipedia.org/wiki/Battle_of_Hampton_Roads.

Figure 1.2 Aircraft engines produced unprecedented sound, so in order to hear them at a distance, the war efforts developed listening devices. A two-horn system at Bolling Field, USA, 1921. Sound location equipment sometimes had four acoustic horns, a horizontal pair and a vertical pair, connected by rubber tubes to stethoscope type earphones worn by two technicians that enabled one to determine the direction and the other the elevation of the aircraft. Source: Unknown author/Wikimedia Commons/Public Domain.

which travels at the speed of light instead of the speed of sound. Japanese acoustic locators were colloquially known as "war tubas," which I hope sounds as funny in Japanese as it does in English.

Practical radar technology was ready just in time to turn the tide during the Battle of Britain, thanks to the cavity magnetron [16] and amateur scientist and Wall Street tycoon Alfred Lee Loomis, who personally funded an enormous amount of scientific research at his private estate before leading radar research efforts during WW2 [17, 18]. The atomic bomb may have ended the war, but radar and sonar won it. Then, during the entirety of the Cold War, uncounted billions were spent continuing to refine radar and sonar technology, countermeasures, counter-countermeasures, etc. with much of that high-level and mathematically esoteric scientific work quite highly classified. The result is virtually undetectable submarines that patrol the world's oceans and stand ready to assure mutual destruction as a deterrent to sneak attack. More visibly, but highly stealthy, radar-evading fighters and bombers carrying satellite-guided precision weapons can destroy any fixed target anywhere on the planet with impunity while minimizing collateral damage. It's both comforting and horrifying at the same time.

What humans have been trying to figure out since Maxim's pamphlet, is how to interpret the various radar blips, sonar pings, and ultrasound images [9]. The fundamental issue is that the shape, size, orientation, and composition of the object determines the character of the scattered signal, so an enormous amount of mental effort has gone into mathematical modeling and computer simulation to try to understand enough about that exceedingly complex physics in order to detect navigation hazards, enemy aircraft and submarines, tumors, structural flaws, etc. Much of that work has been what is called by mathematical physics *forward scattering*, wherein I know what I transmit, and I know the size and shape and materials and location and orientation of the scattering object. I then want to predict the scattered field so I'll know what to look for in my data. The true problem is mathematically much more difficult, called *inverse scattering*, wherein I know what I transmit, and I measure some of the scattered field. I then want to estimate the size and shape and materials and location and orientation of the scatterer. Many scientific generations have been spent trying to solve inverse scattering problems in radar, sonar, and ultrasound. There has been a fair amount of success [19–23].

1.1.4 Medical Ultrasonography and NDE

X-rays were discovered entirely by accident. Professor Roentgen was messing around in his laboratory with some new-fangled cathode ray tubes and he noticed that photographic plates were being fogged even though they were still wrapped tightly in paper and had never been exposed to light. He shut himself into his laboratory and worked tirelessly to explore the behavior of these unknown rays (which he gave the symbol "X") before announcing his discovery to the world and winning the first Nobel Prize. His first X-ray image is still used in textbooks today. It's his wife's hand with her large ring. Presumably she was bringing him a sandwich or something and he said, "Put your hand here, bitte."

Getting the occasional X-ray isn't a problem, but if you X-ray your hand each time you tune up the machine, you're going to lose that hand. Edison recognized the adverse health effects of X-rays pretty early on, and personally stepped back from the development efforts in his laboratory. He ended up losing his head X-ray technician bit by bit, starting with fingers and then hands.

It's a little hard to overstate how quickly X-rays became important; it took a matter of several weeks. In those days, doctors made house calls, of course, but they couldn't really do all that much. They would often do their diagnosis without even having their female patients disrobe, so it's not all that surprising that a common mansplainy diagnosis was "women's troubles." X-rays were a revelation. Some considered them shockingly improper in that they could see through clothing and make photographs of bones and other private things.

Personally, I find X-rays kind of boring. All they do is go in a straight line getting absorbed along the way according to the tissue density. CT scans are cool, of course, but the radiation dose is a concern. They're also expensive.

I like diagnostic ultrasound quite a lot. It's so safe we use it on pregnant women. It's cheap. It's portable. It's real time. The physics is really complicated. It works for medical imaging and structural health monitoring, with surprisingly few differences. The same equations also describe underwater sound and bat echolocation. Medical ultrasonography dates from the early 1950s[4] although ultrasound for structural inspection is just a bit older.

In my research group, we do both medical imaging and structural health monitoring using ultrasound. We also do quite a lot of other things because every so often the world changes dramatically and unpredictably. For example, when the Space Shuttle Challenger exploded in January 1986 (Figure 1.3). I was a second-semester senior, aerospace engineering major, about to be commissioned as an officer in the US Air Force with orders to go to Space Command. I was in my apartment in Boston doing propulsion homework when the anomaly happened and the entire space program imploded.

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4 John Julian Wild was born in Kent, England and received BA and MA degrees in Natural Sciences (with honors) from Cambridge University. In 1944, he joined the Royal Army Medical Corps and attained the rank of major and then after World War II, he was a fellow in the Department of Surgery at the University of Minnesota. He had become interested in treating bowel distention, which was often fatal, following bomb blasts from buzz-bombs. He needed to measure the changes in thickness of the bowel wall and pulse-echo ultrasound was considered a possibility, but commercial nondestructive testing (NDT) equipment developed by Donald Sproule in England and Floyd Firestone in the United States for detecting cracks in tank armor plate, operated at too low a frequency to achieve the resolution required for bowel wall measurement. A much more sophisticated piece of ultrasonic equipment developed during wartime to train flyers to read radar maps of enemy territory operated at 15 MHz. Using this equipment Wild quickly confirmed the possibility of measuring living bowel wall thickness at that frequency. Experiments with a surgical specimen of cancer of the stomach wall proved the concept of using pulse-echo ultrasound for tumor diagnosis and detection, although the use of ultrasound in medicine was skeptically received. http://www.washingtonpost.com/wp-dyn/content/article/2009/09/23/AR2009092304474.html.

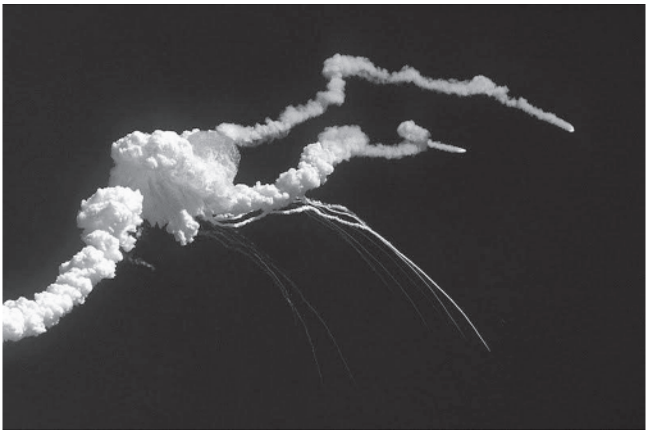

Figure 1.3 We've grown used to wonders in this century. It's hard to dazzle us. But for 25 years, the United States space program has been doing just that. We've grown used to the idea of space, and perhaps we forget that we've only just begun. We're still pioneers. They, the members of the Challenger crew, were pioneers. We'll continue our quest in space. There will be more shuttle flights and more shuttle crews and, yes, more volunteers, more civilians, and more teachers in space. Nothing ends here; our hopes and our journeys continue [24]. The loss of the Space Shuttle Challenger may have effectively ended a generation's hopes of going to space, but it did cause an explosion of R&D. Source: NASA/Public Domain.

Since the Air Force suddenly didn't have anything for me to do, they let me stay at the university for a year and get a master's degree. I wrote a thesis on elastic wave attenuation due to scattering from inhomogeneities, with applications in seismology. That went well enough that I requested to delay my active duty service commitment for three more years and get a PhD. The Air Force didn't need second lieutenants with doctorates, so they issued me orders to report to San Bernadino, CA where, for four years, I would do something or other entirely unrelated to either of my freshly minted engineering degrees.

From his hospital bed where he was recovering from colon cancer surgery, my advisor phoned a three-star general and got my orders changed so that I would be assigned to the Air Force base outside of Boston and could then continue on with graduate school in my spare time. Even back then, I knew how unusual that was. So, I cut my hair, put on my uniform, and reported for duty on 21 July 1987. They had more lieutenants than they knew what to do with because this was just about at the peak of the Reagan military buildup. In modern terms, it was a lieutenant bubble.

The commanding general had a policy of making the various program offices on base compete for the new talent, so I was told to take two weeks and interview around base and then come back and tell them where I wanted to be assigned. It was an easy choice because I had just finished a master's thesis with applications in seismology, and the one place in the Air Force where that kind of research was done was the Air Force Geophysical Laboratory up on the Hill with an excellent library and grass and trees and such. Recall that the whole point of getting my orders changed was so that I could both serve on active duty and finish my PhD.

It turned out that AFGL was a tenant organization on the base, and so I could choose to be assigned anywhere except there. If you're familiar with the way bureaucracies function, that outcome should give you comfort because my story was going far too well to be believable. So, there was a little cinder-block building up on the Hill near the library, where a small group of people were doing electromagnetic scattering for counter low-observables, that is, stealth. They didn't need me or have anything for me to do, but I had myself assigned there and they gave me a big gray steel desk in a corner where I could try to come up with something for myself to do related to electromagnetic scattering.

It worked out reasonably well. I finished my PhD on schedule, despite my advisor dying from colon cancer. Along the way, I taught myself quite a lot about electromagnetic scattering for stealth at a time when the big aerospace companies were paying enormous salaries to anybody who could recognize Maxwell's equations in neon lights. If you're doing the math in your head, you may have calculated that the Cold War ended just before my four years in the Air Force were up. I learned early on in my career to focus on the fundamental mathematics and physics that can be applied to a variety of applications so that you can reinvent yourself as needed. You'll need to.

Meanwhile, the Challenger disaster and a sequence of aircraft accidents caused by structural flaws (Aloha Airlines Flight 243 and United Flight 232) caused the field of nondestructive evaluation[5] to explode, in a good way.

Flight 243 was caused by cracks around rivets in fuselage lap joints, which developed due to metal fatigue after many years of pressurization for innumerable short hops between islands. Flight 232 was caused by a crack in the titanium engine rotor hub that developed due to a hard alpha inclusion in the titanium billet the rotor hub was forged from. Both tragedies should have been prevented by proper inspections. In 232, only 100 people died; in 243, only one person died. Only is the key word, except that *nobody* should have died dammit!

At NASA Langley Research Center in Hampton, VA, the Nondestructive Evaluation Sciences Branch grew much faster than their allotment of civil service slots would allow. The answer was to bring on board most of the scientific researchers as contractors rather than government employees, and The College of William & Mary in Virginia was one of those contractors. I was excited to come to Williamsburg to help build the Applied Science Department and oversee the NDE graduate program, with very close ties to NASA LaRC because we had a number of graduate students and research scientists who worked on the Center. We also often work with the people building aircraft carriers, just across the peninsula from NASA. There seems to be a never-ending sequence of scientifically interesting and technically challenging NDE problems both places. I've been at W&M for 62 semesters and counting. I plan to stay here for an even 100 semesters, so I guess you could count down: T-minus 38 semesters. You may note that many of the notables who developed the scattering we'll be discussing had quite long and productive scientific careers.

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5 Donald O. Thompson recognized that there wasn't an adequate science base for NDT to be more quantitative, so he convinced the Defense Advanced Research Projects Agency (DARPA) to fund university researchers in a coordinated manner. A key feature of the program was the Annual Review of Progress in QNDE, the proceedings of which now represent 40+ years of the progress literature for QNDE. I had a chance to talk with Don briefly a week before he died at the age of 86. It was at the 2013 QNDE meeting in Baltimore and after the dinner and speeches, where he was recognized as a leader in the development of the global NDE community, I knelt down in front of his wheelchair and we chatted a bit. Later I commented to my graduate students who weren't there that they missed a chance to see me genuflect. Don deserved that level of respect from the NDE community. He was responsible, perhaps more than anyone, for turning NDT from a collection of technician-level engineering methods into a stand alone scientific field. He had a particular talent for recognizing scientific talent, combined with the political savvy to convince funders to fund the research of the scientists he had convinced to cooperate instead of compete. I have a complete set of the QNDE proceedings in my laboratory, and have been attending the conference with some regularity since 1993. The origin of the meeting is that Don didn't want to have to write long technical reports every year, so instead he arranged for everybody to come to a conference and submit progress reports on their work for that year, and the collection of these papers were lightly edited and served as both conference proceedings and technical report. It seems obvious in retrospect, but it is really genius. One of Don's long-time colleagues said of him, "Don ruled with an iron hand, but was compassionate and the best boss I have ever known."

1.2 Ultrasound Immersion Tank Scans

So I ended up doing radar scattering for a living by accident, and then ended up doing ultrasound scattering for NDE by accident. I am also accidentally a leading expert in dental ultrasonography and developed a sequence of prototype machine-learning-based prostate cancer diagnosis systems that used both trans-rectal and trans-urethral ultrasound scanners. It's new things all the time, which is part of the fun, especially since the math and physics we've worked hard to master doesn't change. We'll get to all that, but first I think it would be helpful to describe some of the ways that the data we'll be modeling with those equations is acquired. We'll start with ultrasound, which is a subset of acoustics.

Acoustics describes the phenomenon of mechanical vibrations and their propagation in solid, liquid, or gaseous materials. Sound waves above 20 kHz or so are inaudible and are referred to as ultrasonic or ultrasound. Ultrasound is useful for medical imaging and structural flaw detection because it propagates well in many solids and liquids, and because it is sensitive to local changes in material properties. Ultrasonic wavelengths are of the same order as flaw sizes that are often of interest.

Here's a simple question for you: What are ultrasonic wavelengths at 100 kHz, 1 MHz, 10 MHz, 100 MHz, and 1 GHz for several common structural materials? This question is going to come up again throughout the book, so I'd suggest taking a few minutes and tabulating the numbers. More importantly, keep in mind about what the answers turn out to be.

Here's another question: What can I do to keep the sound from my neighbor's stereo from coming through the wall of my apartment? *The Straight Dope* explains nicely a few key concepts that are in play in response to apartment-dweller-Derek's question, so I think I'll just include three paragraphs here from Cecil Adams' overnight staff reporters[6]:

Everyone knows intuitively – it barely counts as an observation – that sounds get weaker (i.e. become attenuated) as they travel farther from their source. But why? Much of it is scattering and absorption. A sound wave passing through any medium – air, say, or drywall – does so by causing the medium's molecules to vibrate. Scattering is the extent to which the wave gets fragmented and redirected upon striking an obstacle in its path. (Picture ripples on the surface of a pond breaking into subripples when they encounter a rock or stick poking out of the water.) Absorption is the drop in volume caused by energy loss in the form of heat – the result of making all those molecules move around. And the effects of both scattering and absorption increase with the frequency of the wave – the higher the frequency, the greater its tendency to die out. Thus, the treble and midrange sounds coming from your neighbor's apartment get scattered and absorbed more thoroughly as they pass through the various matter surrounding it, leaving the big, dumb low-end waves to lumber along till they find you.

If the frequency and volume are right, sound waves can cause entire objects to vibrate sympathetically – surely you've heard of those souped-up car stereos that turn their host vehicles into gigantic joy buzzers. Because of their relatively large mass, things like walls and floors resonate more at low frequencies than at high ones, and thus can help to pass the bass notes along, particularly if the speaker is touching the potentially resonant surface. Long-term resonance can be pretty destructive: Thanks in part to vibrations caused by the wind that regularly swept over it, in 1940, the old Tacoma Narrows Bridge[7] shook itself to pieces and collapsed into Puget Sound.

6 https://www.straightdope.com/21343871/why-is-bass-so-boomy-and-what-can-i-do-about-it.
7 I always have my structures class look up "who died" when Tacoma Narrows collapsed. It was a cocker spaniel named Tubby who was left in the car you can see in the video.

Low-frequency noise is weird stuff. Years back, I noted that infrasound – sound pitched below the hearing range of most humans, which stops at around 20 Hz – can cause dizziness. Some recent research suggests it may do more than that. After taking spectrum analysis readings at a couple of UK sites repeatedly described by visitors as “haunted,” Vic Tandy and Tony Lawrence of Coventry University have argued that the presence of 18.9 Hz infrasound is responsible for the creepy feelings described. (In one case, they concluded that a terrifying, seemingly paranormal experience of Tandy’s had likely resulted from the whirring of a laboratory extractor fan causing his eyeballs to resonate.) And in 2003, the use of 17 Hz infrasound at London concerts of experimental electronic music correlated with audience reports of “unusual experiences” including nausea, momentary anxiety, tingling, and a sense of coldness. Ideally, Derek, by the time your neighbor has traded his bass for an ultra-low-end tone generator, one of you will have found someplace else to live.

Here’s another question: Is there some sort of semiaudible acoustic weapon causing concussion-like symptoms among US diplomats around the world? Havana Syndrome caused quite a lot of noise a few years ago, although it turned out to be a fairly typical case of mass psychogenic illness. The sounds that diplomats were hearing were crickets and cicadas, but it’s not true that the ill effects were all in their heads. Psychogenic illnesses can, in fact, result in physiological symptoms [25]. To be clear, infrasound generated by wind turbines does not manifest ghosts in your basement or bats in your belfry [26]. Bats do use ultrasound to echolocate, though. Typical frequencies are around 50 kHz and it’s a good thing that those frequencies are inaudible to us because bats are really loud and they screech COVID into the miasma while I’m trying to sleep.[8]

The last time I went to the eye doctor to get my prescription updated, I was very excited to have him scan my eyeball via Optical Coherence Tomography. He was equally excited to have a patient who knew the technology and how to interpret the images. We may have chatted for a while and backed up his other appointments. My bad.

OCT uses low-coherence interferometry to produce a two-dimensional image of optical scattering from internal tissue microstructures in a way that is analogous to ultrasonic pulse-echo imaging. Indeed, the display looks rather a lot like ultrasound B-mode, but OCT has longitudinal and lateral spatial resolutions of a few micrometers and can detect reflected signals as small as 10^{-10} of the incident optical power. I’ve been following this technology development from the earliest day. The first NSF review panel I ever served on, back in the 1990s, was for OCT. The most unwieldy review panel I ever served on was when NIH was pushing hard to get this technology out of the laboratory and into clinical usage. That panel had 50-ish reviewers on it, and we were trying to do the premeeting streamlining of the noncompetitive proposals via an old-fashioned

8 As a student, Donald Griffin and a fellow student, Robert Galambos, found that bats could use reflected ultrasound to detect objects. In 1944, Dr. Griffin coined the term echolocation to describe the phenomenon. To many, the idea was outrageous. Dr. Griffin once wrote, “One distinguished physiologist was so shocked by our presentation at a scientific meeting that he seized Bob by the shoulders and shook him while expostulating, ‘You can’t really mean that!’ “ While echolocation is well accepted today, Dr. Griffin’s pleas that animal thinking and consciousness become standard fare for research have met with more mixed success. The numerous and vocal critics of the growing field of cognitive ethology include both scientists and philosophers. Scientists complain the field is too dependent on anecdote, highly subjective and anthropomorphic, more akin to the way a dog owner envisions his pet’s day than the way a scientist typically approaches the study of animal behavior.

Whitlow W.L. Au was born in Honolulu in 1940 and earned his bachelor of science in electrical engineering from U. Hawai’i at Manoa and his PhD from Western Washington University, and then joined the U.S. Navy’s Naval Undersea Center. Following his seminal paper in 1974 on the echolocation signals of Atlantic bottlenose dolphins, Au went on to methodically quantify the performance and signal characteristics of dolphins and other small whales that echolocate under water. His book, “The Sonar of Dolphins” published in 1993, remains as the primary source for describing dolphin echolocation. He died in 2020 at age 79.

conference call. The problem was that the panel chair was on his cell phone driving in his car, and when his call would drop, we'd all have to wait on the phone until he dialed back in.

Because OCT uses near-IR wavelengths, there's sufficient penetration of opaque soft tissues to use it for a variety of superficial applications. Many are being developed in dentistry these days. Since the light can be delivered via fiber optics, there are all manner of endoscopic applications of OCT. You'd be surprised to know what urologists will jam where and still call it noninvasive.

Ultrasonic frequencies used for medical imaging and NDT of structural materials tend to be in the low MHz range. At these frequencies, the wavelengths are quite small and attenuation is usually a concern. The trade-off is that you'd like to go to higher frequencies in order to get better resolution, but attenuation often scales like the square of frequency, so doubling the frequency quarters the depth of penetration. As a personal aside, I think all this is pretty interesting because it requires a fair amount of understanding of the propagation properties of the ultrasound in order to design sensible measurement schemes. The first ultrasound measurement scheme we should talk about is immersion tank scanning.

Figure 1.4 is a cartoon of an ultrasound immersion tank. At MHz frequencies ultrasound doesn't propagate through air much at all, so if you can immerse your test specimen in water, then you can use that water bath to couple the ultrasound from your transducer into and back out of the specimen. The transducer is typically held by a search tube which is connected to a scanning bridge that moves it to and fro and back and forth under computer control.

Immersion tanks come in a variety of sizes (Figure 1.5), but the electronics is all pretty much the same. The computer that manages the motion control also communicates with the ultrasonic pulser-receiver, which sends and receives the voltage signals to and from the transducer as well as with the analog/digital conversion unit, which turns analog voltage signals into digital computer values and vice versa.

In Figure 1.6, I've isolated just the part that we'll need to model, at least initially. The transducer emits an ultrasound pulse which is incident upon the test specimen, which for simplicity I've drawn as a slab. The acoustic properties of the slab are, of course, different from the water it's immersed in.

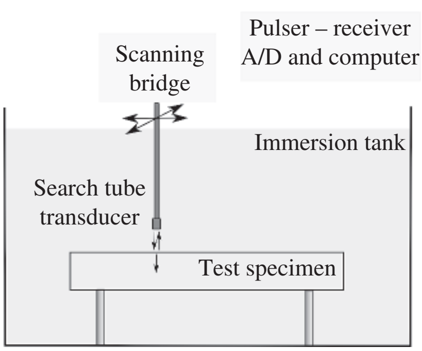
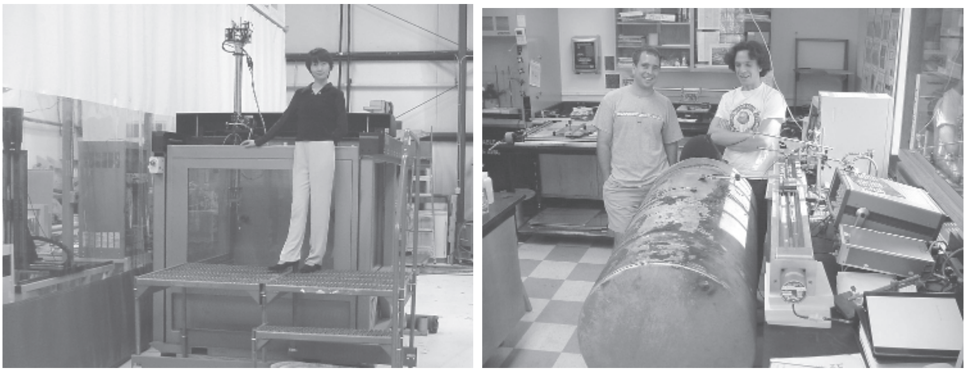


Figure 1.4 Ultrasound immersion tank provides a convenient way to scan a specimen for flaws, if the specimen can be immersed in water. The ultrasound transducer is attached to the end of a search tube, which is rastered across an area via stepper motor in a scanning bridge. At each point in the scan, the pulser–receiver sends a voltage spike to the transducer, which excites an ultrasonic wave pulse at the resonant frequency of the PZT crystal in the transducer. That ultrasound wave both reflects from the test specimen and is transmitted into it. The resulting echoes are received by the same PZT crystal, which then sends an analog voltage trace back to the receiver, where it is amplified and filtered before being converted to a digital signal and stored on the computer, which also controls the scanning and triggers the pulser. Each digitized voltage trace, called an A-scan, carries information about the various material interfaces and discontinuities because time delay of the echoes corresponds to depth, scaled by the speed of sound.



(a) (b)

Figure 1.5 Immersion tanks can be quite large, as in this one (a), which holds 6 × 6 × 6-feet of water. Note a smaller tank that holds 2 × 2 × 3-feet of water at the lower left of the image behind the window. In acoustic microscopy where very high frequencies are used to find tiny flaws in small samples, an immersion tank may be a small water container on a high-precision scanning bridge atop a vibration-isolation table. Ultrasound can also be done in contact mode (b), either with hand-held transducers or with scanners configured to have the transducer(s) follow any curvature of the surface.

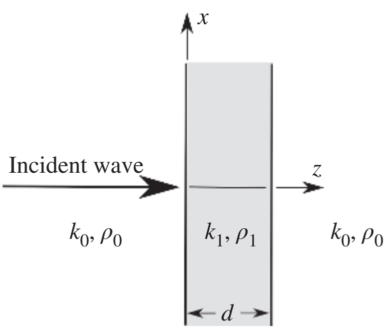


Figure 1.6 Consider an incident plane wave interacting with a slab of thickness d. For an acoustic model, we need to know the speed of sound and density in order to characterize the wave behavior, but since $k = \omega/c$ it's also convenient to use wave number and density. Here we assume that the material to the left and to the right of the slab are the same fluid, that is, water in an immersion tank, but the slab is some other material, so the subscripts are different.

I hope it doesn't throw you off that I've drawn it sideways because one of the key skills we're going to need is the ability to analyze a physical measurement scenario and isolate just the parts of it that are important for our models. When I teach mechanics of materials, I always insist on a good free-body diagram as the first step in solving a problem. If a student gets that right but makes some mathematical errors during the solution that leads to the wrong answer, I can still give lots of partial credit with the caveat that if you screw up the math in the real world and the structure you designed falls down, that's all on you.

Since the point of scanning a sample in an immersion tank is to inspect for flaws, Figure 1.7 shows the ultrasound inside of the sample reflecting from a flaw. The whole name of the game is going to be analyzing such reflections from flaws in order to tell as much as you can about the flaw. It's not good enough to just find a flaw, we want to know how deep it is, how large it is, what kind of flaw it is, how a flaw of that sort could impact the viability of the structural element, whether the flaw is likely to get worse (they never just magically heal themselves), or can I still use this structural element for a while longer.

If putting the sample in an immersion tank isn't practical, ultrasound measurements can be done with the transducers placed directly onto the surface of the structure, typically with some sort of couplant. Medical ultrasound uses hypoallergenic gels that can even be warmed for patient comfort.

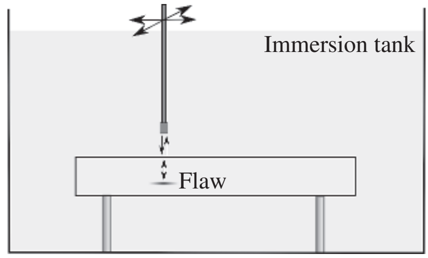


Figure 1.7 Reflections from a flaw in the test specimen will give echoes in the A-scan that are between the front-face and back-face echoes. Indeed, the time delay of the flaw echo tells its depth accurately, and as the transducer is raster scanned across the test specimen, the peak corresponding to that flaw echo can be tracked to determine the lateral extent of the flaw.

NDT uses a variety of specialized couplants, which don't need to be warmed, but sometimes just a little film of water can work fine. Honey also works, but it gets so sticky so just don't. The function of the couplant is to make sure that there's no air gap between the transducer face and the surface. Oh, and for structural health monitoring applications, we sometimes just glue the transducers to the surface and leave them there. Figure 1.5 shows a few contact scanning apparatus in the laboratory, both for a cylindrical storage tank in the foreground and two plate scanners in the background. Figure 1.8 shows two examples of portable ultrasound systems, where the ultrasound pulser-receiver and A/D functions are in the small black box connected to either a tablet or a laptop via USB. It has been quite interesting over the years watching ultrasound electronics shrink down from two racks of equipment to a pocket-sized unit connected to a tablet. Visitors to the lab are often a little disappointed that there aren't more flashing lights and whirring equipment to show them. Field trips to newspaper offices and telephone exchanges also used to be more interesting.

The pulser-receiver exchanges analog voltage pulses with the transducer. Figure 1.9 shows a cut-away view of a typical ultrasound transducer. Sorry that it's not more exciting than a piezoelectric crystal disc metallized on the two flat faces so that a voltage across it causes it to vibrate and emit ultrasound, and then when it's vibrated by returning ultrasound echoes, it gives a voltage response. I have some cut-away transducers for visitors to handle.

Figure 1.8 In recent years,both the computers and the ultrasonic instrumentation have shrunk dramatically. A tablet or laptop controls a USB-powered *nanopulser*, which is a combined pulser-receiver and A/D unit connected to a contact transducer or handpiece.

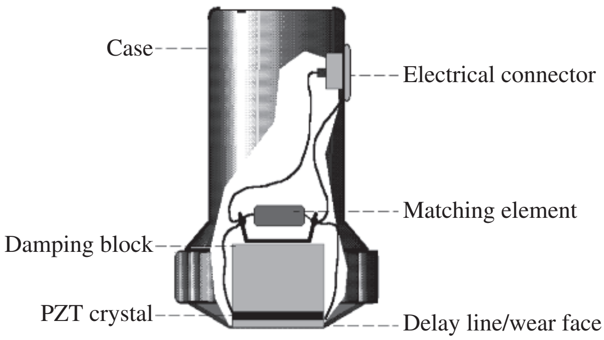


Figure 1.9 Cutaway view of an ultrasound transducer. The PZT crystal has metallized faces, so it vibrates in thickness mode when excited via a voltage spike. The damping block is typically tungsten-loaded epoxy, and keeps the transducer from ringing so that reflections can be recorded. The delay line is used to couple the ultrasound more optimally to water for immersion scanning or metals for contact scanning.

1.3 A-, B-, C-Scans, M-Mode

We're going to have to introduce some jargon. I've included some cartoons that I hope will be helpful, but I made these figures while learning a drawing package so they're not fancy. Most people get these concepts best when they collect some data themselves, or at least see some animations/demonstrations so don't be shy about looking up some of those.[9]

Figure 1.10 shows an A-scan or A-line. A stands for amplitude, and this representation is pretty much just the voltage of the transducer as a function of time. Back in the day, this is what you would see on the little green (or orange) screen of your oscilloscope and then you'd take a polaroid picture of it to paste into your laboratory notebook with rubber cement.

If you send a spike voltage to the transducer (Figure 1.10), it will give a shape kind of like I've drawn because the transducers are damped (so as to not reverberate like a bell) and reflections from material interfaces will give reflections that are about that same shape. The nearest interfaces will

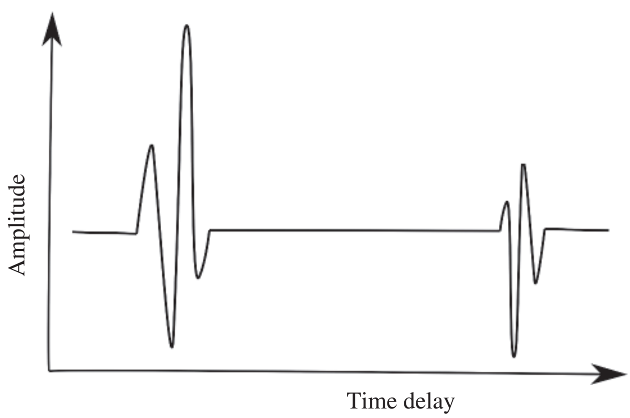


Figure 1.10 A pulse-echo waveform is called an A-line, which shows amplitude vs. time delay. In this cartoon, the first pulse is the front-face reflection from a sample and the later pulse is the back-face reflection. Knowing the speed of sound in the material allows the thickness of a sample to be measured.

9 Here are some books you'd find in my lab: [27–48].

give the first reflections, and deeper interfaces will give later reflections. Assuming a fairly constant speed of sound, the time delay of the reflections gives the depths of the interfaces. The amplitude of the reflection is related to the difference in acoustic properties between the materials at the interface because some of the incident wave is reflected and some of it is transmitted. Subsequent interfaces will only see that transmitted signal, so their reflections will be smaller. Attenuation will also tend to reduce the amplitude of deeper reflections. Again, playing with this in the lab for a few minutes makes this all intuitive. Assuming you know what material you're testing and you look up the speed of sound, as long as you include a factor of 2 because the reflection goes to the interface and then comes back, it's a pretty simple matter to verify that the two pulses in Figure 1.10 are the front face and back face reflections from the slab. If you're doing these tests in an immersion tank, you can also reach in and lift up the slab and watch both peaks in the A-line move toward you. Try to remember to roll up your sleeve first, though.

Once you've verified that the peaks you're looking at are the front and back face reflections, and of course dried off your sleeve, you can look for any echoes between them, which might be due to flaws, as Figure 1.11 shows. As before, the time delay of the echo from the flaw tells how deep it is, and the amplitude of that echo carries information about how reflective the flaw is. The ultrasound beam always has some lateral dimension to it, more like a flashlight than a laser pointer, but the A-line doesn't give you much spatial, that is, lateral, information. Focused transducers will give a larger reflection if the flaw is at the focal depth, of course, so again it really helps to get a feel for this if you can play around in the lab for a while. Roll up your sleeve this time.

Since you can just save the data to your computer and don't have to take a ruler to that Polaroid in your lab notebook, the first thing you're going to do with the A-lines is to window out the front and back face reflections. We usually call that process gating (Figure 1.12) and there used to be knobs on your ultrasound instrument that you would use to adjust the gates while you were recording data. It was always disappointing when you set the gate(s) wrong and recorded useless data. You and your soggy sleeves often had to take a few tries at things to get the gate and amplification and such just right before you got the data you needed. The point is that you don't care about the front and back-face reflections; you care about the often much smaller echoes from the flaws and you want to zoom in on those to analyze the details.

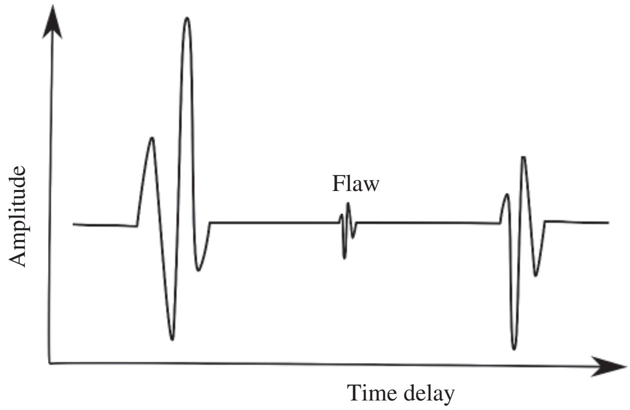


Figure 1.11 A flaw in a sample will occur between the front-face and back-face reflections. Time delay of the flaw echo tells the depth of the flaw, and analysis of the detailed character of the flaw echo is the essence of quantitative nondestructive evaluation.

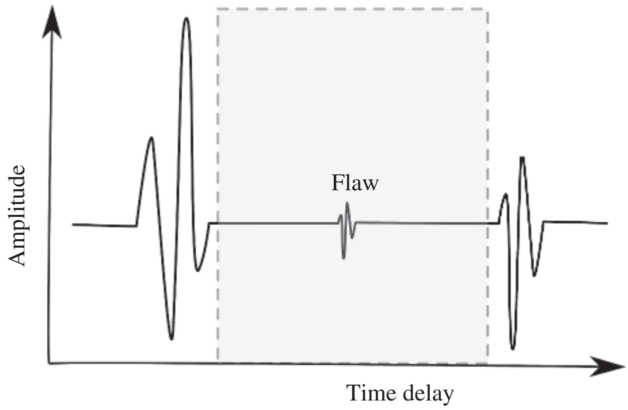


Figure 1.12 Since it's the flaw that's of interest, typically one gates the A-lines to exclude the front- and back-face echoes. The width of the gate, shown in the shading, can be adjusted to isolate particular depth slices of interest by ignoring any echoes that are not inside that time-delay window.

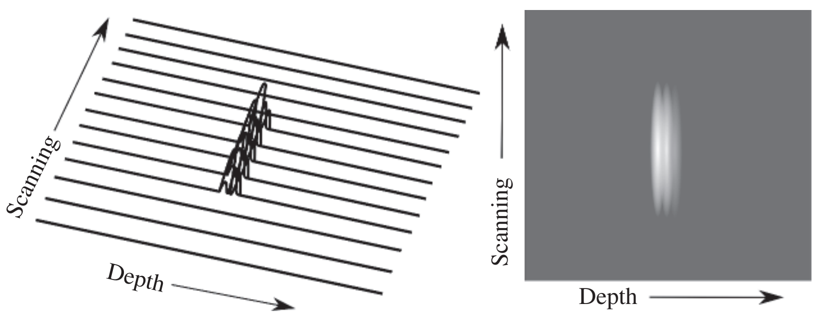


Figure 1.13 As the transducer is scanned laterally, a number of A-scans can be registered next to each other in order to determine the lateral extent of the flaw. If the amplitudes of the registered A-lines are shown as brightness, the two-dimensional representation is called a B-scan. In medical imaging, the A-lines are connected in a fan shape, so the familiar ultrasonographic B-Scan will be fan shaped. For a small intra-cavity probe, the transducer array may be annular and the B-scan image is a hollow circle.

If the search tube that holds your transducer is attached to a stepper motor system, then while your soggy sleeve is drying, a sequence of A-lines could be recorded as the transducer is moved laterally. Figure 1.13 shows several A-lines spread out next to each other, and since I've gated out the front- and back-face reflections, it becomes obvious what the lateral extent of the flaw probably is. Figure 1.13 also shows this same 2D data set but with amplitude of the echoes converted to brightness of the corresponding pixels. Since you're doing this with a scanner and you want to make pretty B-mode images, you record lots of A-lines to get lots of pixels. I hope you noticed that B stands for *Brightness*. In addition, if you're reading the printed version of this book or the ebook on a tablet, please rotate it so Figure 1.13 shows scanning across the top and depth pointing down.

So B-scans are just a bunch of A-scans lined up next to each other because your computer-controlled scanner does that without you having to pedal it, and we get these lovely intuitive images that tell us the depth and size of flaws. Surely you've noticed that most scanners can scan in two directions, so you can make a bunch of B-scans and stack them up adjacent to each other as in Figure 1.14. Old timers who remember gluing Polaroids into their lab notebooks with rubber

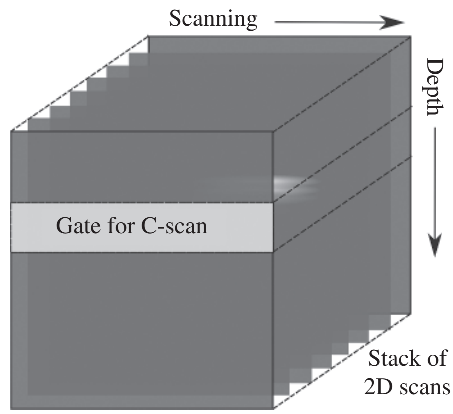


Figure 1.14 The 3D volume of data can be sliced vertically to give a B-scan or horizontally to give a C-scan. Typically, the A-scans are all gated to analyze the echoes from a particular depth range and then the C-scan image is rendered by using the highest amplitude echo within that gate at each location as the image pixel value there. The depth gate can be as large or as small as you like, and you can form as many C-scans as you like. If you prefer you can just acknowledge that you've got a 3D volume of data that can be sliced in a variety of ways to make 2D images. Be careful using words like slice when you're talking to expectant parents about their fetal ultrasounds, though.

cement are all jealous that you can acquire this much data.[10] It seems too easy to people who had to get up off the sofa and walk across the room to flip between the three stations on the television or turn the record over.

Back to gating. Once you've got that 3D volume of data, you can slice it in a variety of ways. A C-scan is a horizontal slice as shown in Figure 1.14. Recall that the point is to locate the flaws and then to tell something about them, so a C-scan allows you to isolate just the echoes from the depth range that includes the flaws of interest. This used to be tricky. High-resolution scans can take a long time, and before computers could handle 3D volumes of data you had to set the gates for the C-scan *before* you started the scan. It wasn't unusual to have to try a few different scans to get the data that you needed because if the gate was at the wrong depth or the gate was too narrow you would end up with a garbage image. Sometimes you stood there shaking the Polaroid waiting for the image to come into view only to find you had your thumb over the lens.

The C-scan is going to end up being a 2D image, with pixel brightness corresponding to echo amplitude, but it's the orthogonal view to a B-scan. Typically, the pixel values are the largest amplitude echoes of each A-line inside the gate, but you can also set the gate to be quite narrow and make a bunch of C-scans for a bunch of different depths. Since you've got a 3D volume of data, you can also go back and form B-scans by slicing the data in the other vertical plane. No rubber cement required. You can scroll through a whole bunch of different B- and/or C-scans without even getting up off the sofa.

B-modes are common in medical imaging, but they are often sector scans rather than rectangles. This is because medical ultrasound uses phased arrays to sweep the beam electronically, and to update the images at video frame rates so we can see motion. The images are still formed from a bunch of A-scans next to each other, with echo amplitudes converted to brightness. Speckle is just the manner that inherent tissue inhomogeneities present in brightness mode.

10 Professor John M. Reid was born in Minneapolis and received the BS (1950) and MS (1957) degrees in Electrical Engineering from the University of Minnesota, as well as the PhD in Electrical Engineering from the University of Pennsylvania (1965). Reid developed the first clinical ultrasonic scanner with John J. Wild via a grant from the National Cancer Institute. Reid was the sole engineer to build and operate Wild's ultrasonic apparatus. They built the first linear B-mode instrument, a formidable technical task, in order to visualize tumors by sweeping from side to side across breast lumps. In May 1953, this instrument produced a real-time image at 15 MHz of a 7 mm cancer of the nipple in situ along with A-mode differential reflections. Based on technology from WWII radar, Reid devised important circuitry to compensate for the attenuation of ultrasound in tissues by setting the receiver gain as a function of the tissue depth. Similar mechanisms were deployed in most medical and NDT ultrasound systems that followed. I'm just old enough to have used these analog time-gain compensation units, and to have met Prof. Reid once briefly.

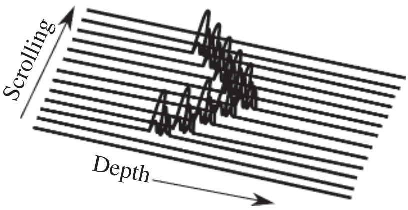


Figure 1.15 In addition to A-, B-, and C-mode images, there's also M-mode, which stands for motion. It's basically just a scrolling B-scan, but can be quite useful assessing motion in cardiology and other areas. As the sequence of A-lines scroll, the interface causing the echo moves distally and then back toward the transducer. It's much more exciting when it's animated, sorry.

The coolest thing about real-time imaging is that you can watch things moving inside a living being, for example, a beating heart. M-mode images are also formed from a sequence of A-lines with amplitude converted to brightness, but here the A-lines scroll across the screen in a sort of waterfall plot. I'm a little disappointed with my cartoon in Figure 1.15 though. Of course, M stands for *Motion*, and of course, the amplitudes are converted to pixel brightness values so that M-mode images are pretty. The name of the game in medical imaging has always been to present the clinician a set of high-resolution images to interpret in making a diagnosis. These days machine learning can often assist the licensed medical professional by highlighting suspicious features in images, but artificial intelligence algorithms are typically prohibited by regulators from actually making any diagnosis.

The above measurement schemes are all what we call pulse-echo because the same transducer both transmits the ultrasound pulse and then records the returning echoes. In many situations, particularly for structural health monitoring, it is useful to have one transducer transmit the ultrasound pulse and another transducer record the ultrasound transmissions at some other location. We call this a pitch-catch measurement, but don't have some sort of alphabetical nomenclature to categorize them so I'll describe a few.

A common scheme is to transmit the ultrasound beam into a specimen and then record what comes out the back side with a transducer along the line of sight. Flaws or other material imperfections that reflect some energy will reduce the energy in the transmitted wave that is recorded, and if the two transducers are attached to a yoke system, they can be scanned across an area to look for things like disbonds and delaminations that reflect strongly and hence give a pronounced shadow effect in the transmission. Pitch-catch schemes can also be quite useful for guided waves because large areas of extended structures can be screened for imperfections quickly. Guided waves also often have the useful feature that their speed of propagation depends on a structural property, like plate thickness, so a pitch-catch measurement can look for subtle changes in arrival time of a wave packet that indicates a thickness change due to corrosion along the path of travel. There are also a variety of tomographic geometries where a large number of criss-cross pitch-catch measurements can be used to reconstruct an image of the interior tissue or material variations [49–56].

Of course, the transmitting and receiving transducers can both be on the same side of the sample. Perhaps they are offset just a bit and at angles to the surface so that the echoes are recorded at specific angles. As we'll see, this simple generalization makes things much more complicated because ultrasound waves in solid materials can be either longitudinal or transverse modes, and interaction with interfaces, imperfections, etc. causes mode conversion between them. Angles of reflection and refraction are also different for longitudinal and transverse modes, so you can set up a measurement to transmit longitudinal modes at angles that refract and/or reflect specific wave modes that allow you to inspect parts for specific flaw types. Any good ultrasound lab will have a whole cabinet of transducers of different frequencies, sizes, shapes, etc. Some will be for immersion scanning and some will be for use in direct contact with the specimen surface using a gel or oil (but not honey) couplant. They all look pretty similar and the distinguishing numbers on them are hard to read. Let's pause here for a few minutes while you go gather up the transducers you've been using and put them away properly.

1.4 Monostatic, Bistatic, Doppler

The radar equivalent to pulse-echo ultrasound is called monostatic. An antenna transmits the radar pulses and also records the backscattering.[11] Because the speed of light is so much larger than the speed of sound, the electronics necessary to simply record the RF waveforms and process them afterward is pretty recent. Figure 1.16 shows a typical setup with a software-defined radio connected to a tablet for transmitting and/or receiving electromagnetic waves. With one of these setups, you're doing monostatic measurements, but if you have a couple of them and transmit with one and receive with another that is called bistatic. Three would be tristatic, I suppose. The point is that these are quite portable and it's now a simple matter to go out and about and collect RF waveforms in monostatic or bistatic configurations, etc. without getting your sleeves wet. You should wear a hat, though.

The textbook example of the Doppler effect is the change in pitch of a train as it passes you. I'm pretty old and I don't recall ever waiting at a railroad crossing while this happened. I've ridden Amtrak a couple of times, but that was a miserable experience where we seemed to mostly wait while freight trains used the tracks that Amtrak borrows. It didn't smell great.

The good news is that doppler imaging typically doesn't work according to the Doppler effect. I'll explain in terms of doppler ultrasound that is used to map blood flow, especially in cardiology. These color images are typically overlaid onto a higher-resolution B-mode gray-scale image. It's much more exciting when you can see the motion, so feel free to look some up on the internet and then I'll describe how it's done.

The basic idea is that you send in a rapid sequence of pulses and then compare the various echoes in the several A-lines to calculate how much those peaks in the A-lines have shifted from one

Figure 1.16 The portable, inexpensive, high-performance USRP is a scalable software defined radio platform that features a customizable field programmable gate array for high-performance digital signal processing and full duplex capabilities.

11 Merrill Skolnik served as superintendent of the radar division of the U.S. Naval Research Laboratory in Washington, D.C., for more than 30 years. While there, he made significant contributions including helping to develop high-frequency, over-the-horizon radar; a system that can identify friend or foe during combat; and high-resolution radar techniques. He is best known for his introductory text "Introduction to Radar Systems" and for editing the "Radar Handbook." He died in 2022 at age 94.

pulse to the next. That's straightforward to do because the shifts from one A-line to the next are small if the pulse sequence is rapid enough. Color-code the peaks approaching the transducer one color and code the peaks retreating from the transducer another color. Usually, the colors are red and blue.

In addition, you may have noticed that the color doppler part of the image is just for a certain region. That's because the sequence of doppler A-lines are often done in between the video frame rate B-mode image pulses, so there's a limit on the number of doppler pulse sequences that can get done and still update the whole image fast enough that it looks all natural to the human eye.

Doppler radar that weather guessers use to mislead you about whether you should grab an umbrella on your way out the door could work according to the simple scheme I just described for doppler ultrasound, but there's this issue with the speed of light compared to the speed of sound and the need to digitize RF waveforms and process them . . . . In practice, pulsed doppler radar employs a number of signal processing tricks to map out the velocity of whatever backscatters the radar beam, but again it's not really the doppler effect like an enormously long coal train that blows its whistle to taunt you as you're waiting at the RR crossing with your windows up because you've heard breathing coal dust might be bad for you.

"The Big Short" is a book by Michael Lewis and film starring Christian Bale, Steve Carell, Ryan Gosling, and Brad Pitt which tells the story of hedge fund bros who saw the collapse of the housing bubble coming and made quite a lot of money betting on that. You may or may not remember that the Great Recession was caused by the logical fallacy that because people who own homes are better off, everybody should own a home. Home mortgages were given to people who had no business buying homes because the risk of default on loans was disconnected from the decisions to write the loans by converting them to mortgage-backed securities that could be traded on Wall Street. The PhD Quants understood that there was an assumption of statistical independence in their models, but their MBA Banker bosses didn't and the bankers' CPA cronies at the accounting firms formally assured everybody that the risk was minimal because the only way things could ever go wrong was if housing prices all fell at once and that would never happen. It was a happy ending for the Wall Street Bankers, though, because their other cronies in Government bailed them out. Act two in this play was student loans, BTW. Act three is subprime car loans.

Alfred Loomis saw the stock market collapse coming and liquidated his holdings beforehand. Loomis was a brilliant math major and inventor at Yale, but after attending Harvard Law School, he joined a prominent Wall Street law firm and became one of its brightest young stars, specializing in complicated corporate financial transactions. Throughout the years, while he traded vast sums of money on the financial markets during the week, in the evenings and on weekends he worked with the world's greatest scientists at his own self-funded laboratory. Loomis had bought a second mansion, a giant mock Tudor home with concrete floors in Tuxedo Park, where he invited many of the world's most distinguished scientists to come and spend time [18]. Albert Einstein called it "a palace of science."

In the late 1930s, Alfred Loomis became increasingly convinced war was coming in Europe and that the United States would be drawn into it. Then, in early 1940 Winston Churchill organized the Tizard Mission to introduce U.S. researchers to several new technologies the British had been developing. Loomis welcomed them to his hotel suite in New York, where he learned about the cavity magnetron, which was a key piece of technology that made radar small enough to put on airplanes. Loomis was instrumental in establishing the Radiation Laboratory at MIT, arranging for funding and clearing bureaucratic roadblocks. The Rad Lab developed the radar systems that gave the Allies control of the skies, enabled the sinking of U-boats, spotted incoming German bombers, and provided cover for the D-Day landing. The Rad Lab became the Air Force Cambridge Research

Laboratory after the war, with many activities eventually moving to Hanscom, AFB where I spent four years and a day. I even met R.W.P. King once.[12]

1.5 Didey Wagon vs. War Wagon

I learned to drive at age 13. It was in the orange 1968 VW bug with a pumpkin stem on top shown in Figure 1.17. I've never gotten a straight answer from my mother about whether she was in on the joke when it came back from the paint shop garish orange instead of light blue. My brother occasionally got in trouble when that car was reported having been seen at some place he shouldn't have been. Tracking teenagers is much easier these days.

Figure 1.17 You'd be pretty unlikely to get a speeding ticket in a pumpkin car even going downhill. The highly rounded front hood and fenders won't backscatter radar all that much, and it's rear-engine and air-cooled, so there's no radiator to reflect the radar. There's no heat in the winter, but the engine is directly above the narrow rear wheels so it's really good in the snow even without studded snow tires. If back in the day, I'm tooling down the road in my wine-colored Volvo 240 Wagon blowing past a candy-apple red Corvette, there's no way in hell I'm getting a speeding ticket, even though any radar reflections are coming from me and my dad-mobile and not from that hopelessly insecure, compensating-for-something, former frat-star in the slow lane.

12 Professor Ronold W. P. King's academic tenure at Harvard University spanned all or parts of eight decades, and his legacy is perhaps best defined by the fundamental nature of his research, his exceptional insight into the physics of problems in applied electromagnetics, and his mentorship of over 100 PhD students. He became a Gordon McKay Chaired Professor in 1946, and was Professor Emeritus from 1972 to 2004. He remained active in his research efforts until late in his life, completing his last book at age 87, producing his last PhD student at age 94, and publishing his last paper at age 99. He was honored by his past students on his 100th birthday, and died in 2006. For the 67-year period from 1938 to 2004, he directed an active research group at Harvard investigating the applications of electromagnetic theory to problems in antennas, radiowave propagation, and subsurface communications. The 1960s were characterized by work on scattering and diffraction of electromagnetic waves from spheres, cylinders, strips, and disks, some with dielectric coatings. In his autobiography, he describes when he reached the proscribed retirement age of 67 in September 1972. "President Pusey, as required by Harvard rules, came to my office in McKay Laboratory to thank me for my services and announce my becoming a Professor Emeritus. I requested permission to continue for five more years, pointing out that I was well able to do so." The rules permitted an additional five years, but the Dean "had requested that this privilege not be granted." King had five or six graduate students at the time and they appealed to the President, who denied the request. Mandatory retirement ages for faculty were outlawed nationwide in 1994, BTW.

I find that I get a speeding ticket about every nine years. Most recently, I was coming back from taking my daughter to register for college and wasn't paying attention because we were talking about life, the universe, and everything. There's a bit of interstate highway that goes through Brunswick County, Virginia and they keep the local economy afloat with aggressive speed traps. It was the most efficient shakedown operation I've ever experienced. I was quite impressed. You can't just pay your speeding ticket on line or by mail; you have to physically show up in court or else pay a local lawyer US 150 to represent you. I was on sabbatical, so I went there and spent a day waiting for my two minute chat with the judge, where he and I commiserated about how hard it is when your youngest goes off to college, and he reduced my fine by US 150. They move through the cases so quickly that there's an on-deck circle where you wait, and then you exit the courtroom into a locked antechamber with two cashier's windows where you pay before they buzz you out. Fortunately, I wasn't speeding when I drove through a speed trap on my way out of town. For four years, each time we went back and forth, we set the cruise control to 69 mph and smiled at our friends when we went through Brunswick Co.

Perhaps the first radar speed gun was put in a former diaper delivery wagon by Alfred Loomis and his crew, although they had it painted Tuxedo Park colors so it wouldn't attract attention. The first time they measured the speed of an oncoming car, one of the physicists noted that they had better not let the police know about this technology. As of 1956, there were already about 1600 radars in use throughout all 48 states. Most of the longer freeway, turnpike, or expressway police patrols had one or more radar speed meters in operation daily, which stinks. Autonomous vehicles with V2V will share real-time information about speed traps, which stinks for Barney Fife.

The greatest weakness of traffic radar is the way it presents its information. Vehicles can range in size from econo-boxes to semitrucks, and all the radar will show is one number because it's made to the lowest bidder specs, so it has to be a relatively simple device. Traffic radar cannot distinguish between targets within range; it cannot identify for the operator which target it's reading; it doesn't say whether the target is coming or going. It's up to the operator to decide which of the vehicles within range is producing the reflection. Is it the closest one to the antenna, or is it the largest one in the pack? A skilled operator intent on justice wouldn't write a ticket unless absolutely sure. A less-skilled operator might write the ticket thinking it was the right answer, and be wrong. A careless operator intent on filling a monthly quota might see the number and single out a likely perpetrator – the red sports car – and be done with it. Traffic radar is not the infallible electronic instrument that it purports to be and because operators have a tough time keeping track of invisible beams, traffic radar invites human error in vehicle identification [57–59].

So what might it take to design a motor vehicle that could elude police radar? Most people think that the answer is to paint on some sort of fancy radar-absorbing material [60]. Nope. At least not at first. The primary way stealth aircraft elude radar is by shaping [61–63].

My wife used to haul me and the kids around in a 1990 Volvo 240 wagon. We called it the War Wagon (Figure 1.17) because it was basically a tank. I don't think I ever got a speeding ticket driving it because it just looks so damn sensible and slow, even though it could eventually get up to speed. We once drove it from Scranton, PA to Rochester, MN in a single day, but that was before we had kids. Duh.

A boxy Volvo seems simple enough that we could get a feel for what it looks like on radar. Metals reflect radar like mirrors reflect light. Pretty much any nonmetals in the Volvo will be transparent to radar. The grill was plastic in 1990, so that is invisible to the radar. Windows are transparent at both visible and radar wavelengths. Rubber bumper cover and the small amount of plastic ground-effects equipment, mud flaps, hubcaps, side mirror enclosures, etc. are all invisible. Headlights are plastic, but the reflector that focuses the light is a metallization so that almost certainly redirects radar right back to PoPo. In any event, the radiator that is right behind the plastic grill is big and flat and reflects the radar, sorry. At least the US-spec license plate hangs down a bit and usually gets bent. In addition, the steel bumper is only a little bit curved, so it probably gives a pretty strong reflection.

I currently drive a white 2014 Ford Fusion, which is named Whitey Ford even though I root for the Red Sox. I call it my old man car because it had been my old man's car and when he died nobody else in the family wanted it, so I bought it from my mother because it was time for me to buy a car anyway and it was my fault he bought the car because I read an excellent book [64] about the turn-around at Ford and passed the book to my father afterward. The car sits low enough to the ground that my wife fusses at me whenever she rides in it. She's kind of a car slob anyway, so I don't really want her driving it. She has never gotten a speeding ticket.

Sports cars are designed to look like they're speeding even when they're standing still because it sucks to get old and lose your hair. In a speed trap, radar is operating in monostatic mode so the relatively small radar gun is both transmitting and receiving. Once you know which things reflect radar (metals) and which things are transparent to radar (nonmetals), you can easily assess the relative stealthiness of different vehicles.[13] Yes, the Corvette is low profile and it's difficult to get into, but the real reason that it's stealthier than my old man car is that the fiberglass bodywork is transparent and the radiator is tilted back. My car's radiator is perpendicular to the airflow to maximize cooling efficiency as I invisibly glide through the speed trap at 69 mph.

Sometimes cars have a bra over the nose to minimize paint chips from pebbles and whatnot. Putting a bra on a Volvo 240 wagon is ridiculous, which I know because I did that. I considered going the next step toward radar invisibility by incorporating some wire mesh into the bra so that it would be reflective. Actually, I considered patenting that concept in the late 1980s until I found out how much it cost to get a patent.

The point of the above discussion is that reduction of the radar cross section of a vehicle relies both on choice of materials and shaping. All modern stealth designs are very careful to avoid vertical flat surfaces and especially right-angle retroreflectors where two flat planes come together to make an interior corner. Materials also matter quite a lot. Figure 1.18 shows the Horten flying wing, which is inherently stealthy because it's largely nonmetallic.[14] It also has a fairly stealthy shape.

Figure 1.19 shows a couple of views of the F117 Nighthawk stealth fighter. This aircraft was developed in secret and used operationally for some years before it was acknowledged to exist. It was developed and tested and based at the secret airfield in the desert near Roswell, NM, where people who want you to please go there on holiday and spend tourist dollars say there are probably flying saucers. Certainly, these flying objects flitting about at dusk would have been unidentified.

I was as surprised as anybody when the F117 was introduced publicly, and I was an Air Force officer doing radar scattering analysis for a living. There were rumors about a stealth fighter, but we thought it would be called the F19 and maybe look like the best-selling Testors Model. I didn't know, even though the Air Force gave me a medal for writing radar-scattering equations on a chalkboard during wartime.[15] I had a security clearance, of course, but I didn't have a need to know about the

13 Eugene Knott received his MS in EE from Michigan in 1966 and pursued research in microwaves and radar at Michigan, Georgia Tech, UTexas Austin, and Boeing. You should get a copy of his "Radar Cross Section Measurement" (1985) or the update, "Radar Cross Section" that was published in 1993. He died in 2014 at age 82.

14 This can be seen up close at the Udvar-Hazy Center near Dulles Airport. "Raiders of the Lost Ark" in 1981 had a fight on the ramp around the fictitious "BV-38" flying wing. Indiana Jones backed his opponent into the spinning propellers with suitable bloodshed. The BV-38 was supposedly based on a Horten test bed from Germany, but it also borrowed features from several Northrop flying wing prototypes. Jack Northrup didn't live long enough to see the B2 Stealth Bomber fly, but before he died, the Air Force read him into the program to show him models and plans.

15 To be fair, it was like the participation trophy in youth soccer. They gave that medal to everybody who was on active duty during the First Gulf War.

Figure 1.18 The Horten [65] flying wing would have been quite stealthy even if its wings weren't made from plywood. After the war, Reimar Horten said he mixed charcoal dust with wood glue to absorb radar and shield the aircraft from detection by British radar that operated at 20–30 MHz. Source: HawkeyeUK/Wikimedia Commons/CC BY-SA 2.0.

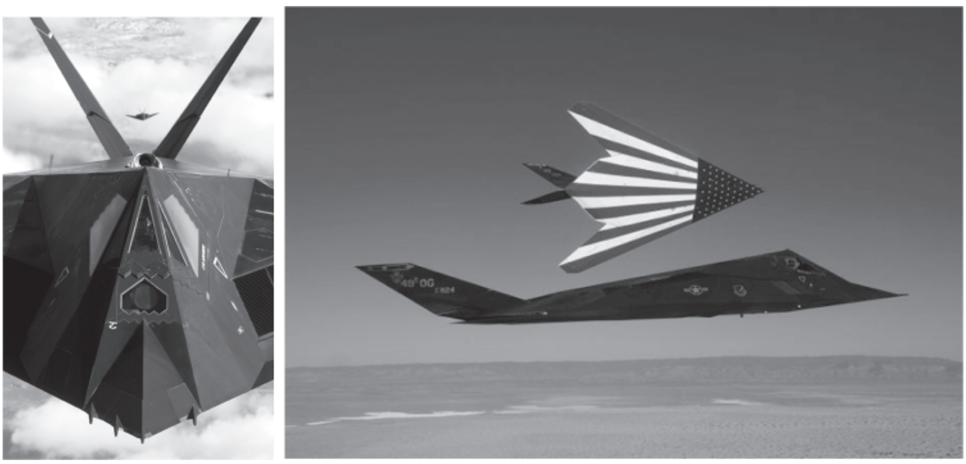


Figure 1.19 Most people first became aware of stealth aircraft when the F117A Nighthawk was used to great effect in Iraq in 1991. The faceted shape is designed to redirect radar, not absorb it. Source: (a) Master Sgt. Lance Cheung/U.S. Air Force/Wikimedia Commons/Public domain. (b) Senior Master Sgt. Kim Frey/U.S. Air Force/Wikimedia Commons/Public domain.

top secret operational stealth fighter. I now understand that the faceted nature of the design was due to the limitations of computers and methods for calculating radar cross section back in the day.

The main thing to notice from the pictures in Figure 1.19 is that there are no flat vertical surfaces or right angles. The facets do actually line up, so that the incoming radar beam is reflected off into a few carefully chosen directions, with only diffraction from corners and edges sending radar energy back toward the transmitter. It's also a relatively small aircraft, and it turned out to be quite effective at sneaking unnoticed all the way downtown and using precision munitions to turn off the radars and antiaircraft installations of adversaries. The infrared camera that it used to sneak about at night also made for compelling press conferences. You can see an F117 up close in the Cold War Gallery at the National Museum of the United States Air Force in Dayton, OH. The Testors F19 model kit might still be available on eBay.

Teenagers these days are all walking around with semidisposable supercomputers in their pockets, which they mostly use to post their brunch to *Instagram* and make *TikTok* videos. I'm not quite old enough to remember when computer was a job description rather than an electronic machine, and I missed punch cards by about a year, but I do remember assiduously backing up my computer files onto reel-to-reel tape. I still kind of miss programming in FORTRAN77. I don't miss waiting in line at the computer center for a terminal until 4 a.m., so I could get my programming assignment done.

Back in the day, you had to first identify the components of the scattering that were contributing to your total radar cross section and then analyze those individual scattering centers. The elegance of the design of the F117 was not its beauty or aerodynamic performance (it had neither); it was that from a radar perspective, it was flat plates, edges where flat plates joined at a minimum number of angles, and corners at the intersection of three plates. Those were doable with the kinds of computers I remember fondly from my twenties.

Figure 1.20 shows a standard airframe geometry with typical scattering centers and mechanisms identified. Decades of mental effort documented in innumerable doctoral dissertations was expended to develop the mathematics and computational methods to understand these sorts of contributions. Any locally flat surfaces will give rise to specular reflections where the angle of reflection is equal to the angle of incidence, measured relative to the surface normal at that point. The facets on a 117A are carefully angled so as to control reflections. Any surfaces at right angles to each other will give retro-reflections that send the energy right back to the transmitter for a large range of incident angles. So if you're going to have horizontal stabilizers, you don't want anything vertical. Once those two contributions are minimized, you might think we're good. Nope. The tip of the nose of the fuselage will give tip diffraction in pretty much all directions. Both the leading and trailing edges of the wings and tails will give edge diffractions, which will depend on their sweep angles. Any corners will give corner diffraction, and any discontinuity in curvature will also diffract. Any gaps or seams around a door or hatch or control surface will scatter. Engine inlets and outlets will give cavity returns and maybe even a characteristic doppler signal if the rotating fans are in view. Some of those contributions are small, of course, but to be truly stealthy they need to be knocked down systematically. Here's a couple more that are rather surprising. At certain angles of incidence, surface waves will be generated. We call them traveling waves if they're going down the long axis of a body and creeping waves if they're going around the short axis. They'll scatter if they hit a discontinuity or edge or the back end or whatever. Oh, and if you change materials, that will also scatter.

Figure 1.21 is a cartoon of my wife's Volvo, with scattering centers identified. Figure 1.22 shows what you could do to minimize its radar cross section. The main contribution to radar backscattering is the radiator and engine block, so you'd want to put an angled reflector in front of that because tilting the radiator reduces the cooling efficiency. Once that's taken care of then the next level of stealthiness comes from preventing scattering inside the passenger compartment; aircraft canopies solve that problem with a thin metallization layer that is optically transparent but reflective in the radar threat band. I also noted a few additional steps one could take.

The car I wanted to buy back in the late 1980s was a blue Saab 900S four-door sedan. I thought the Saab and Volvo would complement each other nicely in my garage. I do understand that there was a healthy Yankees–Sox sort of rivalry between Volvo and Saab back in the day before they were sold to China and killed, respectively, by American auto companies, but unlike baseball, you don't have to choose sides. Volvos have always been very safe because the founder's wife was an ER doctor and presumably she told him over dinner about the mangled after-effects of car crashes she had tried to humpty-dumpty back together again at work that day. Saabs have always been quirky because they held onto their form-follows-function aerospace design heritage, which as an aerospace engineer, I liked quite a lot. If you do the same things for the Saab that I suggested for the Volvo in Figure 1.22,

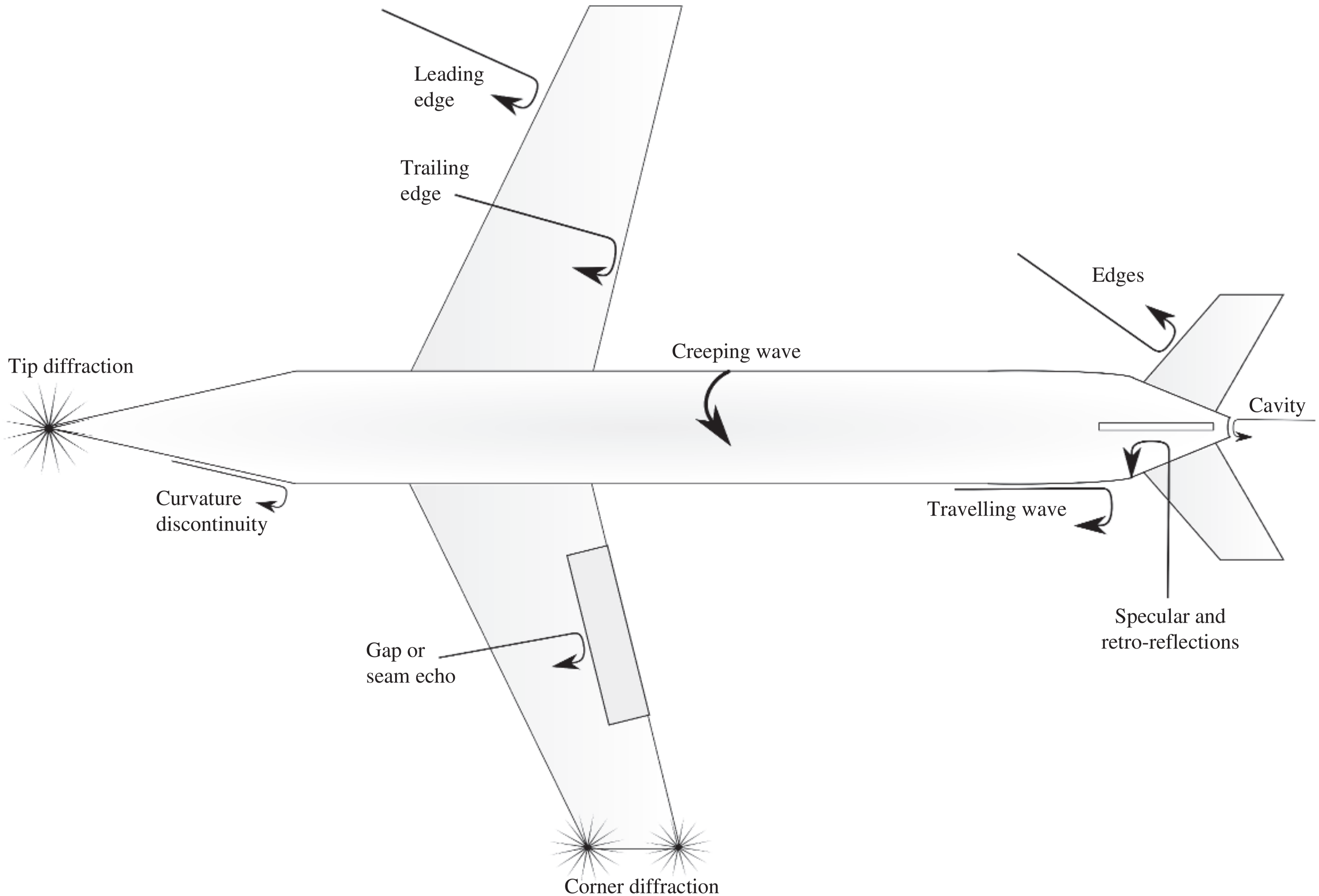


Figure 1.20 A simplified cartoon of an air vehicle allows us to consider what geometric features cause scattering.

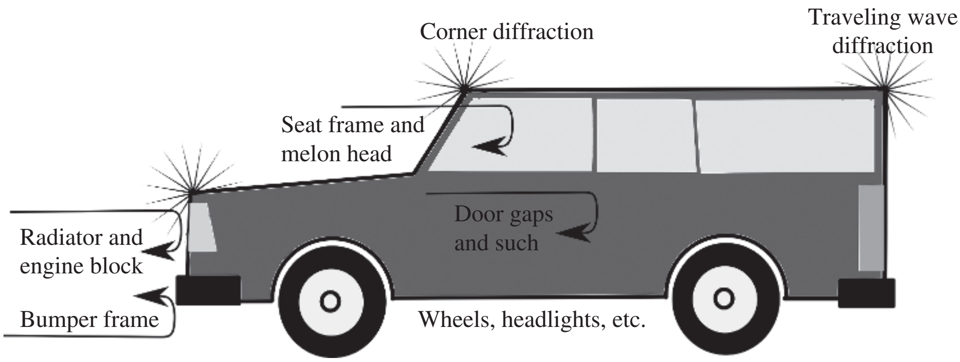


Figure 1.21 The primary contribution to radar backscattering for a Volvo 240 wagon is going to be the radiator and engine block or firewall. The windshield is transparent, of course, so next are probably metal seat frames and maybe your melon head, especially if it's covered in tin foil. Metalized coatings on headlight reflectors might be pretty significant, and of course, the steel bumpers under the rubber coverings will reflect even though they're just a bit curved. Then what? I see some corners, which will diffract. Traveling waves on the long flat roof will diffract from the gap at the tailgate, and the same goes for the hood. Gaps around doors and body panels will scatter. Wheels would give a Doppler signal if police radar was that sophisticated, but it's not.

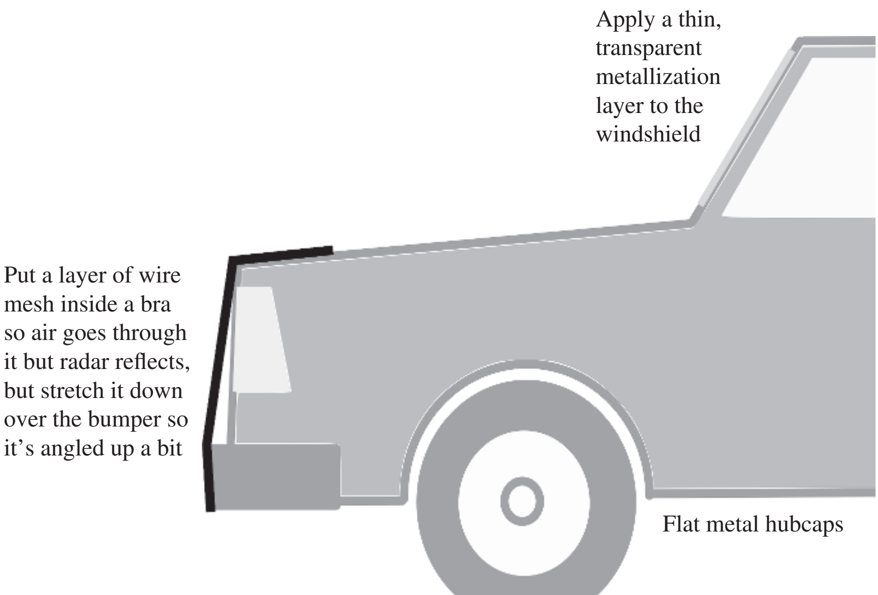


Figure 1.22 Step number one, get yourself a windshield with the Quickclear (https://en.wikipedia.org/wiki/Quickclear) option. The metallic content of the glass has been shown to degrade the performance of certain windshield-mounted accessories, such as GPS navigators, telephone antennas, and radar detectors, so we know it will work nicely to keep your melon head from backscattering police radar. Step number two, get your car a bra which is typically used to protect the paint from pebbles. Carefully peel apart the vinyl and felt layers and add a layer of wire mesh in between them with a grid spacing less than about a cm, and put that on the car. Step number three, get yourself some boring flat metal hubcaps and if you really want to go for broke, replace the side mirrors with cameras and tape over panel gaps with that foil tape HVAC pros use, hidden under PTA-approved bumper stickers of course. Step number four, drive like a maniac while rocking that dad bod. In addition, don't forget to hit a curb to round over your front license plate just a bit.

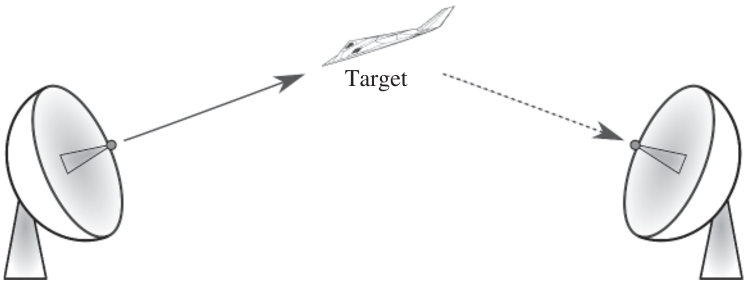


Figure 1.23 The highly swept planform, carefully aligned facets, screened inlets, metalized glass, etc. ensure that the head-on RCS of the F117A Nighthawk is minimal because very little of the radar beam is backscattered. Bistatic radar is a countermeasure to this by trying to pick up those redirected radar echoes with a second receiver.

you would have a very stealthy daily driver that is as good in the snow as an orange VW Bug but also has heat. If you're not familiar with the Saab 900S, look it up. The windshield is quite curved, so if it's metallized to reflect radar, it will backscatter almost nothing. Also note how much the bumper protrudes ahead of the curved nose, so if a mesh-enhanced bra is stretched from below the ground-effects feature, up over the bumper and partway up the bonnet . . . .

All of the above discussion is based on the assumption that the radar illuminating you is monostatic. The radar isn't so much absorbed as it is redirected. An obvious countermeasure to this is sketched in Figure 1.23 where you transmit from one antenna and record the scattered radar signals with another antenna someplace else. Stealth is a game of countermeasures and counter-countermeasures and so on. What you really need is to be able to understand both the operational mission(s) and the scattering behavior of your vehicle, so you can drive to college and not get speeding tickets.

1.6 Acoustic Parametric Arrays

By mid-afternoon of 11 September 2001, we had already begun to work out how the kinds of things that we knew how to do could be adapted to detection of concealed weapons. It was clear that metal detectors had failed, so technologies were going to be needed to detect nonmetallic weapons such as ceramic knives. We had been working on a variety of tomographic reconstruction projects using acoustics, and had begun to explore how sophisticated air-coupled ultrasound in the 50-kHz range might be useful as a mobile-robot navigation sensor. I wrote up a one-page description of my thoughts, a bit of which said, "Ultrasound has an inherent advantage over magnetic and radar-based imaging techniques which are only sensitive to hidden metallic items. Ultrasound can just as easily detect hard plastic items hidden about the body. Indeed, ultrasound is just as sensitive to unfilled gaps as it is to discrete hard objects. Every material – solid, liquid or gas – affects ultrasound in a distinct way. Although that physics is extremely complex, our expertise lies in precisely the esoteric science and technology necessary to harness the complexity and sort it out in computers that are used to automatically process the scan results and identify the suspicious items in real time."

We also modified one of our 3D ultrasound scanners to accept transducers in the 20–200 kHz frequency range and covered a dress-maker's dummy with tissue-mimicking gel, so that we could perform experiments in the lab by putting different types of clothing on "no head" with various simulated weapons underneath. We came to two very important conclusions. First, it's hard to focus the ultrasound beam at any appreciable stand-off distance with even a fairly large transducer because the wavelength is rather big. Second, the acoustic impedance mismatch between air and cloth is large enough that most of the ultrasound beam simply reflected from the surface of the garment. A third conclusion was that the backscattering was really complicated. Part of the answer turned out to be employing a new technology.

Nonlinear acoustics allows one to make a compact, highly directional loudspeaker called a parametric array.[16] If you plug your iPod into it it plays music, but you only hear the music if the speaker is pointed at you. Standard ultrasound transducers are used to transmit an acoustic beam at, for example, 50 kHz along with another signal at 49 kHz. Directionality will be determined by the size of the transducer array compared to the wavelength of the ultrasonic beams. Nonlinear effects in air will then give both the sum and the difference frequencies, 99 and 1 kHz. Since attenuation of sound goes like frequency squared, the 99 kHz beam will attenuate fairly rapidly while the 1 kHz audio beam will propagate much, much farther than the original ultrasound beam, while still being as directional as that ultrasound beam. In order to play music, one of the two ultrasonic beams is simply modulated so that the difference frequency follows the intended melody. The nonlinear acoustics is complex, but the resulting devices are quite simple except that the nonlinear effect itself is a function of frequency, so you might need some pretty sophisticated electronics to make the music sound good. You could also hide a subwoofer under the table when making demonstrations, Woody.

Our approach to stand-off concealed weapons detection was to use parametric arrays to direct a narrow, low-frequency beam of sound toward a person's body. Although the beam of sound is in the audible frequency range because it's not pointed at the person's head, they won't hear it. The low frequencies will penetrate the clothing like your neighbor's bass notes do your apartment's walls, and then if there's a concealed weapon that will backscatter a signal that can be picked up with a microphone. Figure 1.24 shows two versions.

Figure 1.24 Waveform synthesized via Matlab on laptop and sent via headphone jack to parametric array which transmits it via nonlinear ultrasonics. Dish collects back-scattered sound from target and sends it to laptop via microphone jack where Matlab records the digitized waveform for analysis.

16 The parametric array was invented by Peter Westervelt [66] although Woody Norris likes to take credit for it since he seems to be the first one to make and sell devices commercially, which we bought and used in the aughts for concealed weapons detection. Joe Pompei started Holosonics after his PhD at MIT on this subject. He built us a system or two after LRAD took off big and Norris' company wasn't interested in R&D anymore. Sennheiser tried to hire Dr. Pompei and he claims they stole his ideas and then didn't hire him. More recently, there was a kickstarter-funded project that called their small unit the Soundlazer.

As this work progressed and the problem of most interest was suicide bombers approaching checkpoints, we did systematic experiments and simulations to detect concealed explosives. We built a custom system with a curved parametric array to focus the beam at 50 ft because you need to detect the explosive from beyond what is called "the lethal radius," which I took to mean the distance at which if a suicide bomber blows himself up, he doesn't get entrails all over me. Once we got that system working and were ready to begin collecting systematic data of backscattering from a variety of simulated weapons and explosives, as well as benign scattering objects under clothing, our sponsor said, "we meant 50 m, not 50 ft" but then didn't have the budget for us to build that prototype. One member of the development team did volunteer to strap on a test article that simulated an explosive and ball bearing-filled jockstrap, and then be scanned with the parametric array system. I made some excuse to not be available to be there for those tests. We'll do scattering from spheres in Chapter 6, BTW.

We later mounted the parametric array and speaker dish on a mobile robot and took *rMary* out and about to collect backscattering data from approaching vehicles, as shown in Figure 1.24. The parametric array projects a narrow acoustic beam down the street and records with the dish microphone the echoes that backscatter from oncoming vehicles up to 50 m away. Since scattering is strongly frequency dependent, we transmit a linear chirp signal and then use the differences in backscattering as a function of frequency to distinguish different classes of vehicles. It's important when you're sending a robot out to run an errand for you that the robot watches for traffic and not get squished.

1.7 Forward to Scattering

What we'll see in the coming chapters is that radar and sonar and ultrasound and seismology and optics and a wide variety of other physical phenomena, which are usually considered as distinct fields of inquiry, can instead be considered as different aspects of the same thing. The field equations that describe these various wave phenomena are different, of course, but in all cases we ultimately end up solving wave equations to model wave propagation. That seems obvious, but there are some subtle differences in wave modes and boundary conditions that will add richness to wave scattering behavior necessary for our mathematical models to predict actual physical behavior.

The equations and methods of solution that we're going to be discussing are not new. I didn't invent them. I'm not a mathematician. There will be no lemmas, proofs, etc. My goal in this book is to pass along a way of thinking about all these seemingly disparate subjects, along with some of the mathematical toolkit that's necessary to exploit models to understand scattering behavior so as to be able to exploit them to solve problems in the real world.

We're mostly going to be doing *forward scattering* problems and will focus initially on those canonical geometries where exact solutions are in hand. What we'll see is that the scattering behavior for even simple situations has a surprising richness to it, and if we try to make the models just a bit more realistic, we will often end up with equations that are not solvable and thus not all that useful. We'll start at about the time Americans were having a Civil War and trying not to drown in hand-cranked submarines.

In the middle of the 19th century, Alfred Clebsch was trying to mathematically model the refraction of light by lenses. The electromagnetic theory of light hadn't been developed yet, so he was using an elastodynamic theory of the aether to model light propagation and scattering. Much of the mathematics of what's now called Mie Scattering hadn't been worked out quite yet, for example, the necessary special functions and their properties, so Clebsch had to invent the math to solve the problem. In addition, the elastodynamic model of light is unnecessarily cumbersome, particularly the boundary conditions which couple the longitudinal and transverse wave modes at an interface.

In the late 1980s when I was doing scattering research for the Air Force, the USAF Geophysics Library had a robust enough collection that when I needed to read Clebsch's 1861 paper, I simply fetched that journal volume from the stacks and gingerly photocopied it. I then manually transliterated it (and Mie's famous 1908 paper) from German so I could follow the mathematical development. The scattering literature over the last half of the 19th century was surprisingly interesting to read, as people realized that the electromagnetic theory of light worked so much better than elastodynamics. There's even a 1900 paper by Lamb [67] with a disclaimer to the effect: I worked on this elastodynamic model for a very long time and I realize that the electromagnetic model is better in every way, but I'm publishing this anyway in case someday somebody might find it useful. I guess publish or perish has always been a thing. I do hope you find some of the rest of this book helpful.

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