Weird Data: The Element of Surprise in Underwater Acoustic Sensing

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The Challenge of Underwater Acoustics

Dive underwater and the world changes. The color you see shifts toward blue green, your ears pop and fill with water, and suddenly things sound different (e.g., Casper et al., 2022). The splashes and bird calls above the waves disappear and are replaced by groans, clicks, and pops (Dahl et al., 2007). What are these sounds? Where do they come from?

Or maybe you are on a boat over a trench thousands of meters deep. Suddenly, the depth sounder seems to think that the water is only 500 meters deep, but the chart says it should be 5,000 meters. The instrument jumps from 500 to 5,000 meters and back for a few minutes and then settles. What happened?

The commonality between a boat's depth sounder and those mysterious sounds you hear when you dive beneath the waves is underwater acoustics, a field in which even the most experienced practitioners struggle with understanding all of the many sources of interference, noise, and changing physics needed for data interpretation. Users of ocean acoustic instruments don't control whale calls, shipping, snapping shrimp distribution, fish finders on other vessels, nesting creatures, or pile driving and cannot predict ahead of time all of the possible sources of interference in acoustic data. The complexity of underwater acoustic systems provides further challenges; is that unexpected signal a new source in the environment, a potential signal of interest, or system noise?

This complex interaction of environment, uncontrolled and uncorrelated noise sources, internal noise sources, and unexpected reflections leads to a lot of "weird data" in underwater acoustics. These weird data are the segments in any underwater acoustic time series that don't answer the fundamental questions at the core of the experiment or are mysterious in origin.

Humans are driven to find patterns in the chaos and to try to understand the whys and wherefores of our world. Everyone experiences trying to understand weird sound data in daily life. For example, you might hear an unexpected squeak or beep at home and spend a few minutes walking around the house, turning your ears in different directions, sticking your head out windows, and pausing to listen, all to try to find the noise source. Or perhaps you apply sound pattern recognition while trying to diagnose a suspicious rattle in a car engine, pressing the gas pedal and then the brake, querying your partner to determine if the sound got quieter or louder with the change of variables.

The quality of underwater acoustic measurements constantly changes based on uncontrolled, capricious factors. Therefore, interpretation of underwater acoustic data is like hunting that unexpected squeak, groan, rattle, or flutter, generally without the benefit of being able to stick your head out the window or adjust self-noise to see if the sound is still there. This sometimes frustrating process is the quintessential center of science: taking in the unexpected and using that new information to question the foundations of knowledge. There is a lot to be learned by our weird data, and in surprises that provide insight into systems, biology, and oceanographic processes in the ocean.

Categories of Interference

Surprises in underwater acoustic signals occur when our a priori understanding of the environment, ambient-noise sources, and the paths of transmission of acoustic energy are incorrect or incomplete. The ocean environment is stochastic in nature (Colosi, 2016), with properties of both signal and noise varying constantly in ways that are difficult to predict (Miksis-Olds et al., 2018). Understanding underwater acoustic data becomes difficult when the

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noise level is higher or when the signal level is lower than expected. The objective of this article is to show examples of these categories of interference and provide some stories illustrating how they were diagnosed.

These underwater acoustic surprises fall into four general categories:

(1) External sources: acoustic energy from nonsignal sources in the environment;
(2) Environmental propagation effects: changes in transmission loss between the receiver and the source due to sound speed and boundary effects;
(3) Internal system noise: sources within a system such as mechanical vibrations, electrical interference, crosstalk, flow noise, and self-noise; or
(4) Unexpected reflection: reflection and scattering from water column sources, (e.g., ships, volume inhomogeneities, thin layers, organisms).

External Interference

Sound is emitted into the water by a wide variety of anthropogenic and natural sources (Bradley and Nichols, 2015), and it is the resulting "external interference" that comes to mind when most people think of underwater noise. **Figure 1** shows a few of the many sources of external interference for acoustic systems in the ocean that result in noisy underwater acoustic data.

The background noise level in the ocean is often approximated as a single decibel number based on sea state, weather, and frequency/prevalence of shipping. Although this ambient noise estimate is an approximation of the ambient-noise level, the geographically and temporally variable true ambient noise in the ocean is far more complex. Weird data due to external interference occur when noise levels exceed expectations and/or vary significantly with time. Sources of this type of "surprise" external interference in underwater acoustics might include natural sources of sound (e.g., cetaceans, fish calls, snapping shrimp, noise from weather, waves, or geology) and anthropogenic sources of sound (e.g., ships, sonar systems, acoustic modems, pile driving, or airguns).

Natural Noise Sources

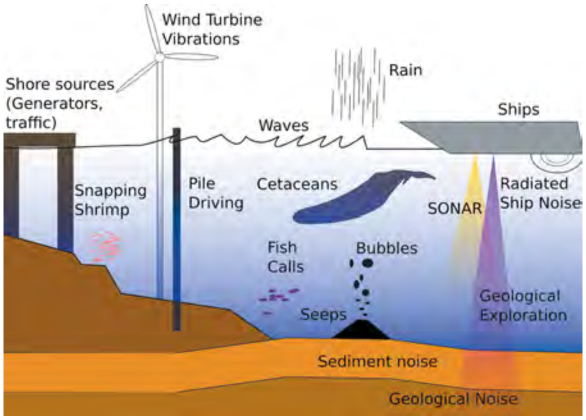


Figure 1. *Examples of external interference that may be picked up by a receiver in the ocean. These sources are uncontrolled, and many often occur together to emit sound at varying frequencies into the water that can affect underwater acoustic sensing systems.*

Biological noise sources can cause significant problems with autonomous processing or detection methods because cetacean communications are often in the same frequency band used for underwater communication and navigation systems. Matt Palanze of the Woods Hole Oceanographic Institution (WHOI), Woods Hole, Massachusetts, experienced just how challenging it can be to operate acoustical systems in the presence of marine mammal noise when his team was attempting to trigger an acoustic release:

> "On an OOI cruise, we approached a large surface mooring for recovery. We communicated with the acoustic releases with a deck box located in the ship's lab. There are three releases on this mooring, two are connected in parallel for redundancy, specifically in the case of a failure. We can release the other with no other intervention being needed. None of the releases would reliably respond to queries and commands; there is a very low historical probability of this occurring. After approximately 20 minutes (which, as you know, is forever in ship time!), one of our colleagues came into the lab and announced, 'There's about a thousand dolphins out there!' We went out on deck, and sure enough, there were dolphins and whales to the horizon. We could hear their calls from the deck. We had to stand by for an hour or so until the pods moved on. After that, we released the mooring and recovered as normal. I believe this event went into the cruise report as 'Operations delayed due to Mammalian Interference'" (personal email, 2022, used with permission).

Dolphins and whales are not the only creatures that can create external interference for acoustic systems, as Emma Cotter of the Pacific Northwest National Laboratory, Richland, Washington, experienced with a passive acoustic data recorder in the ocean:

> "When we deployed an autonomous system, the hydrophone data showed periodic sound at low frequencies (<1 kHz) that we couldn't explain. We initially thought it might be electrical noise or flow noise, but eventually realized it was the result of crabs scraping their carapaces on the metal surfaces of the lander" (personal email, 2022, used with permission).

Another common biological noise source is snapping shrimp. When these extremely loud, impulsive signals are present, they can significantly affect the acoustic system signal-to-noise ratio (SNR) in frequency ranges from low kilohertz to 10s of kilohertz. If you ever go scuba diving, you might hear the signal from snapping shrimp as a crackling high-frequency sound near reefs.

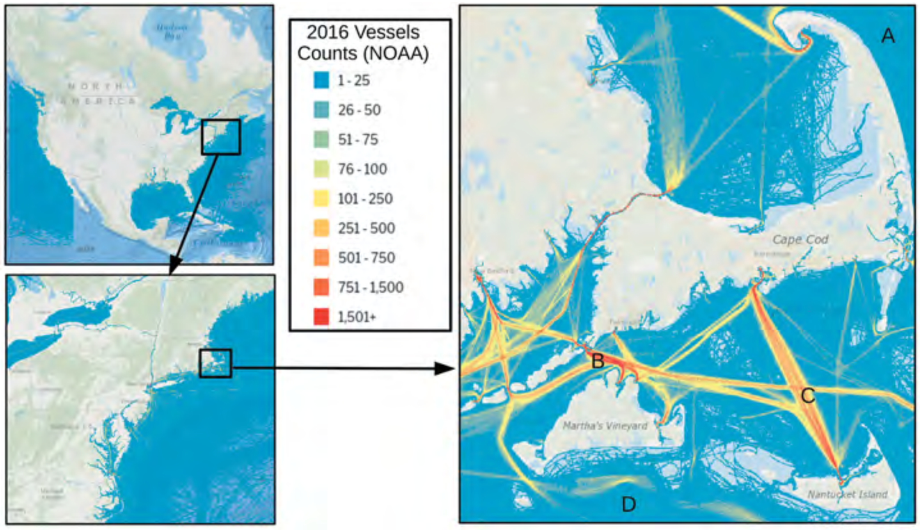
In addition to biology, the ocean environment itself is a source of natural external noise. Examples include sea ice (Worcester et al., 2020), glacial action (Deane et al., 2019), sediment noise, surface weather and waves, magma displacement, and earthquakes.

Anthropogenic Noise Sources

The actual noise level due to shipping is highly linked to latitude, longitude, and depth relative to strong propagation paths from shipping lanes. Worldwide automatic identification system (AIS) maps are available that show historical counts and densities of ship traffic, revealing striking patterns in ship movements. **Figure 2** shows an example of one of these maps from 2016 for the waters around Massachusetts using publicly available National Oceanographic and Atmospheric Association (NOAA) data. Unsurprisingly, choosing a sensor location near a shipping channel or ferry route significantly increases the ambient-noise level due to ships (e.g., B and C in **Figure 2**), whereas a location with only a few ships per year (A and D in **Figure 2**) will have a much lower noise level due to shipping.

The impact of nearby boats on an instantaneous SNR is striking when seen in a spectrogram or beamformed passive acoustic data from an underwater hydrophone array. **Figure 3**, *top* and *bottom right*, shows the results of a boat crossing near an array of recorded acoustic data. Ship noise is complicated because it overwhelms most other signals, is aspect (angle) dependent, and is subject to Doppler shift and multipath effects; this causes an interference pattern that shifts in frequency with range

Figure 2. *Automatic identification system (AIS)-based ship counts from National Oceanographic and Atmospheric Association (NOAA) for 2016 around Cape Cod, Martha's Vineyard, and Nantucket Island in Massachusetts. Geographical location in the ocean has a large impact on the ambient-noise level. For example, a sensor located at point A or D would experience far lower noise from ships and boats than a sensor at a location experiencing multiple times daily ferry traffic (point B or C).*



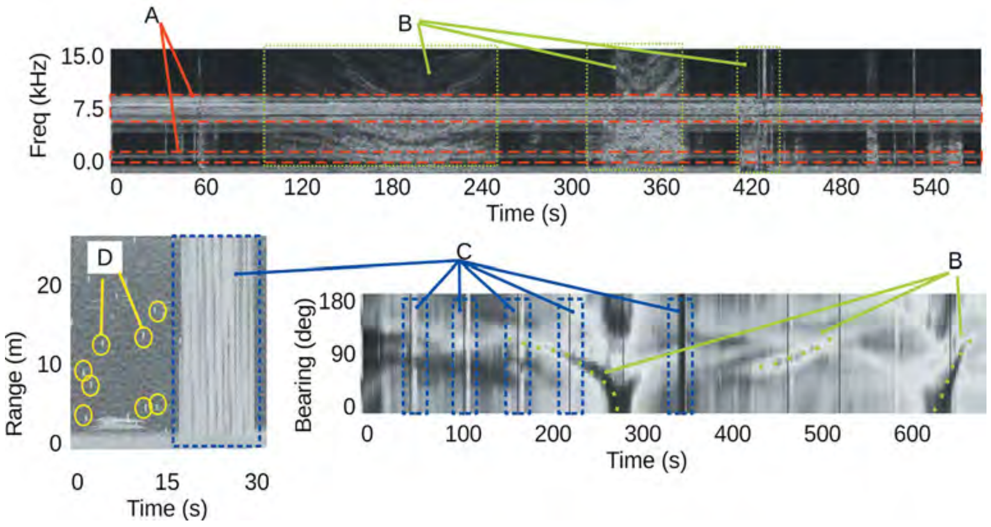


Figure 3. *Examples of interference in acoustic data. All plots show grayscale decibel levels of received power.* ***Top:*** *spectrogram of passive acoustic data. Significant features of the spectrogram include ship noise (point B) and broadband electrical power noise (point A).* ***Bottom left:*** *broadband echo sounder data that include acoustic modem noise (point C) and acoustic Doppler current profiler (ADCP) interference (point D) that obscures scattering from water column features.* ***Bottom right:*** *beamformed acoustic array data indicating the direction of arrival (bearing) in degrees of energy versus time. Ship transects are visible and change in bearing versus time (point B). Acoustic modem noise is also present in the bearing color plot (point C,* ***vertical dashed lines****).*

(Gassman et al., 2017; Miksis-Olds et al., 2018). Other common sources of anthropogenic noise include airguns, pile driving, wind turbine noise (Amaral et al., 2020), and vibrations transmitted through other types of structures (e.g., traffic near a dock, oil platform vibrations).

Given the prevalence of anthropogenic noise, and ship noise in particular, many researchers have been working over the last decade to use these "sources of opportunity" to better understand the ocean. This includes gleaning estimates of biomass in the ocean (Haris et al., 2021) and temperature and salinity (e.g., Kuperman et al., 2017) via a process known as acoustical tomography.

Environment Propagation Effects

The underwater environment includes the surface, water column, and bottom. Received acoustic signals in the ocean are affected by all three. In all underwater acoustics, the received signal is affected by transmission loss, which is the spread and attenuation of the source signal by environmental factors and absorption. In the simplest estimate of transmission loss, a line is drawn between a source and receiver, and the received amplitude is calculated as the source level minus the geometric spreading loss (spherical and/or cylindrical) and absorption (Francois and Garrison, 1982).

Although this would be the approximate case for a uniform sound speed profile, sound in the ocean curves, is reflected, and gets trapped based on boundaries and sound speed versus depth, range, and time. In all these cases, an essential fact of underwater acoustic propagation is that temporal and spatial changes in the surface, bottom, and sound speed impact instrument measurements.

Boundary Effects

Boundary effects, such as sound bouncing off the surface, the bottom, and ice, are illustrated in **Figure 4**. Surface, ice, and bottom interactions all can cause scattering, reverberation, and reflection. The resulting signal multipath varies significantly based on surface and bottom roughness and slope or from jagged features of the ocean bottom. Additional boundary effects are driven by the fact that the ocean seabed is not homogenous; layering is common, with changes in density and sound speed causing reflections and changes in the signal.

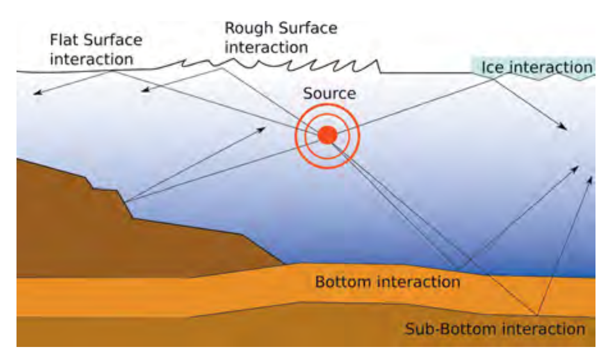


Figure 4. *Interactions with the surface and bottom change acoustic propagation. The ocean surface and bottom can have varying roughness. Ice on the surface can also cause reflections. Layering in the ocean bottom can also cause subbottom reflections.*

Bottom topography, in particular, can cause acoustic arrivals at the receiver from unexpected angles, at large intensities and unexpected time delays. Peter Brodsky of the Applied Physics Laboratory, University of Washington (APL-UW), Seattle, described a particularly startling reflection he experienced:

> "Years ago (many) I was on a Navel Oceanographic Office ship — the USNS Lynch — performing seismic surveys in the South Atlantic. Our typical acoustic sources were airguns and sparkers, but in really deep water we'd use explosives. On one occasion we dropped a final charge, heard it go off, then went off to get dinner. A minute or so later there was a BIG bang that shook our soup bowls in the mess. The Chief Engineer (CE) ran out and raced down to the engine room, cursing about some incompetent oiler who let the engine throw a rod (again). Turns out it was a reflection of the last charge off a submerged ledge of some kind; far away but oriented perfectly to direct the sound right back at us. The CE never showed up at regular mealtimes again" (personal email, 2022, used with permission).

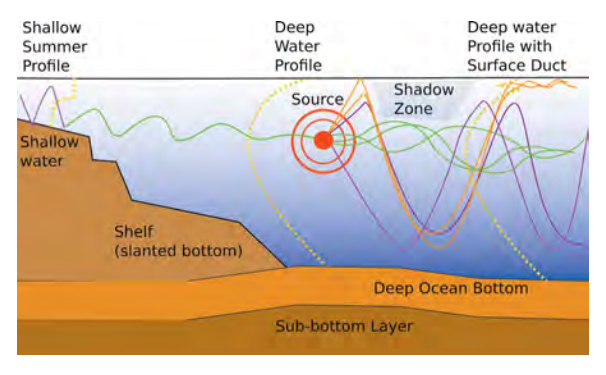
Volume Effects

The second major impact of the underwater environment on propagation is that sound energy refracts (i.e., curves) due to changing sound speed with depth and range. This creates convergence zones, shadow zones, ducted sound, and long-range propagation of low-frequency energy. **Figure 5** shows some of the ways the sound speed profile affects the refraction of sound in the ocean. Sound curves toward a lower sound speed, and this causes the complex behavior observed in ocean propagation. This includes SOFAR paths (**Figure 5**, *green*) that are refracted above and below to channel around the sound speed minimum, deep convergence paths (**Figure 5**, *purple*) that are caused by steeper launch angles and refract at deeper and shallower points than the SOFAR paths, surface ducts (**Figure 5**, *orange*) where a local sound speed minimum can trap sound near the surface, and downward refracting profiles that commonly cause increasing bottom interaction and signal attenuation in shallow water. Another feature of environmental ocean propagation is the creation of shadow zones where little energy is received due to the bending of rays.

Changes with Time

Fading of signals and/or amplification of noise due to changing environmental conditions is another common underwater acoustics challenge to signal interpretation. Temporal variability in sound speed is caused by submesoscale to mesoscale (i.e., 1-100 km) variations in temperature and salinity, such as eddies, warm core rings, internal waves, and buoyancy fluctuations (Colosi, 2016).

Figure 5. *Examples of volume propagation effects due to sound speed changes with range in the ocean. Three different sound speed profiles are shown (**yellow dotted lines**): a summer shallow-water sound speed profile (**left**), a deepwater sound speed profile (**center**), and a deepwater sound speed profile with a surface duct (**right**). **Green**, so-called SOFAR or deep sound channel paths; **purple**, convergence zone (cz) paths; **orange**, convergence zone/surface duct paths; **magenta**, downward-refracting paths that result from a shallow-water summer sound speed profile; **gray box**, shadow zone where little acoustic energy is received.*



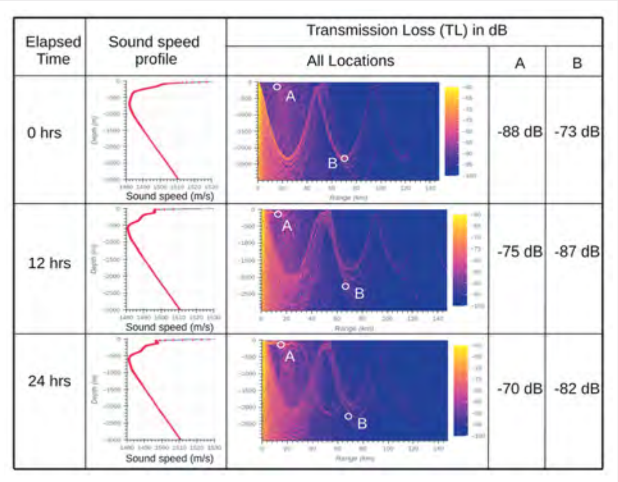


Figure 6. *Example of sound speed evolution versus time and the associated change in transmission loss (TL) for deepwater. At 0 hours, the profile is a conventional deepwater profile, with no surface ducting and a deep convergence path (**top**). After 12 hours, a surface duct begins to form, with a decrease in transmission loss at point A and increase in transmission loss at point B (**center**). After 24 hours, the surface duct is fully formed for an additional decrease in TL at point A (**bottom**).*

One example of an environment changing with time is currently being studied in the Arctic Ocean, where an intrusion of warm salty water in the Beaufort Sea is creating a sound speed minimum around 200 meters that is significantly impacting use of acoustic communication and navigation systems (Worchester et al., 2020). Shorter timescale changes in acoustic transmission occur due to buoyancy fluctuations, tidal effects, and internal waves. **Figure 6** shows how propagation characteristics can also change significantly over just 24 hours. For the same geographic location, small changes in the ocean sound speed versus depth (i.e., the "sound speed profile") have a profound effect on the resulting transmission loss versus range and depth over several days. The resulting fields are qualitatively quite different for an identical source depth of 100 meters when the sound speed profile has changed with time due to a passing eddy.

Internal System Noise

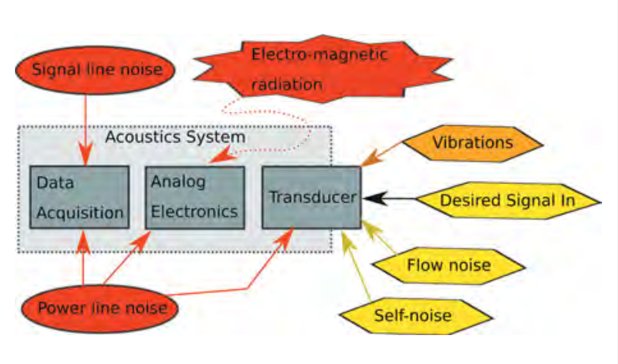
Internal system noise plagues underwater acoustic systems. **Figure** 7 shows how electrical noise, vibrations, and through-water system noise (e.g., flow noise and self-noise) couple into an acoustics system composed of a transducer, analog electronics, and a data-acquisition system. Most of these noise sources are related to the fact that acoustic instrumentation is generally deployed on a platform (e.g., a vehicle, vessel, or mooring) with moving parts, power systems, and/or communication systems.

Self-Noise and Vibrations

Passive and active acoustics systems are often mounted on some kind of vehicle, and it is common to have multiple sonar systems in use at a single time on a single vessel. This leads to vibrations, flow noise (due to motion through the water), and self-noise (due to acoustic sound put into the water by the vessel itself and/or pinging acoustic systems onboard). Christopher Bassett of the APL-UW experienced this type of ship noise, with a mystery signal that persisted across multiple sonar systems:

> "Working on a hydroacoustics survey we encountered a cyclical noise issue that caused significant drops in signal to noise ratios (SNR) across numerous narrowband echosounders. This noise would appear somewhat randomly even when the vessel operating conditions didn't change. Fortunately, the vessel had hydrophones installed and we were able to observe that periods of low SNR corresponded to times when elevated noise levels were observed. The hypothesis was that this was attributed to an issue with the bearing that produced a crunching sound tied to the prop's rotation rate, which was consistent with the mechanical nature of the sound and the temporal structure of the measured noise. Following time in dry dock, the noise ultimately disappeared, suggesting we were

Figure 7. *Typical sources of internal system noise in underwater acoustics. **Red**, electrical noise sources; **orange**, structurally coupled vibrations; **yellow**, acoustic (through-water) signals; **black arrow**, desired signal input, also a through-water signal.*



> on the right track and that the faulty bearing(s) ultimately played an important role in the degraded data quality on a commercially important acoustics survey" (personal email, 2022, used with permission).

As an example of co-interference of active acoustic systems, an acoustic modem, acoustic Doppler current profiler (ADCP), echosounder, and passive acoustic array may all be used at the same time on a single platform. In **Figure 3**, *bottom left*, interference from a 20-kHz WHOI micromodem shows up in a 333-kHz echosounder; the ADCP signal is also seen in the echosounder data as single-time specks with varying range. In **Figure 3**, *bottom right*, interference from a 20-kHz WHOI micromodel also affects bearing estimates in a target-tracking problem, showing up as strong cross-bearing features in beamformed passive acoustic data.

Electrical Noise

One of the biggest challenges to designing and building any effective acoustics system is electrical noise. In underwater acoustics, electrical noise problems are exacerbated by the restricted space in the required waterproof enclosures so that noisy components are generally physically nearby noise-sensitive elements. Furthermore, the limited pins available on underwater connectors often result in combined ground lines and limited sensor isolation. Those same underwater connectors are notorious for degrading signal quality.

As a result, underwater electrical systems need to be designed extremely carefully to ensure isolation between noisy and sensitive components. One common issue is the sensitivity of underwater acoustic systems to the resonances of platform power sources and loading on a power system; a system with low noise plugged into a ship laboratory when the ship is running on battery can experience a sudden high-noise floor with severe narrowband frequency interference when the ship's generator kicks in. Another challenge arises from other sensors or systems in use on the same platform. It is extremely common to locate multiple acoustic systems on the same platform with the same power system. Active acoustic systems can interfere with recordings on a different acoustic sensor acoustically through sound put into the water, through the power system, through electromagnetic interference, or through signal ground lines. Other systems, such as actuators, radio communication systems, and spinning drives, can also create a combination of acoustic, vibration, power, and signal noise that interferes with most acoustic sensors. Any active voltage converters can also create interference that impacts acoustic data recordings (**Figure 3**, *top*) where a significant part of the spectrogram is obscured by power system noise). These issues should be taken into consideration when designing, building, and deploying systems and when analyzing data.

Unexpected Reflections, Scattering, and Clutter

Sound is used to explore the ocean because it provides so much information, but sometimes that information is difficult to understand. Unexpected reflections and scattered sound are another source of surprises in underwater acoustic data. The most frequent issues caused by unexpected reflections are signal saturation, false positive detection, or confounding between the "signal" targets you want in your experiment and other targets ("clutter"). For example, in an experiment to count fish, an echosounder might show returns from fish but also returns from copepods, or changes in water density, shear instabilities, bubbles, and kelp (Stanton et al., 2021).

Man-made objects and structures also can cause unexpected reflections and scattering, even in the most controlled of experiments, as related by Aubrey Espana of the APL-UW when her team was running a seabed target-scattering experiment and found that a surprise ship reflection limited their working area:

> "During BAYEX14, a side lobe from our source reflected from the bottom of the boat. The timing of the path was such that it overlapped the 15m target line. So essentially, we couldn't put any objects out at that ground range. The boat was in a 4-pt moor, so moving it was not an option" (personal email, 2022, used with permission).

Reflections off boats, vessels, and underwater structures can have significant effects on sensing, navigation, and communication systems by presenting echoes that can confound the desired signal. Because acoustic systems are often mounted on some kind of platform, the platform itself can be a pernicious and difficult to identify source of reflection, as Nicholas Rypkema of WHOI observed firsthand:

> "During the integration of an ultra-short baseline receiver (USBL) on an autonomous underwater vehicle, I spent a few frustrating weeks trying to figure out exactly why I was not getting the accuracy I was expecting. Eventually, I realized that the position at which the USBL receiver was located on the vehicle changed the accuracies that I obtained — ultimately, I discovered that local acoustic effects between the received signal and the body of the vehicle created extremely reproducible biases in the resulting angle estimate" (personal email, 2022, used with permission).

Biological factors are notorious for obscuring or changing expected returns in all types of active sonar systems; fish and plankton scatter sound so they often show up when they are not the object of measurement. This was observed by James Ian Vaughn of WHOI when mapping bottom topography:

> "We were surveying the Kick'em Jenny volcano off the coast of Grenada with an EM302 multibeam some time ago. We saw a bunch of large discrete scatterers sitting in/over the caldera. We quickly followed up the multibeam survey with an ROV dive. Turns out the scatters were a school of large tuna. Too deep to fish for, unfortunately" (personal email, 2022, used with permission).

Hunting down the reasons for initially unexplained scattering and reflections has led to many revelations and discoveries across the ocean disciplines. A perfect example of this is the deep scattering layer. Early SONAR systems observed a so-called "false bottom" at around 500 meters deep. This scattering layer in the twilight zone of the ocean consists of enormous numbers of animals that migrate daily in depth, including fishes, squid, and siphonophores. Understanding this deep scattering layer has been a major objective in marine science and acoustics this decade because disruption due to fishing and deep-sea mining could have profound implications for both biodiversity and the global carbon cycle (Boscolo-Galazzo et al., 2021).

The Value of Weird Data

> "Blink our eyes, and the world you see next did not exist when you closed them. Therefore, he said, the only appropriate state of mind is surprise. The only state of the heart is joy. The sky you see now, you have never seen before" (from the *Thief of Time* by Terry Pratchett).

The attitude of underwater acoustics users in relating tales of weird acoustic data is, indeed, joy mixed with some amount of chagrin. These incidents are clearly not isolated. And when organized into the categories illustrated in **Categories of Interference**, they begin to paint a picture of the types of interference any given system may experience in the ocean. Instead of simply filtering out these surprises, they can be treated as interesting and worth preserving, sharing, and publishing.

Over the last five years, there has been an increasing effort to centralize and process underwater acoustic data (e.g., Wall et al., 2021) and to share code and processing tips among the acoustics community. A great resource list of underwater acoustic datasets is maintained by the United Kingdom Acoustics Network and includes no fewer than 33 separate databases as of March 2022 (see acoustics.ac.uk/open-access-underwater-acoustics-data). Each database has different sensor characteristics in a mix of active and passive acoustics.

In terms of processing code, the development of MATLAB toolboxes and open-source packages in Python for underwater signal processing and array processing make sophisticated analysis of acoustic data far more accessible. There are also domain-specific efforts to connect community members for information sharing, such as a new Bioacoustics Stack Exchange (see acousticstoday.org/wPQmt), built to provide a centralized discussion space for conversations about processing and understanding bioacoustics data in particular.

Including specific identification and labeling of weird data within broader datasets and processing tools as a part of this community-wide effort feels both natural and necessary, for three main reasons. First, there is an incredible potential of "found data" for other researchers, where weird noise in one discipline can be identified as a signal by another. Second, cross-sensor, labeled examples of interference would pave the way for the use of machine-learning tools in the development of ubiquitous underwater acoustic classification tools for autonomous identification of interference sources. Finally, these types of tools would make underwater acoustic data interpretation significantly easier and would also provide more information about the oceans, feeding back into providing found data across disciplines.

A brilliant use of this type of fortuitous data was related by Arthur Newhall of WHOI:

> "Unexpected data can be useful. One of our colleagues ADCPs blew up underwater from a lithium battery leak during SW06 field work off NJ. We knew the exact millisecond that happened from our local data collection receivers there, so used it to calibrate Comprehensive Test-Ban Treaty Organization (CTBTO) hydrophones off the coast of South Africa" (personal email, 2022, used with permission).

The first step to seizing on opportunities like Newhall's is talking about our weird data and starting to develop categories and classifications. Automatic, cross-system identification of several of the types of interference listed in **Categories of Interference** would not be big lifts computationally but will require databases of examples across the many types of acoustic systems and, eventually, open-source filters. The basis of more community-wide libraries and labeled datasets of unusual observations might start with acousticians keeping a folder on their computer of screenshots and brief metadata on surprises. Why not leverage all that weird underwater acoustic data by sharing and identifying all the surprises that the ocean throws at us?

Acknowledgments

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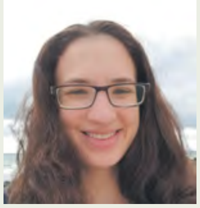

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