Global Positioning Systems: Over Land and Under Sea

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Introduction

Imagine with me a pre-COVID world. We are at an Acoustical Society of America (ASA) meeting in, say, Chicago, IL. We've just enjoyed a stimulating afternoon session, and our brains are fried. We need to find a coffee shop for a chat and some caffeine. What's the first thing we do? We quickly pull out our mobile phones and open a Yelp or Google Maps app to find a location within a five-minute walk of the conference venue with a four- or five-star review, and we are on our way, following turn-by-turn directions until we reach the destination. This mapping solution is delivered courtesy of a Global Navigation Satellite System (GNSS).

It is hard to imagine a world without GNSS. Even during quarantine, when we cannot be out having coffee with our colleagues in a new and exciting city, the motivated among us still use mapping applications to chart out our neighborhood walk or bike ride to see how far we have gone. We can "drop a pin" or share our location with the push of a button and find a friend in a parking lot or in the middle of the woods.

This positioning has become indispensable in the land, air, and space domains; however, as the electromagnetic signals sent by satellite systems do not transmit well in water, they are not available for undersea applications. Acoustic signals, however, propagate very well underwater and are commonly used for navigation of underwater vehicles as well as tracking marine mammals, fishes, turtles, and even lobsters. Typically, this tracking is done at short propagation ranges, but long-range signals can be used for positioning as well. Would it be possible to have a "Global Navigation Acoustic System" for the underwater domain that would be an analogue to the GNSS that we have become so reliant on? To answer this question, let's first familiarize ourselves with the GNSS.

Global Navigation Satellite Systems

Positioning from the GNSS is available all over the globe to provide localization, tracking, navigation, mapping, and timing, all of which are closely related but separate applications. Their availability and use have transformed the world in which we live. The most obvious relevancy of a GNSS is for the transportation industry. Mapping and route-planning applications include traffic avoidance features that have saved millions of dollars, reduced emissions, and limited time wasted in traffic. Aircraft pilots rely on the GNSS among other instruments when visual observations are not reliable.

Even the agriculture industry has been revolutionized by the GNSS. In the current age of precision agriculture, positioning systems in tractors and farm equipment can have centimeter accuracy to ensure that all of the fields are covered without driving over the same area twice. Snowplow operators also use the GNSS to locate edges of roads covered in snow.

Scientists who do field work, whether on land or at sea, would be lost without the GNSS. We rely on these satellite systems to locate our sensors and associate data with a position on the earth. Metadata for any type of dataset, acoustic or otherwise, typically contains time and location data provided by the GNSS.

The modern military uses the GNSS for guided missiles and drones to minimize collateral damage. In fact, the Global Positioning System (GPS), the US-based GNSS that we used to find coffee on our hypothetical trip to Chicago, was originally developed for military purposes. Before the development of the GPS, it was the task of several soldiers, sailors, or pilots to navigate the troops, ships, or planes. Tasking this to a remote and automated system minimizes the number of people involved in the

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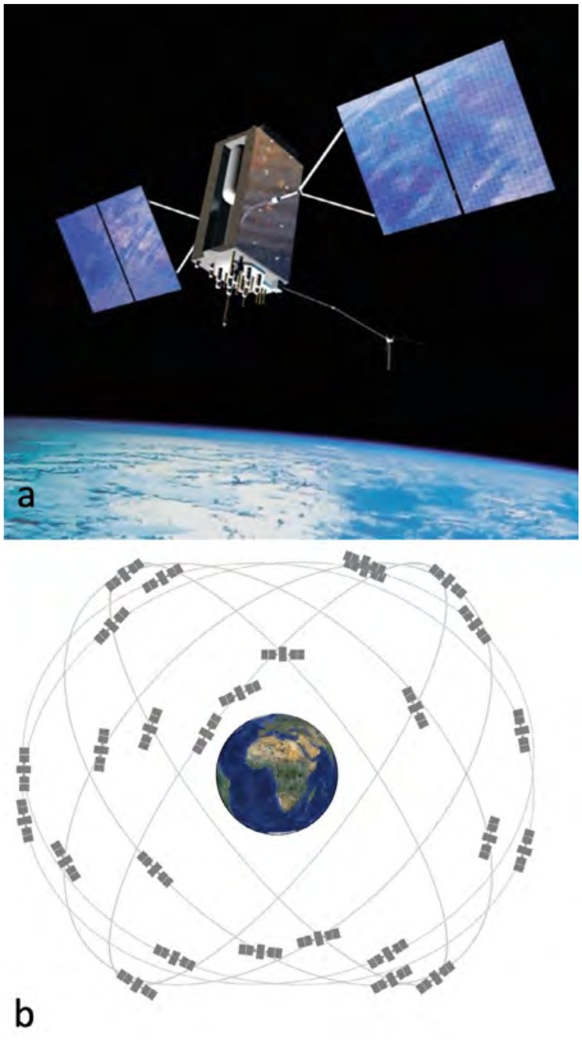
operations, freeing them up for other tasks as well as reducing human errors.

Overview and History of the Global Positioning System

The GPS is owned by the US Government and is operated and maintained by the US Air Force out of Shriever Air Force Base in Colorado. The system is young, relatively speaking. The GPS project was started in 1973, and the first NAVigation System with Timing and Ranging (NAVSTAR) satellite was launched in 1978. The 24-satellite system became fully operational in 1995. A photograph of a modern GPS-III satellite and a depiction of the satellite constellation are shown in **Figure 1**.

Figure 1. ***a:*** *Image of Global Positioning System (GPS) III satellite. A GPS III satellite is roughly the size of a small car and orbits approximately 20,200 km above the earth.* ***b:*** *Configuration of satellite constellation. The original constellation contained 6 orbitals with slots for 4 satellites each, and only 24 satellites are required to operate at any given time. But, in 2011, this was expanded to accommodate additional satellites to improve coverage. Source: United States Government (available at gps.gov/multimedia/images).*



A precursor to the GPS, the Transit System, was designed specifically to provide accurate location information to US Navy Polaris nuclear submarines and became the first operational satellite navigation system in 1964 (Guier and Weiffenbach, 1998). There is not enough space here to go into all of the science and technology advances that paved the way for the modern GPS, including the satellite geodesy work of Gladys Mae West (featured in Shetterly, 2016, and the movie *Hidden Figures*), but the gps.gov website, maintained by the national coordination office for space-based positioning, navigation, and timing and hosted by the National Oceanic and Atmospheric Administration (NOAA) has a wealth of useful information and links.

The US-based GPS satellites are not the only navigational satellites orbiting the earth. Indeed, a Russian-based GLObal NAVigation Satellite System (GLONASS) became operational around the same time as the GPS. The United States and Russia both started construction of their own GNSS constellations at the height of the Cold War. More recently, in June 2020, China launched the final satellite in the third generation of the BeiDou Navigation Satellite System, which now provides worldwide coverage. Europe has launched Galileo, which has been operational since 2019, and the complete 30-satellite system is expected by the time you read this article. Galileo is the only purely civilian system; the systems launched by the United States, China, and Russia are all at least partially owned or operated by the military. Most modern smartphones have the capability to receive signals from multiple constellations.

How Does the Global Positioning System Work?

GPS satellites continuously broadcast electromagnetic signals that travel through the atmosphere, providing their location and precise timing information. (I refer to the GPS, but this can be applied more globally to other GNSS constellations as they operate using the same principles.) A GPS satellite transmits multiple signals,

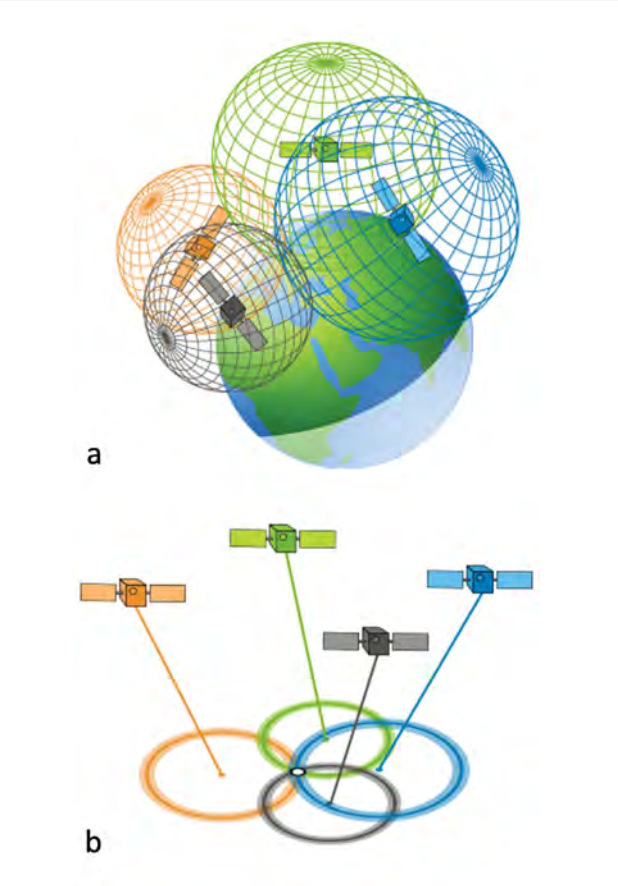


Figure 2. ***a:*** *Depiction of positioning of a GPS receiver using trilateration in three dimensions. Each sphere with a satellite at its center represents the distance calculated from Eq. 1. The four spheres intersect at the location of the GPS receiver.* ***b:*** *Trilateration with four satellites projected onto two dimensions with the single point of intersection determining the location of the GPS receiver. Presented with permission from gisgeography.com.*

including ranging signals and navigation messages. The original GPS design contained two ranging signals: a coarse/acquisition (C/A) code and a restricted precision (P) code reserved for military and government applications. Each satellite transmits a C/A code with a carrier frequency of 1,575.42 MHz. Galileo and BeiDou also transmit signals at this carrier frequency, which is in the microwave band, outside of the visible spectrum.

The time that it takes the signal to reach the receiver is used to calculate a range or distance (d) from the satellite with the following simple relationship

$$d = c \times t \tag{1}$$

where c is the speed of light (299,792,458 m/s) and t is the time of flight for the signal traveling through space. This time of flight is the difference between the time the signal is broadcast by the satellite and the time the signal is received. Once a GPS receiver obtains the distance between itself and at least four satellites, it can use geometry to determine its location and simultaneously correct its time.

The concept is relatively simple and is demonstrated in **Figure 2**. If we know just the range from a single satellite, the location of the receiver could be anywhere on an imaginary sphere with the satellite located at its center. Combining the ranges received from 4 satellites, along with precise timing information, provides a single intersection point in 3-dimensional space that corresponds to the position of the GPS receiver. This is referred to as trilateration (often confused with triangulation, which involves measuring angles rather than distances).

Apparent from **Eq. 1**, an inaccurate estimate of the signal travel time will give an incorrect distance from receiver to satellite and therefore an inaccurate position. Precise timing is therefore vital to GPS operation. Nanoseconds in timing error on the satellites lead to meters of positioning error on the ground. Each satellite has an atomic clock onboard, which provides precise timing information. These precise clocks are updated twice a day to correct the clock's natural drift using an even higher precision atomic clock based on land.

Underwater Positioning and Navigation Using Acoustics

It is interesting to note that satellite navigation systems were first designed with submarines in mind even though the GPS is not useful beneath the sea surface. Electromagnetic waves from the satellites travel very efficiently through the atmosphere but are quickly attenuated underwater. Underwater vehicles and underwater instrumentation are therefore unable to take full advantage of the GPS infrastructure.

Submarines do take advantage of underwater acoustic signals, and the field of underwater acoustics has largely been driven by military applications (Muir and Bradley, 2016). Acoustic waves are mechanical pressure waves and therefore do not propagate well in the (near) vacuum of space but travel more efficiently and more quickly in denser media. Because of this, sound travels faster in seawater than in air and it is less quickly attenuated.

The same basic relationship from **Eq. 1** that is used to calculate the distance from satellites can be applied to acoustic signals as well. Here, rather than multiplying the time that the GPS signal has traveled by the speed of light, the travel time of the signal is multiplied by the speed of sound in the medium through which it is traveling. The speed of sound in the ocean is roughly 1,500 m/s. This is much slower than the speed of light, and it is also quite variable because the speed of sound in seawater depends on the seawater temperature, salinity, and depth.

Traditional Underwater Positioning and Local Vehicle Navigation Systems

Underwater vehicles routinely get position and timing from a GPS receiver when they are at the surface, but once they start to descend, this is no longer available. Vehicles navigate underwater using some combination of dead reckoning, vehicle hydrodynamic models, inertial navigation systems (INSs), and local navigation networks (Paull et al., 2014). Positioning in the z direction, the depth in the ocean, is straightforward with a pressure sensor, which can reduce the dimensionality of the problem to horizontal positioning in x and y, or longitude and latitude, respectively.

Dead reckoning estimates the position using a known starting point that is updated with measurements of vehicle speed and heading as time progresses. Larger vehicles, such as submarines, may have an onboard INS that integrates measurements of acceleration to estimate velocity and thereby position. These measurements are, however, subject to large integration drift errors.

Because of the need for more position accuracy than afforded by the submarine systems discussed above, it comes as no surprise that underwater vehicles also use acoustics for localization. A long-baseline (LBL) acoustic-positioning system is composed of a network of acoustic transponders, often fixed on the seafloor with their positions accurately surveyed. The range measurements from multiple transponders are used to determine position. LBL systems typically operate on scales of 100 meters to several kilometers and have accuracies on the order of a meter. Transponder buoys at the surface can also provide positioning accuracy similar to a seafloor LBL network. These buoys have constant access to GPS positioning so they do not require a survey.

Short-baseline (SBL) systems operate on a smaller scale, and the SBL transducers are typically fixed to a surface vessel. Ultrashort-baseline (USBL) systems are typically a small transducer array, also often fixed to a surface vehicle, which use phase (arrival angle) information of the acoustic signals to determine the vehicle position.

These types of acoustic localization work in a similar way to GPS localization, with electromagnetic waves; however, they all operate in relatively small regions. Note that these acoustic-positioning methods have been described in the context of underwater vehicles, but they can be used for other purposes as well, including tracking drifting instrumentation or even animals underwater.

Long-Range Underwater Acoustics

Propagation in the SOFAR Channel

Attenuation of acoustic signals in the ocean is highly dependent on frequency. The signals commonly used for LBL, SBL, and USBL localization networks typically have frequencies of tens of kilohertz and upward. These signals may travel for a few kilometers, but lower frequency signals on the order of hundreds of hertz or lower are capable of traveling across entire ocean basins underwater. This was demonstrated in 1991 by the Heard Island Feasibility Test, where a signal was transmitted from Heard Island in the Southern Indian Ocean and received at listening stations across the globe, from Bermuda in the Atlantic Ocean to Monterey, CA, in the Eastern Pacific Ocean (Munk et al., 1994).

Refractive effects of the ocean waveguide are usually taken into account when using the acoustic-positioning methods described above because an acoustic arrival often does not take a direct path from the source to the receiver, and often a number of arrivals resulting from multiple propagation paths are received. The refractive effects of the ocean waveguide become even more important as ranges increase. Acoustic arrivals can be spread out over several seconds; however, the time arrival structure can be predicted based on the sound speed profile.

The speed of sound in the ocean increases with increasing hydrostatic pressure (depth in the ocean) and with higher temperatures that occur near the surface. This leads to a sound speed minimum referred to as the sound channel axis, which exists at approximately 1,000 m depth, although the depth can vary depending on where you are on the globe (**Figure 3**).

The SOFAR channel, short for SOund Fixing And Ranging, refers to a sound propagation channel (Worzel et al., 1948) that is centered around the sound channel axis. Sound from an acoustic source placed at the sound speed minimum will be refracted by the sound speed profile, preventing low-angle energy from interacting with the lossy seafloor and enabling the sound rays to travel for very long distances, up to thousands of kilometers.

The rays take different paths when traveling over these long ranges, as seen in **Figure 3**. The arrival time at a receiver is an integrated measurement of travel time along the path of the ray. Rays that are launched at angles near the horizontal stay very close to the sound speed minimum. Rays that are launched at higher angles travel through the upper ocean and deep ocean, and although they take a longer route than the lower angle rays, they travel through regions of the ocean that have a faster sound speed and therefore arrive at a receiver before their counterparts that took the shorter, slower road.

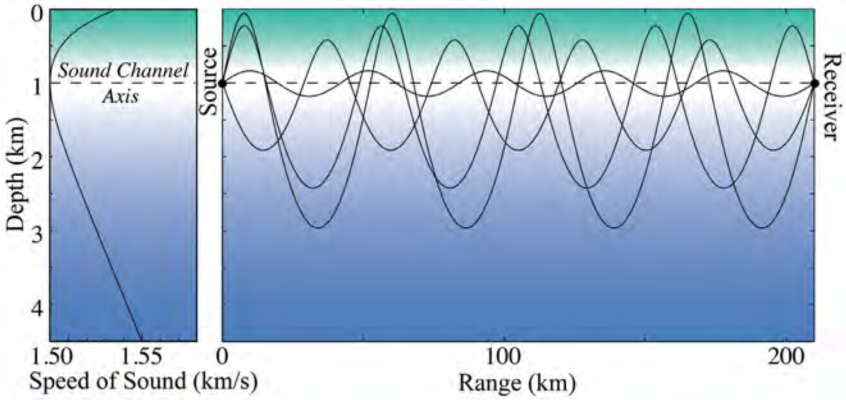
Ocean Acoustic Tomography Measurements

Ocean acoustic tomography takes advantage of the variability in measured travel times for specific rays to invert for ocean temperature. Each ray has traveled a unique path through the ocean and therefore carries with it information on the sound speed along the particular path that it has traveled. On a very basic level, we are looking again at the relationship from **Eq. 1**, but here distance and travel time are known, and we are inverting for sound speed, which is a proxy for temperature. In ocean acoustic tomography, the variability in these acoustic travel times is measured regularly over a long period of time (acoustic sources and receivers often remain deployed in the ocean for a year at a time) to track how the ocean temperature is changing. This method was described by Worcester et al. (2005) in the very first issue of *Acoustics Today* and more thoroughly in the book, *Ocean Acoustic Tomography*, by Munk et al. (1995).

The variability in these travel times is measured in milliseconds; therefore, as with a GNSS, the acoustic travel time measurements must be extremely precise. Great care is taken to use clocks with low drift rates and to correct for any measured clock drift at the end of an experiment.

The locations of the acoustic sources and receivers also must be accurate because inaccuracies in either position would lead to an inaccurate calculation of distance, which would impact the inversion for sound speed based on the simple relationship of **Eq. 1**. The sources and receivers used in typical ocean acoustic tomography applications are on subsurface ocean moorings, meaning that there

Figure 3. ***Left:*** *canonical profile of sound speed as a function of depth in the ocean (**solid line**).* ***Right:*** *refracted acoustic ray paths from a source at 1,000 m depth to a receiver at 1,000 m depth and at a range of 210 km. The Sound Channel Axis (**dashed line**) is located at the sound speed minimum at a depth of 1 km. Adapted by Discovery of Sound in the Sea (see dosits.org) from Munk et al., 1995, Figure 1.1, reproduced with permission.*



is an anchor on the seafloor with a wire stretched up to a buoy that sits below the surface to hold the line taut. The sources and hydrophone receivers are mounted on this line. Additional floatation is also mounted on the line to keep the mooring standing upright, but it is subject to ocean currents, so it moves around in a watch circle about the anchor position. An instrument at the top of a 5,000-m mooring could be swept several hundred meters from the latitude and longitude position of the anchor by ocean currents. A LBL array of acoustic transponders, as described in ***Traditional Underwater Positioning and Local Vehicle Navigation Systems***, is typically deployed around each mooring position to track the motion of the sources and receivers throughout the experiment to correct for the changes in distance between the sources and receivers.

Positioning with Long-Range Underwater Acoustic Measurements

The same core concepts of inferring distance from measurements of signal travel time that we see in GNSS and local underwater acoustic networks can also apply at long ranges. Neutrally buoyant oceanographic floats called swallow floats were equipped with acoustic pingers to be tracked by a nearby ship; these were adapted to take advantage of the deep sound channel and were subsequently known as SOFAR floats. The first SOFAR float was deployed in 1968 and was detected 846 km away (Rossby and Webb, 1970).

The SOFAR float signals were originally received by the SOund SUrveillance System (SOSUS) of listening stations operated by the US military. This system tracked more than just floats and enemy submarines. It also received acoustic signals from earthquakes, and there is a wonderful 43-day record of passively tracking of an individual blue whale, nicknamed Ol' Blue, as it took 3,200-km tour of the North Atlantic Ocean (Nishimura, 1994).

The existing listening system was convenient, but equipping each float with an acoustic source was technologically challenging and expensive. In the 1980s, the concept was flipped so that the float had the hydrophone receiver, and acoustic sources transmitted to the floats from known locations to estimate range to the float. The name was also flipped, and the floats are known as RAFOS, an anadrome for SOFAR (Rossby et al., 1986).

RAFOS sources have been useful to track floats in open water, but when there is sea ice present and the float is unable to get to the surface for a GPS position, underwater positioning becomes even more important. A recent study in the Weddell Gyre near Antarctica tracked 22 floats under ice that were unable to surface to obtain position from the GPS for eight months (Chamberlain et al., 2018).

Similar to RAFOS, a separate long-range navigation system in the Arctic used surface buoys to transmit GPS positions to floats and vehicles for under-ice ranging, with an accuracy of 40 m over 400-km ranges. This system operated at 900 Hz, with a programmable bandwidth from 25 to 100 Hz (Freitag et al., 2015).

RAFOS signals have a bandwidth of 1.6 Hz and therefore less time resolution than a more broadband source. **Figure 4**, **a** and **b**, contrast predictions of the arrival structure at a 1,145-km range for a RAFOS source with a broadband source having a bandwidth of 50 Hz. In both cases, the latest arriving energy is concentrated near the depth of the sound channel axis, corresponding to rays that stayed at depths with low sound speeds. The early arrivals are from rays that ventured into the higher speed regions of the sound speed profile (in **Figure 3**, ***dark blue*** and ***green***) and therefore also span more of the ocean depth. In both cases, we can see that the energy is spread over about 4 s, but the broadband source provides better resolution.

Figure 4, **c** and **d**, shows slices of these acoustic predictions at a 2,000 m depth. The broadband signal shown in **Figure 4d** exhibits sharp peaks in the arrival that can be identified with individual ray paths.

The increased bandwidth is one of the design suggestions for a potential joint navigation/thermometry system addressed in Duda et al. (2006). A system of sources is suggested with center frequencies on the order of 100-200 Hz and a 50-Hz bandwidth.

The acoustic sources used for ocean acoustic tomography applications are broadband sources designed to transmit over ocean basin scales. A 2010-2011 ocean acoustic tomography experiment performed in the Philippine Sea featured six acoustic sources in a pentagon arrangement and provided a rich dataset for evaluating long-range positioning algorithms. The sources used in this particular experiment had a center frequency of about 250 Hz and a bandwidth of 100 Hz.

The sources were used to localize autonomous underwater vehicles that had access to a GPS at the sea surface but only surfaced a few times a day. Hydrophones on the vehicles received acoustic transmissions from the moored sources at ranges up to 700 km, and these signals were used to estimate the position of the vehicle when it was underwater (Van Uffelen et al., 2013). The measured acoustic arrivals were similar to the modeled arrival shown in **Figure 4d**. The measurements of these peaks collected on the vehicle were matched to predicted ray arrivals to determine range. This method takes advantage of the multipath arrivals in addition to signal travel time. As with other acoustic methods and with the GPS, ranges from multiple sources were combined to obtain estimates of vehicle position. The resulting positions had estimated uncertainties less than 100 m root mean square (Van Uffelen et al., 2015).

Other long-range acoustic-ranging methods incorporate predictions of acoustic arrivals based on ocean state estimates (Wu et al., 2019). An algorithm introduced by Mikhalevsky et al. (2020) provides a "cold start' capability that does not require an initial estimate of the acoustic arrival and has positioning orders on the order of 60 m. These results were validated using hydrophone data with known positions that received the Philippine Sea source signals. As with the aforementioned method, this algorithm relies on the travel-time resolution afforded by the broadband source signals.

How Feasible Is a Global Navigation Acoustic System?

Because acoustic signals are able to propagate over extremely long ranges underwater, acoustics could provide an underwater analogue to the electromagnetic GNSS signals that are used for positioning in the land, air, and space domains. There are definite differences between using an underwater acoustic positioning system and a GNSS, however. GNSS satellites orbit the earth twice a day and transmit continuously. Acoustic sources do not need to be in orbit, but proper placement of the sources would enable propagation to most regions in the oceans of the world.

The far reach of underwater acoustic propagation is demonstrated by the International Monitoring System (IMS) operated by the Comprehensive Nuclear Test Ban Treaty Organization (CTBTO). The IMS monitors the globe for acoustic signatures of nuclear tests with only six underwater passive acoustic hydrophone monitoring stations worldwide. **Figure 5** shows the coverage of these few stations. Signals received on these hydroacoustic stations were used to localize an Argentinian submarine that was lost in 2017 using acoustic recordings of the explosion on IMS listening stations at ranges of 6,000 and 8,000 km from the site (Dall'Osto, 2019).

You may note that **Figure 5** does not show much coverage in the Arctic Ocean and that the sound speed structure is quite different at high latitudes because it does not have the warm surface that we see in **Figure 3**; however, long-range propagation has been demonstrated in the Arctic

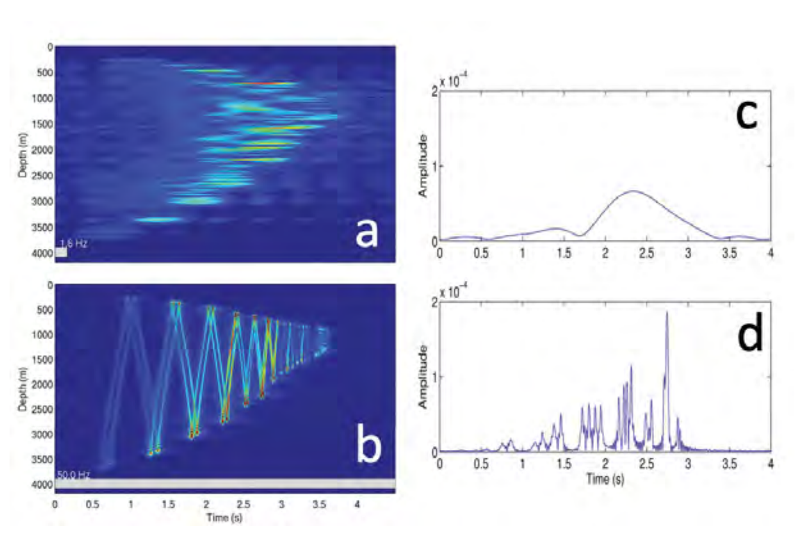


Figure 4. *Predictions of the acoustic arrival for a 260-Hz source at a range of 1,145 km. for a RAFOS source with a bandwidth of 1.6 Hz (**a**) and for a source with a bandwidth of 50 Hz (**b**). The arrivals in both cases are spread over about 4 s, with early arriving energy from higher angle rays and later arriving energy from rays launched at low angles that stayed near the depth of the sound channel axis. Slices of the plots shown in **a** and **b** were taken at a depth of 2,000 m for the RAFOS source (**c**) and broadband source (**d**) to contrast the travel time resolution. Adapted from Duda et al., 2006, with permission.*

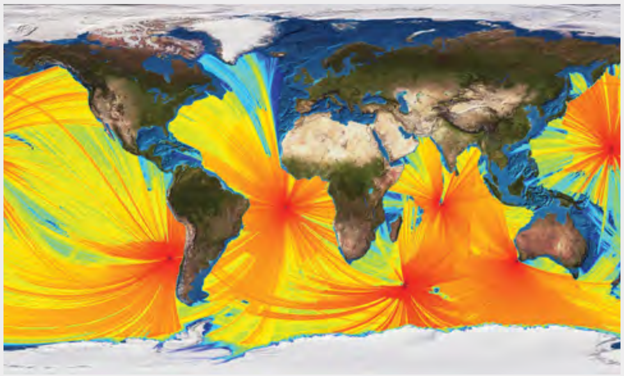


Figure 5. *Global coverage of the Comprehensive Nuclear Test Ban Treaty Organization (CTBTO) International Monitoring System (IMS), shown by a 3-dimensional model of low-frequency (<50-Hz) propagation. The property of reciprocity is invoked by placing sources at the locations of the six IMS hydrophone listening stations (**red areas**) from where the sound radiates. Colors represent transmission loss with a range of 70 dB. Figure created by Kevin Heaney and reproduced from Heaney and Eller, 2019, with permission.*

Ocean as well. In a 2019–2020 experiment, 35-Hz signals were transmitted across the Arctic Ocean over the North Pole (Worcester et al., 2020).

The electromagnetic signals broadcast by GNSS satellites are outside the visible spectrum, so we do not notice the signals that are continuously emitted by the satellites. In addition to the engineering challenges that would face continuous acoustic transmission, the frequency band of long-range propagation is within the hearing range of many animals, and the impacts to the environment, including potentially masking marine mammal vocalizations, would need to be considered. Long-range acoustic transmissions for scientific purposes go through an intense permitting process that takes into account the environment and the impacts on marine animals in the environment.

Each GNSS satellite broadcasts navigation messages that includes the date and time as well as the status of the satellite. It broadcasts ephemeris data that provide its specific orbital information for more precise localization of the GPS receiver. Localization using dedicated networks of sources, such as the example in the Philippine Sea, which incorporates precise source position and timing as necessary for localization of an acoustic receiver as it is for GPS has been discussed. A vision for a multipurpose acoustic observing system (Howe et al., 2019), would transmit this information as well to enable mobile platform positioning and navigation. Such a system could also provide ocean acoustic tomography measurements and passive acoustic monitoring for biological, natural, and anthropogenic sources.

Final Thoughts

The GPS satellite constellation was originally designed to meet national defense, homeland security, civil, commercial, and scientific needs in the air, in the sea, and on land. The age of artificial intelligence and big data has made GPS data on land incredibly useful to all of us in our everyday life. Not only can we use information on our own location from our cell phone to find the nearest coffee shop, we can take advantage of the location information on many different devices to look at traffic patterns to gauge what is the best way to get to that coffee shop. It won't be too long until we will be riding in self-driving cars, automatically taking the best route and precisely positioned relative to each other. All of this happened in just the last few decades because it has been only 25 years since GPS became fully operational.

An underwater analogue to a global navigation satellite system would revolutionize any operations in the underwater domain including oceanographic science, naval military applications, underwater vehicles, and even scuba diving. Acoustics is the most promising way to approach this on a large scale.

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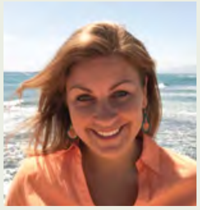
About the Author



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