Underwater Locator Devices – Search Tools and Field Experience

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Introduction

Aircraft accidents in and around water can present some of the most challenging conditions in an investigation. In some cases, even locating aircraft wreckage to begin an investigation can be time consuming and fraught with challenges. The underwater environment speeds the negative effects of corrosion and can serve to scatter important perishable evidence via tides and shifts in the ocean floor. Meanwhile, media and public appetite for information in the wake of an aircraft accident can contribute to the pressure on an investigation team to locate underwater wreckage quickly, in order to identify and communicate factual data rapidly. In short, an aircraft accident in water creates a situation where time is a particularly valuable resource, and the rapid location and recovery of key items like flight data and cockpit voice recorders (FDR and CVR) can set an investigation on a path to success early in the timeline.

Technology provides some resources to perform these searches and help to focus recovery efforts. Side scan sonar provides an image of the bottom of a body of water, and can be used to identify anomalous items (like aircraft components) in the environment. In some water types, human divers can visually scan for aircraft wreckage and associated components; doing so in large numbers can provide wide search coverage. In addition, flight recorders typically carry a High-Frequency Underwater Locator Beacon (HF-ULB) that emits acoustic pings at set intervals for a period of 90 days and at an advertised range of approximately two nautical miles (3.7 km). Newer commercial aircraft are similarly fitted with an additional Low-Frequency Underwater Locator Beacon (LF-ULB) – mounted directly to the fuselage – that emits acoustic pings with a hypothetically longer advertised range of 10 miles (18.5 km).

Like some investigative agencies, The Boeing Company owns and operates a handheld, directional hydrophone capable of receiving ULB signals that the company offers in support of ICAO Annex 13 investigative agencies. Boeing’s RJE PRS-275 Pinger Receiver System is a device in common usage that allows an operator to search for a ULB signal by listening to the hydrophone in real time and attempting to identify acoustic signals being emitted by any of the ULBs carried on an aircraft. A recent survey of Boeing’s historical uses of this device, as well as recent testing, indicates that this hardware was not as effective at locating ULB signals as our users had assumed.

This paper will outline several case studies of Boeing’s experience using the PRS-275 to locate FDRs and CVRs associated with aircraft accidents in water, as well as testing that the company has performed using both HF-ULBs and LF-ULBs. Limitations of the existing hardware will be shared, as well as details about the underwater environment that contribute to the challenge of locating ULB signals in the real world and how they can be managed. Finally, the paper will outline ongoing research by The Boeing Company to explore alternative search hardware and methods that can be used both on small scales by independent agencies, and on large scales by coordinated government assets. These findings and methods are applicable to any agency operating similar hardware either in-house or via contractual engagement with commercial search companies.

Investigation Protocol

As an airframe manufacturer, Boeing assists government investigations by providing technical advisors to the US National Transportation Safety Board (NTSB) under the protocols and reporting structure of International Civil Aviation Organization Annex 13. This participation also allows Boeing to review investigative findings as part of a formal internal safety process to identify safety-related findings quickly, and correct them in the product. For any accidents or incidents discussed in this paper, Boeing used the observations and information from our findings to inform our internal safety process with the aim of increasing the safety of our products. Those observations were additionally shared with the Annex 13 investigation as part of Boeing's involvement as a technical advisor to the investigation.

Types of Underwater Locator Beacons

Modern transport-category aircraft are equipped with High Frequency Underwater Locator Beacons (HF-ULBs) attached to each installed flight recorder, to allow the recorder to be located if the airplane is involved in an accident in or around water. Beacons attached to these recorders are built to SAE AS8045A (Minimum Performance Standard for Underwater Locating Devices [Acoustic]) specifications, which specifies a minimum operating time of 90 days. Recorder-mounted ULBs emit acoustic pings at 37.5 kHz, and an interval of 1 second (1 Hz). Industry experience typically holds that the signal should be detectable in calm, uniform water at a distance of about 2 miles, or about 3.7 km (10,000 feet).

Figure 1: HF-ULB Installations on various recorders

Accidents in deep water in 2009 and 2013, and protracted and expensive searches using government assets, forced the industry to reconsider the use of these HF-ULBs as a primary method of locating the wreckage fields. In response, an additional, low-frequency beacon (LF-ULB) was developed whose signal can be detected at much longer ranges, typically advertised as around 10 miles (18.5 km). These new beacons emit acoustic pings at a lower 8.8 kHz, and an interval of 10 seconds (0.1 Hz). They are typically attached directly to the external structure of the airframe, which provides the highest chance of exposure to water, as well as the highest chance of having an unblocked transmission path to potential detectors that are deployed in search of it.

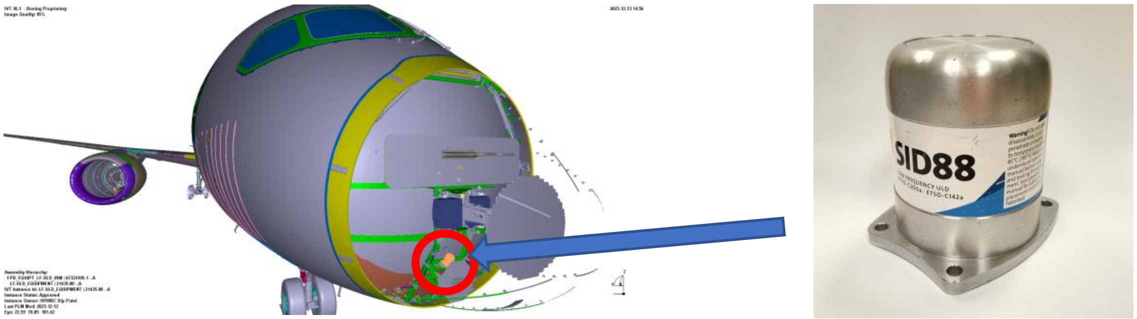

Figure 2: LF-ULB Installation in exemplar location under the radome of a Boeing 787 (highlighted in orange)

Both of these devices work on similar principles. Exposing the device to water typically closes a circuit to activate the beacon, after which an acoustic device begins emitting specified "ping" signals into the water, where they are transmitted through the water column to be picked up by a hydrophone or other listening device. While water provides relatively good propagation of acoustic signals like these, this method also subjects the signals to the effects of the underwater environment itself, which can impede this signal and make it difficult to detect.

The Underwater Environment

The speed of sound in water is most dependent on the density of the water through which it is traveling. Three factors play the largest role in determining density, and thus the ability for a particular water body to propagate sound through it. Each varies differently throughout the ocean environment, in geographic location and in depth:

1. Temperature
2. Salinity
3. Pressure

Of these three, pressure is by far the most consistent variable, increasing all over the world at approximately the same rate, linearly with depth. Meanwhile, salinity varies slightly with both depth and geographic location (with the highest salinity being located near latitudes of 20-25 degrees north and south), but is roughly constant all over the world at depths below about 1,000 meters (3,000 feet). Salinity values range from about 33-37 parts per thousand (ppt, approximately equal to grams of salt per liter of water solution).

In contrast to pressure and salinity, temperature is the most variable and inconsistent factor in determining the density of water. In typical ocean depths below approximately 1,500 meters (5,000 feet), ocean water all over the world generally maintains a consistent temperature of -1°C (water at this temperature stays in liquid state due to pressure from depth). At shallower depths, water temperature is heavily affected by surface air temperature and solar heating.

This means that surface temperatures can vary significantly – not just over geographic areas, but also with seasonal changes and even the local time of day. This surface heating creates a feature called a “thermocline” in the water column, where the surface layer of water can be significantly warmer than the layers below. Seasonal changes, which develop more slowly, create deeper and more consistent thermoclines; while daily changes from solar heating create shallower “Transient Thermoclines” that can change depth and severity over the course of a single day.

Effects on Sound

Since it is made up of waves, sound refracts and changes direction across transitions of higher and lower density similarly to how light refractions cause a straw in a glass of water to look bent. As with light rays, sound rays tend to bend away from regions of higher density (with a corresponding higher speed of sound), and toward regions with lower density (and a corresponding lower speed of sound). Importantly, temperature and salinity effects have greater impact on the density of water above about 200 meters (600 feet), *reducing* the density of water with depth and creating a negative relationship between depth and speed of sound.

Below about 200 meters (600 feet), temperature and salinity become more constant and the pressure changes become the controlling factor in density, *increasing* the density with depth and reversing the trend in the speed of sound. This creates a local minimum of speed of sound at the point where the temperature/salinity effects begin to be outweighed by the depth/pressure effects. This local minimum is called the “Sound Channel Axis” and carries special characteristics. Sounds in this region tend to get refracted back to a constant depth, whether they stray above or below the Sound Channel Axis.

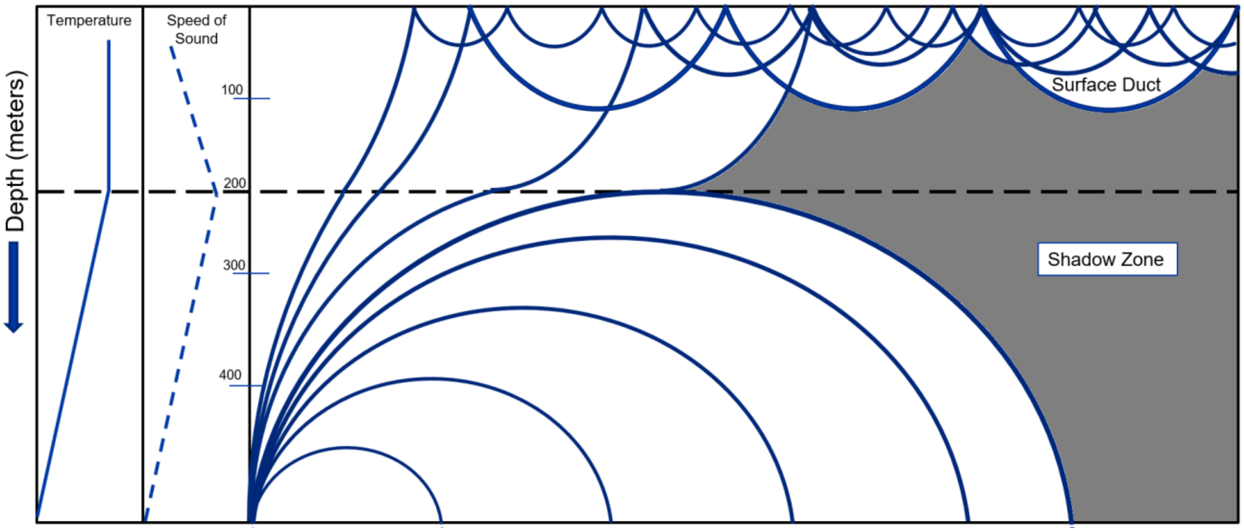

Figure 3: A notional example of soundwave directions when emitted from a source on the ocean floor beyond about 500m depth. Not depicted is the degradation of the signal with distance.

In the case of the straw in the glass of water, there is a single density transition as the light rays from the straw pass from the water and into the air; but in contrast, the water column can contain multiple transitions in density that add to the complexity of the local sound environment.

Acoustic Interference

In addition to density changes in the water column, the reception of underwater signals by hydrophone is also affected by acoustic interference. Human-made things like ship motors, pumps, sonar, and other technical equipment broadcast acoustic signals across a very wide range of frequencies. Marine life also adds to the underwater sound environment, as well as geologic sources like tectonic movement and volcanic activity. Near the surface, environmental factors like wind and precipitation also add to background noise.

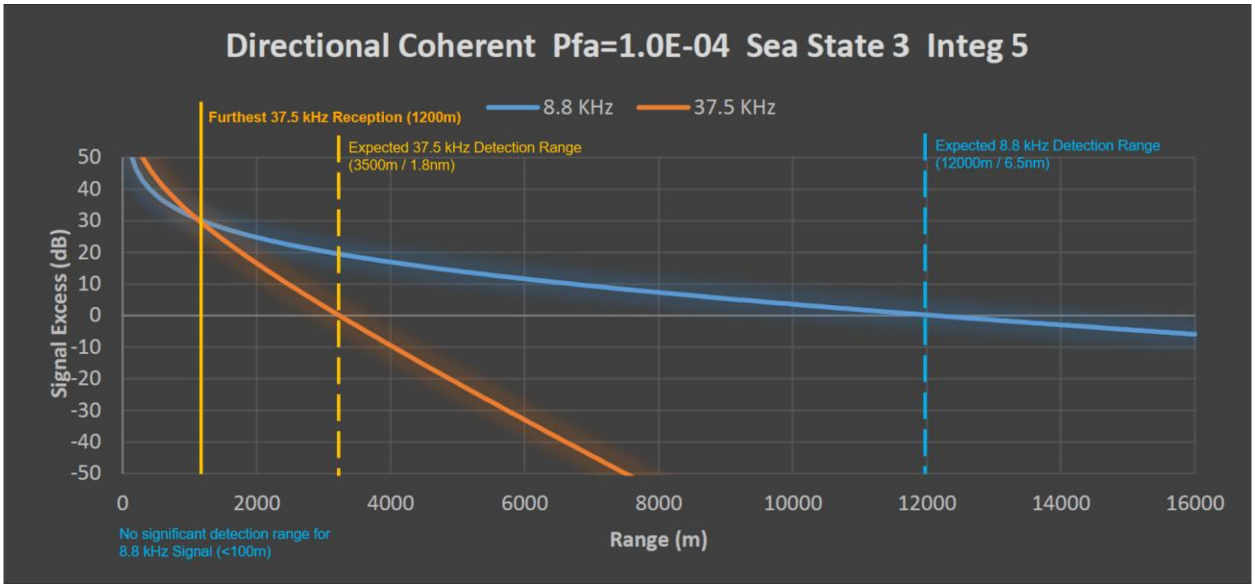

Figure 4: Calculated signal propagation and best-case performance for a typical hydrophone setup

Plotting the frequency and intensity of each of these background noises creates a set of "Knudsen Curves", which are intended to demonstrate where specific interference risks fall relative to others on a frequency/spectrum level plot. Plotting all these noises on a common chart shows several potential sources of interference, and demonstrates that both the 8.8 kHz fuselage and the 37.5 kHz recorder beacons are tuned to higher frequencies than most of those potential interference sources. Potential sources of interference for aircraft- and recorder-mounted beacons comes mostly from environmental factors like precipitation and wind, as well as other tuned hydroacoustic transmitters like depth finders and fish trackers.

Current Detection Equipment

The concept of underwater locator devices, and the equipment to detect them, became household conversation topics after the 2009 accident involving an Air France Airbus A330 and the 2013 accident involving a Malaysian Airlines Boeing 777. In both of these cases, a commercial aircraft was lost in deep water (well over 3,000 meters [10,000 feet]), with only a general understanding of the aircraft's last known location. In both of these cases, it was clear that the depth of the wreckage alone was far greater than the HF-ULDs were capable of being detected, particularly when considering the complicated ocean environment in each case. Investigation agencies in both cases turned to partner government agencies associated with national defense and search and rescue. These agencies retain specialized equipment and personnel in underwater search, although their expertise is more typically applied to more clandestine operations. Mobilizing these assets is a complex and lengthy process.

But these examples, notable as they are, represent an extreme case. More typically, aircraft accidents happen in the general vicinity of an airport. This affords the investigating agency two key benefits: First, very little of the water near airports reaches the depths discussed above, and second, the last known position of an aircraft impacting the water will generally be known with much higher accuracy. Thus it is more straightforward in the majority of cases that an aircraft in a water accident could be located using the existing HF-ULD, as the search is likely to be started within range for the signal to be identified.

Notwithstanding the government assets that are occasionally deployed to locate the most high-profile deepwater aircraft accidents, investigative agencies and their partners try to retain the equipment and expertise to detect and locate aircraft accidents on their own. One popular manufacturer of tools in this effort is RJE International, which offers two popular tools to detect these signals: The PRS-275 Pinger Receiver System, and the STI-350 Surface Acoustic Receiver.

The PRS-275 system relies on a human operator to listen for an underwater acoustic signal with his or her ears, rotating the hydrophone detector head underwater as they attempt to locate the bearing with the greatest signal strength. The STI-350 offers to take the human out of the loop, comparing relative signals from multiple hydrophones in a single detector head and providing a digital display showing whether the signal is coming from the left or the right of the current bearing. Using either of these devices, an operator is expected to identify a single bearing from the operator's location to the source of the signal being detected. Performing this exercise multiple times around a survey area can allow an experienced operator to triangulate the signal source using multiple bearings. Both devices are capable of being tuned across a range of potential listening frequencies, including frequencies that are intended to capture both the 37.5 kHz and 8.8 kHz signals.

Figure 5: The RJE International PRS-275

In between the clear cases where major large-scale search efforts must be made by redirecting government equipment from the defense sector, and the small-scale search efforts where a handheld hydrophone will focus search efforts within the last mile of an established search area, are cases where the increased range of the LF-ULD can be valuable to an investigation agency that is properly equipped and trained to locate them.

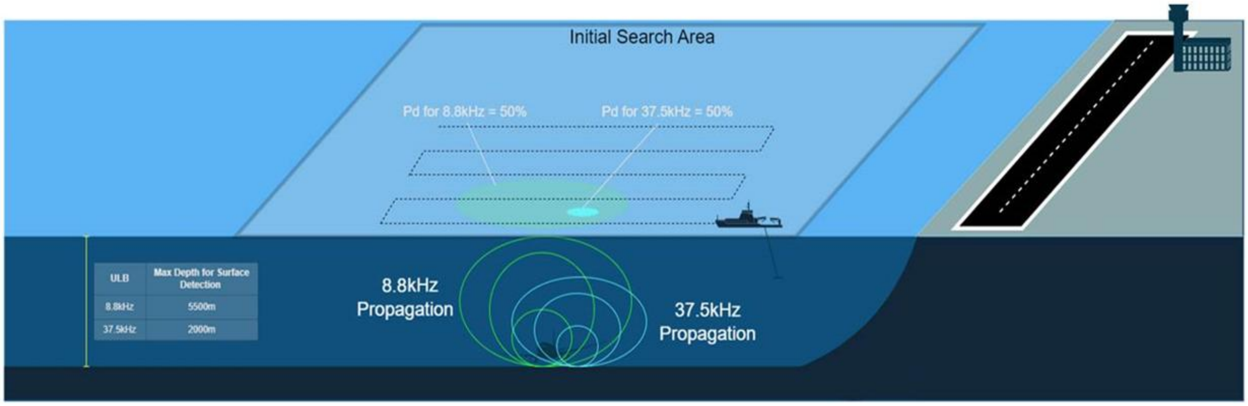

Figure 6: A hypothetical search grid in water of medium depth. The addition of the 8.8kHz signal in the wreckage field provides a much greater probability of detection and allows for a wider grid that can be completed more quickly. Graphic courtesy Matt Ragozzino.

Boeing Testing

Boeing has owned and operated underwater acoustic locators for many years, recently upgrading to the PRS-275 discussed above. In addition, Boeing's air safety investigation team maintains operational currency in the use of the device, and offers it to investigative agencies as part of the technical support that the company offers under ICAO Annex 13. As an airframe manufacturer, Boeing has access to airworthy examples of both LF-ULBs and HF-ULBs to use in testing.

Testing typically takes the form of tethering a ULB to a weight, then deploying the ULB into a freshwater lake at a depth of approximately 30 meters (100 feet). Investigators then board a boat to simulate an aircraft search, maneuvering the boat to multiple locations where the acoustic locator is deployed and a bearing to the signal source is recorded. By tracking the coordinates of both the deployed beacon and of each acoustic locator test point, data can be collected on the accuracy of the test points as well as the distance at which the signal was successfully identified.

Using this method with the PRS-275, Boeing investigators have reliably identified and tracked an HF-ULB signal at ranges in excess of one nautical mile, which roughly aligns with the commonly understood maximum detection range of 2 nautical miles (3.7 km). These results have been duplicated in actual field conditions in several water-based accidents as well, confirming that the test setup is valid for real-world conditions.

Recent testing with LF-ULBs has shown that the 8.8 kHz signal cannot be detected using the device at ranges beyond a few hundred meters, well short of the anticipated range of several miles. These results have been confirmed in coordination with other organizations and agencies that have conducted their own testing.

Boeing’s Underwater Acoustics group offered assistance to the Air Safety Investigation team doing this work, given their expertise working Boeing maritime undersea projects as well as their large testing pool that provided controlled conditions for the team to gather digital recordings and data with each beacon submerged. The goal of these tests was twofold: 1) Explore whether additional or alternate equipment could be deployed by investigators at the same scale as the PRS-275, and 2) Determine whether existing undersea acoustics tools could be used to model the expected performance of a submerged ULB, and to help direct resources that would be used in locating the signal.

Developing Alternate Equipment

Data gathering was accomplished using an Ocean Sonics icListen digital hydrophone. Unlike the PRS-275, which must be tuned to the desired frequency, this hydrophone monitors all frequencies in its range of reception simultaneously. It connects to a standard PC using a USB cable, which allows for real-time processing of the signals it receives. It has a fundamental difference from the PRS-275 in common usage in that it is omnidirectional – it does not identify the direction of the strongest signal. Instead, it provides a total signal/noise ratio for a given reception frequency at its current position. Readings must therefore be taken in multiple locations, and the relative power of those signals compared to one another, in

Figure 7: icListen hydrophone

order to identify a likely location for a signal source. Processing these signals and developing a signal solution requires specialized software.

Figure 8: Testing in progress at Boeing's Undersea Acoustics test pool, Huntington Beach, California

Using the data they acquired from the pool tests, the Underwater Acoustics team created a Matlab program to process the incoming signals. The program is designed to detect short signal spikes in both the 8.8 kHz and 37.5 kHz regions, and to integrate multiple candidate detections over time to evaluate the candidates for regularity. Information classifying the “closeness” of each ping to the expected frequency, and classifying the regularity of receptions against the known ping rates of ULBs, is displayed to the user to evaluate a candidate signal for validity.

Proof of Concept Testing

The combined team took both a PRS-275 and the newly developed tool onto the freshwater testing lake, using the typical testing setup of pingers deployed at multiple locations at depths up to approximately 30 meters (100 feet). Early results from this testing are promising: using a first-draft version of the Matlab program showed that the omnidirectional icListen hydrophone performed comparably to the PRS-275 when searching for HF-ULBs, with a maximum reception range of approximately 2.3 kilometers (1.2 nautical miles). This matches the expectations of the development team, as the signal attenuation of the 37.5 kHz signal makes detection at longer ranges difficult using any other hardware. Detections of the 8.8 kHz beacon were further noted at distances of up to 5.5 kilometers (3 nautical miles), an improvement of more than double over the current handheld signal detection equipment.

Additional Applications

Because the team used existing tools to receive and process data and provide a user interface to searchers, the programs developed by the team could potentially be used in applications beyond a single user with a digital omnidirectional hydrophone. More advanced detection equipment in use by government, research, and military assets around the world often perform their signal filtering using standardized programs similar to the one developed for this effort. Additional testing may show further value in deploying this program to those assets, via existing data-sharing agreements between governments.

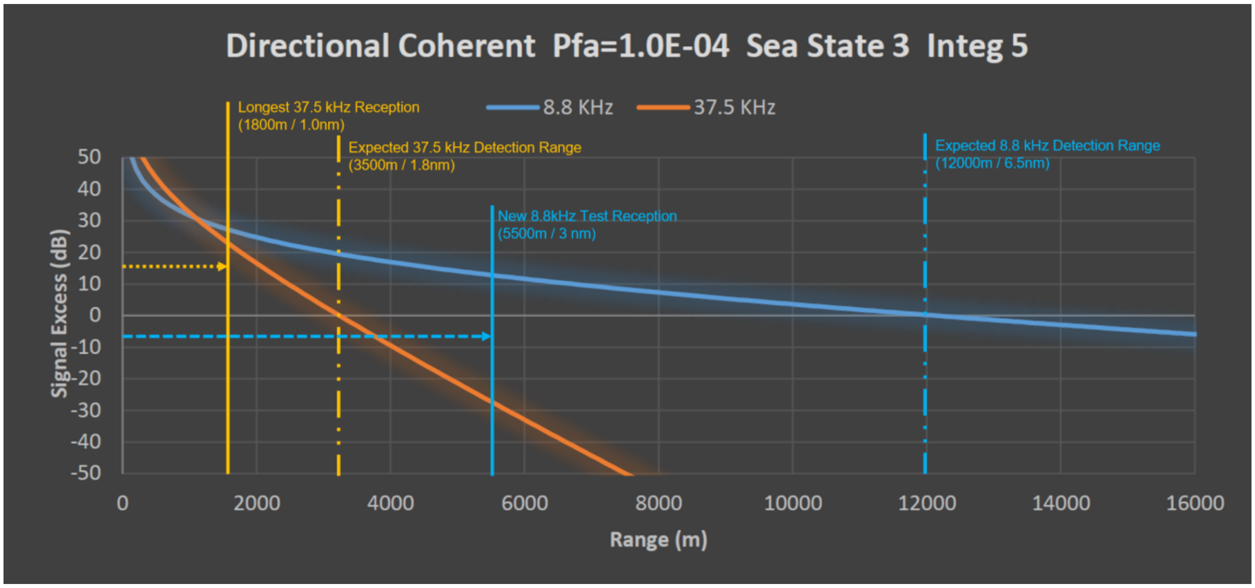

Figure 9: Initial results with the icListen Hydrophone show more than double the existing reception distance for test signals.

Conclusions

The current hydrophone equipment in use by Boeing – and by a variety of investigative agencies – provides a reliable method of identifying and locating HF-ULD signals at close range and in water depths below about 150 meters (500 feet), when the location of the devices on the bottom is known within approximately one-half nautical mile. This hypothetical scenario actually captures a large portion of aviation water recovery efforts, since many accidents happen in close vicinity to an airport, often during departure or arrival from the terminal area. In the realm of underwater search, however, this represents a best-case scenario.

Government assets can be made available from defense agencies and other sources, but often take significant effort to organize and deploy in support of a commercial aviation recovery and safety investigation effort. These assets are therefore typically only deployed for the most extreme cases, where an airplane's last known position may only be known within a few dozen miles and in areas of extremely deep water. In those cases, handheld locator devices of any sort will likely not be feasible tools to locate underwater wreckage.

It is therefore in an investigation agency's (or a support organization's) interest to expand their in-house capabilities as much as possible to increase reliability in the middle ground, between the relatively shallow waters in the vicinity of an airport, and the much deeper waters where large-scale support is unavoidably required. Newly developed LF-ULDs provide a perfect opportunity to fill this gap in the capability of an investigation, provided the investigation has access to tools that are capable of identifying and locating those signals.

Current handheld hydrophones are not capable of reliably receiving 8.8 kHz signals in real-world conditions, but other tools in development show promise. Boeing's testing has shown that it is technically feasible to produce an inexpensive filter which, coupled with a digital hydrophone, can identify useable signals at greater ranges than current equipment, and at greater accuracy. Using these two tools in tandem provides the greatest probability of finding submerged wreckage quickly, increasing the speed and efficiency of recovery and allowing an investigation to focus on what matters most.