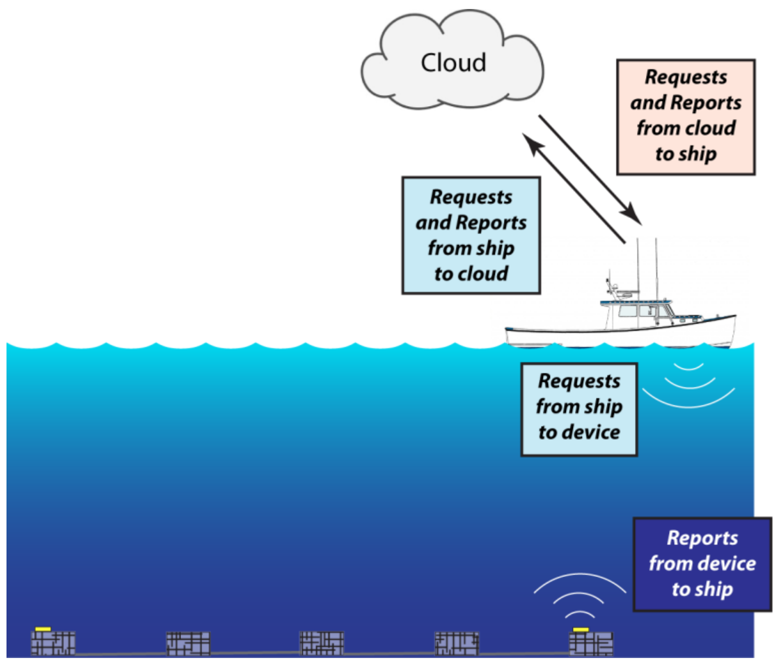
# An open standard for on-demand gear location marking, gear retrieval, lost gear recovery and enforcement


Mark Baumgartner[1], Dale Green[2], Jim Partan[1], Sandipa Singh[1], Julia Rugo[2] and Colin Ryan[1]

[1] *Woods Hole Oceanographic Institution*
[2] *consultant*



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**Roles and disclosures**
The authors of this report met regularly between November 2022 and September 2023 to discuss the challenges of and solutions for reliable acoustic gear location marking of on-demand fishing gear. Mark Baumgartner drafted the report. Appendix A is a report written in 2021 by Mark Baumgartner, Leah Baumwell, Elizabeth (Baker) Vézina and Sean Brillant. Appendix B was written by Mark Baumgartner and Jim Partan. Appendices C and D were written by Dale Green. All content (report plus appendices) were reviewed, discussed, edited and approved by all authors. Baumgartner, Partan, Singh and Ryan are employed by the Woods Hole Oceanographic Institution, a non-profit marine research, engineering and education organization. Dale Green is the retired Chief Scientist of Teledyne Benthos and principal designer of JANUS, and Julia Rugo was a former application engineer at Teledyne Benthos; both worked as independent contractors for this project. A portion of the initial conceptual work was supported by grants from The Pew Charitable Trusts to SMELTS (for Green and Rugo) and to WHOI (for Partan, Singh and Ryan) as well as the WHOI W. Van Alan Clark Chair for Excellence in Oceanography (for Baumgartner). The development of this report was supported by a grant from the NOAA Northeast Fisheries Science Center to WHOI for all authors.

## Introduction

The population of North Atlantic right whales (*Eubalaena glacialis*) has declined precipitously in recent years (from 482 in 2010 to 340 in 2021, a loss of over 250 animals in just one decade; Pettis et al. 2023), and fishing gear entanglements are one of the major causes of that decline (Sharp et al. 2019). Fishing gear entanglements directly cause mortality, but they are also a contributing factor to the low reproduction rates currently affecting right whales (Knowlton et al. 2022). Consequently, seasonal closures of fixed fishing areas have become a common method of mitigating entanglement risk in both the United States and Canada. Fishery closures can be devastating for affected fishers and their communities, so there is great interest in developing technological solutions that will allow fishers to fish in closed areas with gear that will pose little or no risk of entanglement.

Because endlines in fixed fishing gear pose substantial risks to whales and other marine fauna (e.g., sharks, turtles), the idea of fishing without them has been explored as an entanglement mitigation approach for decades. The foundational concept is simple: remove the endlines from the water column until the fisher is on scene and ready to recover his or her gear, then rely on acoustic technology (used in the research, industrial and military communities for decades) to trigger the release of an endline that can come to the surface and be hauled as normal. This approach has come to be called on-demand fishing (also known as ropeless or buoyless fishing). The removal of the endline, however, means the removal of the buoy used both to hold the endline aloft in the water column to facilitate retrieval and to mark the location of the gear for other mariners to see. Without a marking buoy, fixed fishers can inadvertently lay trawls over one another and mobile fishers can inadvertently drag nets or dredges through trawls on the sea floor. These instances of what is called gear conflict is today one of the most challenging aspects of the development of on-demand fishing. In fact, in a 2010 report, the U.S. National Marine Fisheries Service indicated that fishing without endlines could not be made legal until the problem of gear conflict was solved (NMFS 2010):

> Problems with gear conflicts are the main reason why buoy lineless fisheries are not being conducted on a broad-scale basis. Any unmarked fixed gear would be susceptible to being towed through by mobile gear fisheries (bottom trawl, scallop dredge, etc.), and set over by other fixed gear and vice versa. Therefore, in order to encourage buoy lineless fishery operations, … gear conflicts would need to be addressed.

Gear conflict is a safety hazard, and has economic costs to a fisher who must take time to untangle gear, has gear damaged, or loses gear altogether because of an interaction with fixed or mobile fishing gear.

## Requirements

To develop a gear location marking system for on-demand fishing (or for any other system development process, for that matter), it is vitally important that there is agreement on just what that system should do. In other words, the problems that the system is being designed to solve as well as the requirements needed to solve those problems must be explicitly stated. The principal problems that we have set out to solve in this document are gear conflict, lost gear, and enabling enforcement of on-demand fishing by developing a gear location marking system that will work for fishers, enforcement and regulators alike. To date, we are aware of only one effort to gather information from these (and other) stakeholders to develop requirements for a gear location marking system. A team of researchers (Leah Baumwell, Elizabeth Vézina, Sean Brillant and Mark Baumgartner) interviewed fishers, enforcement, federal/state/provincial regulators, conservationists, manufacturers and scientists about gear location marking, both how it works today and how it might work with on-demand fishing in the future, and from these interviews, developed requirements for a gear location marking system (Baumgartner et al. 2021). We have used these requirements to guide the development of the system described in this document. The Baumgartner et al. (2021) report in its entirety is provided in Appendix A, while the original requirements compiled in that study are provided in Table 1, and clarifications have been added as appropriate (provided in italics in Table 1). These requirements are discussed in detail here as motivation for the choices we have made in the proposed system and acoustic standards described below.

*Table 1. Summary of requirements used to guide the development of the proposed standard. Clarifications to the requirements not originally included in the Baumgartner et al. (2021) report are in italics.*

| **Number** | **Function** | **Requirement** |
|---|---|---|
| 1 | Detection distance | (a) For inshore fisheries where trawl lengths are shorter, a minimum detection distance of 0.5 nautical miles is required.<br><br>(b) For offshore fisheries where trawl lengths can reach 1.5 miles, a minimum detection distance of 2 nautical miles is required. |
| 2 | Location accuracy | Location accuracy of at least 25 feet (~8 meters) is required *in areas where there is a high density of fixed fishing gear. Location accuracy can be greater than 25 feet in areas where there is a low density of fixed fishing gear.* |
| 3 | Data display at sea | Gear location information, including location and orientation of trawls, must be displayed on a chart plotter. |
| 4 | Additional information to collect and share | The gear location marking system must provide ownership information (state/federal permit/license number, owner identity), gear type, unique system identifier, number of traps on trawl, length and orientation of trawl, and date/time gear was deployed. |

*Table 1. Continued.*

| | | |
|---|---|---|
| 5 | Data sharing | (a) Gear location information must be available to fishers and enforcement in real time on scene at sea (i.e., within *2 miles of the gear location*) to avoid gear conflict. *Location and orientation information must be available to appropriate marine users immediately after gear deployment.*<br><br>(b) Real-time location information must mirror reality (i.e., locations must be associated with actual gear on the sea floor, and a lack of locations must be associated with no gear on the sea floor).<br><br>(c) The ends of trawls must be marked in a way that is not voluntary.<br><br>(d) All data (including location, ownership information, etc.) must be available to enforcement in real time on scene at sea (i.e., within the detection distance of the system) as well as shared in near real time (within some prescribed time after deployment; e.g., 18 hours) with enforcement on shore (e.g., in an enforcement-accessible cloud database). |
| 6 | Lost gear | (a) The gear location marking system must be able to provide an accurate location for gear even if the gear has moved (e.g., because of storms or being dragged by a mobile fisher).<br><br>(b) The gear location marking system should provide a means for gear that has moved to be relocated and retrieved by the owner. |
| 7 | Environmental impacts | The gear location marking system should (a) minimize the use of disposable plastics, (b) minimize acoustic noise *(number, length and loudness of transmissions)*, (c) choose acoustic frequencies and source levels that minimize effects on marine mammals, fish, and shellfish. *The acoustic frequency should be above baleen whale hearing (> 20 kHz), and although not related to environmental impacts, the maximum frequency used should be below 60 kHz, as acoustic frequencies at and above 60 kHz are regulated by U.S. ITAR.* |
| 8 | Endurance | (a) Any gear location marking device that is affixed to submerged fishing gear must have an endurance of at least 6 months.<br><br>(b) Battery condition (e.g., voltage, charge status) of the gear location marking device must be easily interrogated. |
| 9 | Other | (a) Acoustic-based gear location marking devices must be able to activate whatever gear retrieval mechanism to which the device is attached (e.g., lift bag, bottom-stowed rope).<br><br>(b) The gear location marking system must be capable of sharing data in real time across international boundaries to avoid gear conflict and assist enforcement in these sensitive areas.<br><br>(c) A manufacturer's gear location marking device must be able to communicate with all other manufacturers' gear location marking devices using adopted standards. |

The location and orientation of all fixed fishing gear must be accessible to other mobile or fixed fishers within some distance of that fisher's ship (Requirement 1 in Table 1). For inshore fishers, this distance is at least 0.5 nautical miles (Requirement 1a), whereas for offshore fishers where trawl lengths can be much longer than in inshore fisheries, this distance is at least 2 nautical miles (Requirement 1b). These detection distances are needed so that both mobile and fixed fishers can visualize the terminal ends of a trawl, which allows them to learn the trawl's orientation and to successfully avoid laying gear over it or dragging nets/dredges through it. Location accuracy is particularly important for fishing in areas with a high density of fixed fishing gear, and Baumgartner et al. (2021) specified a minimum accuracy of 25 feet (8 meters) based on interviews with fishers (Requirement 2; note that this means that the true locations of the terminal ends of a trawl should be within 25 feet of the system's representation or estimate of those locations). This accuracy requirement can be relaxed in areas with a low density of fixed fishing gear, since position errors of over 25 feet in these environments are unlikely to cause gear conflict because fishers are not fishing very close to one another. All of the gear location information for nearby gear should be available to fishers in real time on their chart plotters for ease of visualization (Requirement 3).

The system should also collect information on deployed fixed gear that conforms to the information needs of gear owners, regulators and enforcement (Requirement 4), and share this information with appropriate users in a way that preserves the privacy of the gear owner to the maximum extent possible (Requirement 5). To avoid gear conflict and to provide timely information to at-sea enforcement, the location and orientation of fixed fishing gear must be accessible by appropriate marine users immediately upon deployment of the gear (Requirement 5a,b,c). All data collected on a trawl, including its location, ownership and status, should be accessible to gear owners and enforcement on shore in a timely fashion as well (Requirement 5d). We consider gear owners, other fixed or mobile fishers within some specified distance of the deployed gear (e.g., 2 miles), and enforcement agencies as appropriate marine users that should have immediate access to gear location and orientation information. Immediacy is essential for fishers that fish close to one another in space and time; a fisher that enters an area where gear was just deployed by another fisher, say, 15 minutes ago must have access to the position and orientation of that gear in order to avoid laying over it with their own trawl.

The location of gear must be checked regularly, and the location of any gear that has moved must also be made accessible immediately to appropriate marine users to avoid gear conflict (Requirement 6a). Based on fisher interviews reported by Baumgartner et al. (2021), even location changes of a few tens of meters can present a gear conflict hazard and must be mitigated via rediscovery, re-localization, and immediate position sharing. Fixed fishing gear that has moved long distances away from its deployment location, likely by being dragged by a mobile fisher's gear, must be able to be rediscovered by the system, and ultimately relocated and retrieved by the gear owner (Requirement 6b). Without such a requirement, gear that is lost will have no chance of ever being recovered, which represents a cost to fishers and contributes to marine debris.

To minimize the impact to marine biota, the system must minimize acoustic transmissions and source levels to the extent practicable and use frequencies that are at least outside the hearing range of baleen whales (> 20 kHz; Parks et al. 2007) (Requirement 7b,c).

The frequency range allowed by the U.S. International Traffic in Arms Regulations (ITAR) is 20-60 kHz, so all efforts should be made to use frequencies within this range (ITAR is designed to prevent sensitive technologies or methods from being used by potential military adversaries). Minimizing acoustic transmissions and source levels for gear location marking devices on the sea floor also helps to extend battery life for these devices, which should be 6 months or more (Requirement 8a).

The acoustic device used to mark the location of the gear should also be capable of triggering whatever gear retrieval mechanism to which the device is attached (Requirement 9a). Integration between these devices and retrieval mechanisms, even those created by different manufacturers, has been demonstrated already (most notably by SMELTS), and this experience suggests such integration is feasible. The gear location marking system should also work across international boundaries to enable side-by-side fishing by fishers from neighboring countries (e.g., U.S. and Canada) (Requirement 9b).

## Motivation

Without a buoy or endline, on-demand systems must replace the functions that those gear components perform during conventional fishing, including facilitating (1) retrieval of the gear by the gear owner, (2) identification and retrieval of the gear by enforcement, (3) discovery and recovery of lost gear, and (4) marking the location of the gear on the sea floor to avoid gear conflict with other fixed or mobile fishers. While the first function can be done with a proprietary acoustic communication system capable of triggering an on-demand release mechanism, the remaining functions cannot be accomplished practically without a means for different manufacturers' acoustic devices to communicate with one another (Requirement 9c). Put differently, a fisher can retrieve their own on-demand gear with a proprietary acoustic communication system, but the other functions require their system to communicate with other on-demand gear deployed on the sea floor – gear that they don't own and that may have been manufactured by another company or perhaps many different companies. If all of the manufacturers' devices do not acoustically communicate in the same way and use the same data formats when they do communicate, functions like gear location marking, localizing devices, finding lost gear, and having enforcement interrogate and haul gear, cannot work, and without these functions, the federal governments of the U.S. and Canada will not permit commercial on-demand fishing.

This document proposes (1) a comprehensive system for gear location marking, gear retrieval, lost gear recovery and enforcement, and (2) a simple and reliable method of acoustic communications that will support this system. While the acoustic communication methodology is required to move on-demand fishing forward toward legalization, it is not sufficient; hence, we propose a comprehensive standard that will enable all of the required functions. Establishing the acoustic communication methodology alone is akin to agreeing that negotiations for a peace treaty will be conducted in the English language; while necessary to achieving the peace treaty, agreeing to speak in English does not actually achieve the peace, but instead enables discussions that ultimately will achieve the peace. Likewise, the acoustic communication methodology described in Section 2 of this document is designed to enable the system described in Section 1 that will carry out all the necessary functions for safe and legal on-demand fishing. Together, the acoustic communication methodology and the system comprise an open standard for on-demand fishing. This standard describes (1) how the three subsystems (acoustic devices, ships and the cloud) will communicate with one another, (2) what data these subsystems will communicate to one another, and (3) what a subsystem will do when it receives data from another subsystem. Because the acoustic communication methodology is related to JANUS, another open standard for acoustic communication, we call our proposed open standard FONTUS, who was a child of Janus in Roman mythology.

The authors of this document are a group of scientists and engineers who have nearly a century of combined experience in underwater acoustic communications, as well as additional experience in underwater localization and marine technology development. We have significant experience developing and fielding systems at sea that require both underwater acoustic communication between acoustic devices and marine platforms (e.g., autonomous underwater vehicles, buoys, ships) and radio communication between those platforms and shore-side servers (e.g., VHF, cellular, satellite). The authors have experience developing acoustic communication standards (JANUS; Potter et al. 2014), implementing those standards (as well as many other acoustic communication protocols) in acoustic modems (Gallimore et al. 2010), and fielding those modems at sea in a wide variety of applications. The authors also have experience localizing objects underwater, including whales (Baumgartner et al. 2008) and on-demand fishing systems (Baumgartner and Partan 2021). Finally, the authors have been involved in the conceptual and practical development of on-demand gear and gear location systems, as well as the organization of stakeholder community discussions about on-demand fishing through the Ropeless Consortium (ropeless.org), since 2018 (Baumgartner et al. 2018, Myers et al. 2019).

## 1. FONTUS: An open standard for on-demand gear location marking, retrieval, recovery and enforcement

### a. Overview

The FONTUS standard is implemented with three subsystems: a cloud database, a shipboard system, and acoustic devices (hereafter just “devices”) attached to the terminal ends of trawls and in most cases integrated with on-demand retrieval systems (e.g., releases for stowed rope or lift bags; Figure 1). The cloud database is designed to (1) hold information about all currently deployed on-demand fixed fishing gear, (2) direct shipboard systems to periodically verify or update the location of deployed devices, (3) make device location information accessible to a variety of users both on shore and at sea with appropriate permissions, (4) notify gear owners of lost gear, and (5) provide enforcement with information on all currently deployed on-demand fixed fishing gear. When a trawl is deployed, the shipboard system will automatically send information about that deployment to the cloud database, including ownership information, the location and IDs of the devices at the terminal ends of the trawl, and other pertinent information specified by the appropriate authorities. Ships at sea equipped with the shipboard system will query the cloud database via satellite or cellular communications once every 3 minutes, and the cloud will respond with the locations of any trawls (or single traps/pots) within 2 miles of the querying ship. These locations will be automatically displayed on the ship’s chart plotter in such a way that the location and the orientation of the trawl is obvious (e.g., two markers at either end of the trawl with a line drawn between them).

For any devices that have not had their location verified in the past 24 hours, the cloud can direct a passing ship to check the location of that device via acoustic communication and localization. If the resulting position is different from what is stored in the cloud database, this position will automatically be updated in the cloud and on the ship’s chart plotter. When an owner wishes to recover their gear via the on-demand system attached to their trawl, a retrieval command is transmitted via the acoustic communication system, and the device will trigger the activation of the retrieval mechanism. Once the gear is recovered, the ship will automatically notify the cloud database that the gear was recovered, and record of the now complete deployment will be deleted from the cloud database. Finally, if a device detects acoustic communication/localization transmissions from a nearby ship and its location has not been verified in the past 72 hours, it will respond to the nearby ship to let it know of its presence and the ship will relay this information to the cloud. This information can be used by the cloud for two purposes: (1) to identify gear that has been lost, in which case the owner can be automatically notified and the lost gear can be retrieved, and (2) to identify gear that has not been properly deployed (e.g., illegally fished gear), in which case enforcement can be automatically notified and appropriate enforcement action can be initiated.

All three subsystems (i.e., cloud, ship and device on the sea floor) will communicate via requests and reports (Figure 1, Table 2). Requests are issued when one of the subsystems requires information from another subsystem, so a response is expected, and that response is called a report. For example, when a ship wishes to query the cloud for the locations of gear within 2 miles of the ship’s position, the ship will send a request to the cloud; the cloud, in turn, will respond with a report of all the locations of gear within 2 miles of that ship's position. Communication of requests and reports between devices and ships will use the methodology described in Section 2, whereas communication between ships and the cloud will use an at-sea real-time connection to the Internet.  Gear owners on shore or at sea will have access to all information about their own deployed gear, enforcement agencies on shore or at sea will have access to all information about all deployed gear within their jurisdiction, regulators on shore will have access to some data in summarized form (not information about individual fishers), and fixed or mobile fishers at sea will have access only to gear location information within 2 miles of their own vessel.

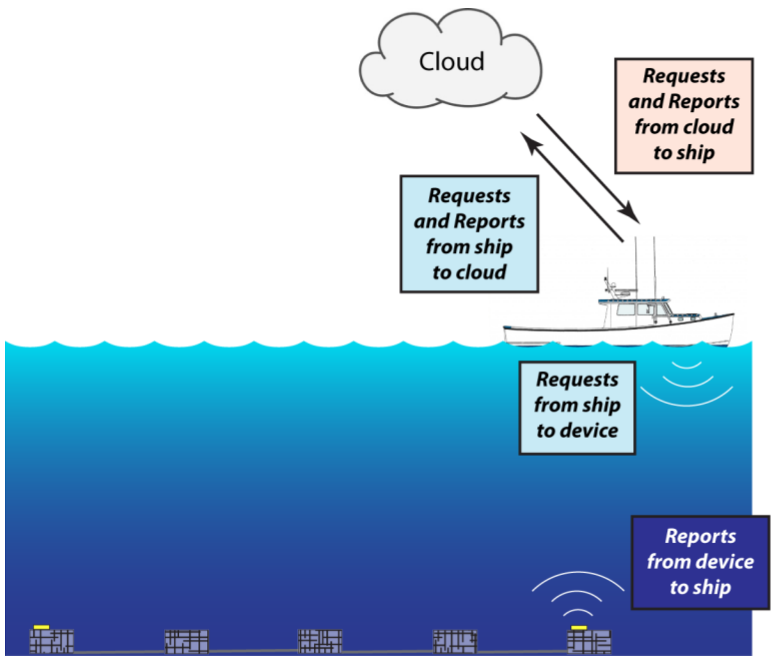


*Figure 1.  Overview of FONTUS, a standard for gear location marking, retrieval and enforcement showing the three vital subsystems: (1) cloud database, (2) shipboard system and (3) acoustic devices (indicated as yellow rectangles at the terminal ends of the trawl).  An on-demand retrieval system may be attached to either or both devices on the ends of the trawl, and the ship may have an optional USBL array in addition to the mandatory acoustic modem.  Each of these subsystems communicate with one another via reports and requests sent via a real-time connection to the internet (between cloud and ship) and acoustic modems (between ship and device).*

*Table 2. Summary of requests and reports issued by the cloud, ship, device and shore in the FONTUS standard.*

| **Communication type** | **From** | **To** | **Description** | **Data** |
|---|---|---|---|---|
| Nearby Gear Request | Ship | Cloud | Request locations of nearby fixed fishing gear | Ship's position, ship ID, acoustic modem present, USBL present, owner ID |
| Nearby Gear Report | Cloud | Ship | Report locations of nearby fishing gear | Gear locations (positions of terminal ends), gear ownership flag, localization request list (for ships with acoustic modems) and lost device request flag (for ships with acoustic modems) |
| Localization Request | Ship | Device | Request intended device respond with information that will aid in its localization | Ship ID, device ID, date/time |
| Localization Report | Device | Ship | Report information that will aid in the device's localization | Device ID, ship ID, response delay, device depth |
| Device Response Report | Ship | Cloud | Report that device responded to localization request | Ship ID, ship's position, device ID, 1-way travel time, bearing to device (if measured) and device depth |
| Initial Device Response Report | Ship | Cloud | Identical to the device response report, but collected immediately after the device was deployed or the device was determined to have moved | Ship ID, ship's position, device ID, 1-way travel time, bearing to device (if measured) and device depth |
| No Device Response Report | Ship | Cloud | Report that device did not respond to multiple localization requests | Ship ID, ship's position, device ID |
| Updated Gear Report | Cloud | Ship | Report with updated position for one or more devices after cloud localization (use same format as nearby gear report) | Gear locations (positions of terminal ends), gear ownership flag, position verification request |
| Moved Gear Request | Cloud | Ship | Request ship to send multiple localization requests to specific device in an attempt to relocate it after it has moved | Ship ID, device ID |
| Lost Device Request | Ship | Device | Request any device respond that has not received a localization request in the last 72 hours (only used in area where no localization requests have been issued) | Ship ID, date/time |
| Lost Device Report | Device | Ship | Report presence if no localization request received in last 72 hours; can be reported in response to lost gear request or localization request directed at another device | Device ID, ship ID, response delay, device depth |
| Found Device Report | Ship | Cloud | Report a device that has been discovered via a lost device report | Ship ID, ship's position, date/time, device ID, 1-way travel time, bearing to device (if measured) and device depth |

*Table 2. Continued.*

| Communication type | From | To | Description | Data |
|---|---|---|---|---|
| Device Deployment Report | Ship | Cloud | Report that device has been deployed | Ship ID, owner ID, device ID, date/time, position of ship upon deployment |
| Device Recovery Report | Ship | Cloud | Report that device has been recovered | Ship ID, owner ID, device ID, date/time, position of ship upon recovery |
| Trawl Deployment Report | Ship | Cloud | Report information about trawl deployment to the cloud | Ship ID, owner ID, IDs and deployment positions of devices at terminal ends of trawl, other information as required by relevant authorities |
| Trawl Recovery Report | Ship | Cloud | Report that trawl has been recovered | Ship ID, owner ID, IDs of devices at terminal ends of trawl |
| Owner Release Request | Ship | Device | Request device trigger release mechanism | Ship ID, owner ID, passkey, device ID, date/time |
| Release Report | Device | Ship | Report to confirm device has activated release mechanism; sent in response to either owner or enforcement release request | Device ID, Ship ID, response delay, device depth (to calculate slant range), status information about release mechanism |
| Owner Status Request | Ship | Device | Request device status information | Ship ID, owner ID, passkey, device ID, date/time |
| Owner Status Report | Device | Ship | Report status information to gear owner | Device ID, Ship ID, response delay, device depth (to calculate slant range), battery voltage, other status information, including proprietary status information |
| Enforcement Release Request | Ship | Device | Request device trigger release mechanism | Ship ID, owner ID, enforcement ID, enforcement passkey, device ID, date/time |
| Enforcement Status Request | Ship | Device | Request device status information | Ship ID, owner ID, enforcement ID, enforcement passkey, device ID, date/time |
| Enforcement Status Report | Device | Ship | Report status information to enforcement | Device ID, Ship ID, response delay, device depth (to calculate slant range), any other status information pertinent to enforcement |
| Owner Query Request | Shore | Cloud | Request for information about the owner's gear contained in the cloud database | Owner ID, passkey, query parameters |
| Owner Query Report | Cloud | Shore | Report information requested by gear owner | Variable depending on original query parameters |
| Enforcement Query Request | Shore | Cloud | Request for information about the all gear within enforcement jurisdiction | Enforcement ID, passkey, query parameters |
| Enforcement Query Report | Cloud | Shore | Report information requested by enforcement | Variable depending on original query parameters |

### *b. Hardware for ships and devices*

Vessels that need to be aware of fixed gear on the sea floor will be minimally equipped with a system capable of requesting and receiving gear location data from the cloud and displaying those gear location data on the ship's chart plotter (Figure 2a). This system is sufficient for fishers aboard mobile fishing vessels to view fixed gear location data and avoid towing nets or dredges through that gear. The system consists of a central command unit (CCU), an attached GPS, a satellite or cellular modem and a connection to a chart plotter. The

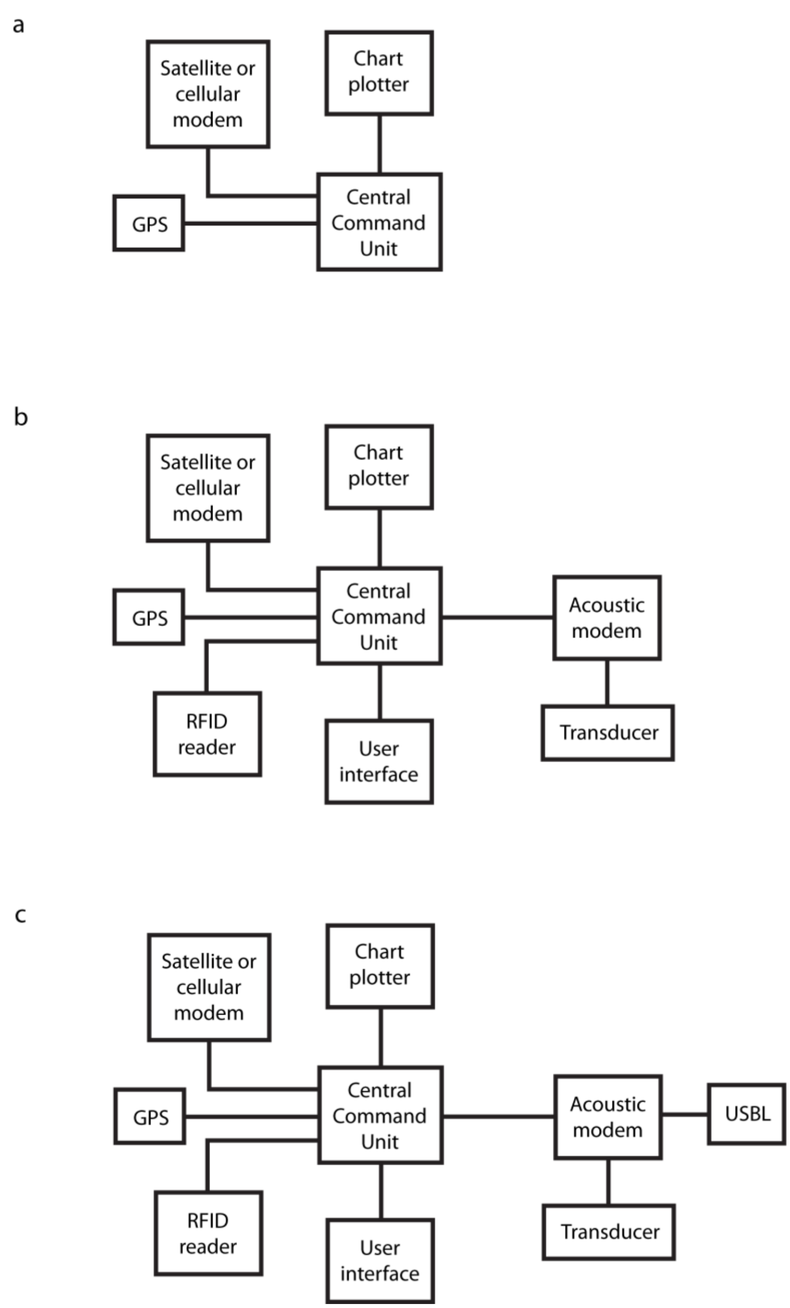


*Figure 2. Block diagram of shipboard system components for a (a) mobile fisher, (b) fixed fisher in fishing in low gear density area, and (c) fixed fisher fishing in high gear density area with optional USBL array.*

CCU is a small inexpensive computer from an original equipment manufacturer (OEM; e.g., Raspberry Pi or BeagleBone) that can have multiple peripherals attached. The ship's GPS that normally attaches to the chart plotter may be sufficient to use as the system's GPS (Figure 2a), as the CCU can act as a repeater for the chart plotter. The satellite or cellular modem will provide full-time access to the internet to allow real-time communication with the cloud; service would need to be provided through a company (e.g., StarLink for satellite, Verizon for cellular) with a monthly subscription. A cellular modem would be useful for fishers that fish exclusively within cellular range of shore, whereas a satellite modem would be required for all other fishers. Finally, this system is envisioned to be used with commercial chart plotters using NMEA messages passed between the CCU and the chart plotter. Ideally, chart plotter manufacturers would modify their software so that fishers could simply update their existing chart plotters to recognize the new NMEA messages and not need to purchase new compatible chart plotters.

For fishers that deploy their own fixed fishing gear, additional hardware will be required, although the CCU, GPS, satellite/cellular modem and chart plotter described above are identical for these systems. The addition of a radio frequency identification (RFID) reader will be needed to automatically identify when devices (which will carry RFID transceivers) attached to the terminal ends of trawls are deployed or recovered (Figure 2b,c). The system will also carry a user interface that will allow the fisher to enter information about their own gear to facilitate automatic deployment and recovery notifications to the cloud (Figure 2b,c); this information would include owner information as well as which devices are attached to which trawls and how many traps are included in each trawl (see section 1c – "Deploying gear" below). This user interface can double as a second chart plotter if a fisher wishes to keep a display of fixed gear separate from their existing chart plotter display. To communicate with devices on the sea floor, the ship's system will also be equipped with an acoustic modem and attached transducer (Figure 2b,c). This acoustic modem will use the acoustic standards described in section 2 of this document. Finally, for fishers that work in areas with high gear density, an optional ultra-short baseline (USBL) array may be needed to provide bearing to devices on the sea floor (Figure 2c). The USBL array allows devices to be localized with fewer localization observations taken from any bearing relative to the device, meaning it can provide more accurate localizations quicker than standard 1-way travel time localizations (for more information, see Section 1d,e and Appendix B). In high gear density areas, it may be in a fisher's own interest to help localize their own gear with their own USBL to help other fishers avoid that gear.

Devices that will be affixed to the terminal ends of trawls will consist of an acoustic modem, a transducer, depth sensor, RFID transceiver and, optionally, an attached on-demand release mechanism (e.g., hardware to release stowed rope or a lift bag) (Figure 3). The acoustic modem is an embedded digital signal processor (i.e., tiny computer) that detects and decodes acoustic communication signals provided to it by the transducer. Being a computer, the acoustic modem is capable of processing and logic, and can therefore perform the procedures described below. The modem will not need a real-time clock (time information will be supplied by the ship subsystem), but it will need non-volatile memory to store state information (e.g., last time of communication with a ship, passkey, owner ID). The acoustic modem will also have an integrated depth sensor to facilitate the localization process as well as a RFID transceiver to assist the CCU on the ship in detecting when devices are deployed or retrieved. The connection

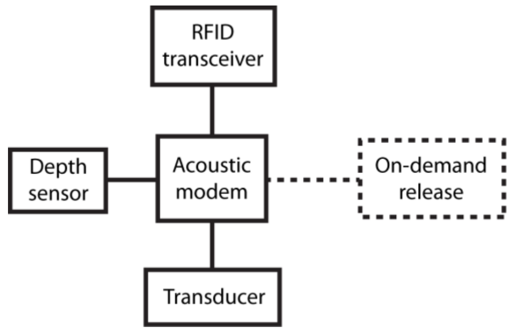


*Figure 3. Block diagram of device attached to fixed fishing gear on the sea floor. The dotted line indicates an optional component.*

to the on-demand release system is optional because not all fishers will fish with such a release system, as is the case when fishers grapple for their gear to retrieve it or use a timed release (e.g., galvanic release). However, when an on-demand release system is attached, the device will be capable of triggering the release mechanism upon acoustic command from the gear owner.

### *c. Detailed description*

The system can be broken down into several basic functions, including (1) documenting the deployment and recovery of fixed fishing gear, (2) determining the location of gear near a mobile or fixed fishing vessel at sea and having those locations appear automatically on that ship's chart plotter, (3) verifying and/or updating the location of devices, (4) discovering, reporting and recovering lost gear, and (5) triggering the on-demand release mechanism and querying the status of devices. A detailed description of each of these basic functions is provided below.

*Deploying gear*

Requirement 5c (*the ends of trawls must be marked in a way that is not voluntary*) indicates that some automatic process must be used to record the deployment and recovery of devices. If the process was not automatic, but instead relied on the fisher "pushing a button" to report the deployment or recovery of their gear, the system can be faked by deploying gear that is not reported to the cloud (i.e., illegally fished gear) or reporting to the cloud that gear has been deployed, when in fact it has not to hold ground. Figures 4a and 5 shows a means to automatically detect the disappearance and appearance of devices on the deck of a ship using RFID, a commonly used technology for tracking objects in air using radio transceivers that can be powered by the radio communication emissions from an RFID reader (identical to highway FastPass or EZPass systems). The reader will send out a broadcast message once a second to determine what, if any, devices are on the ship's deck. Devices that suddenly appear will be considered recovered devices and put on the "on-deck" list by the CCU, and devices that suddenly disappear will be considered deployed devices and will be taken off the "on-deck" list.

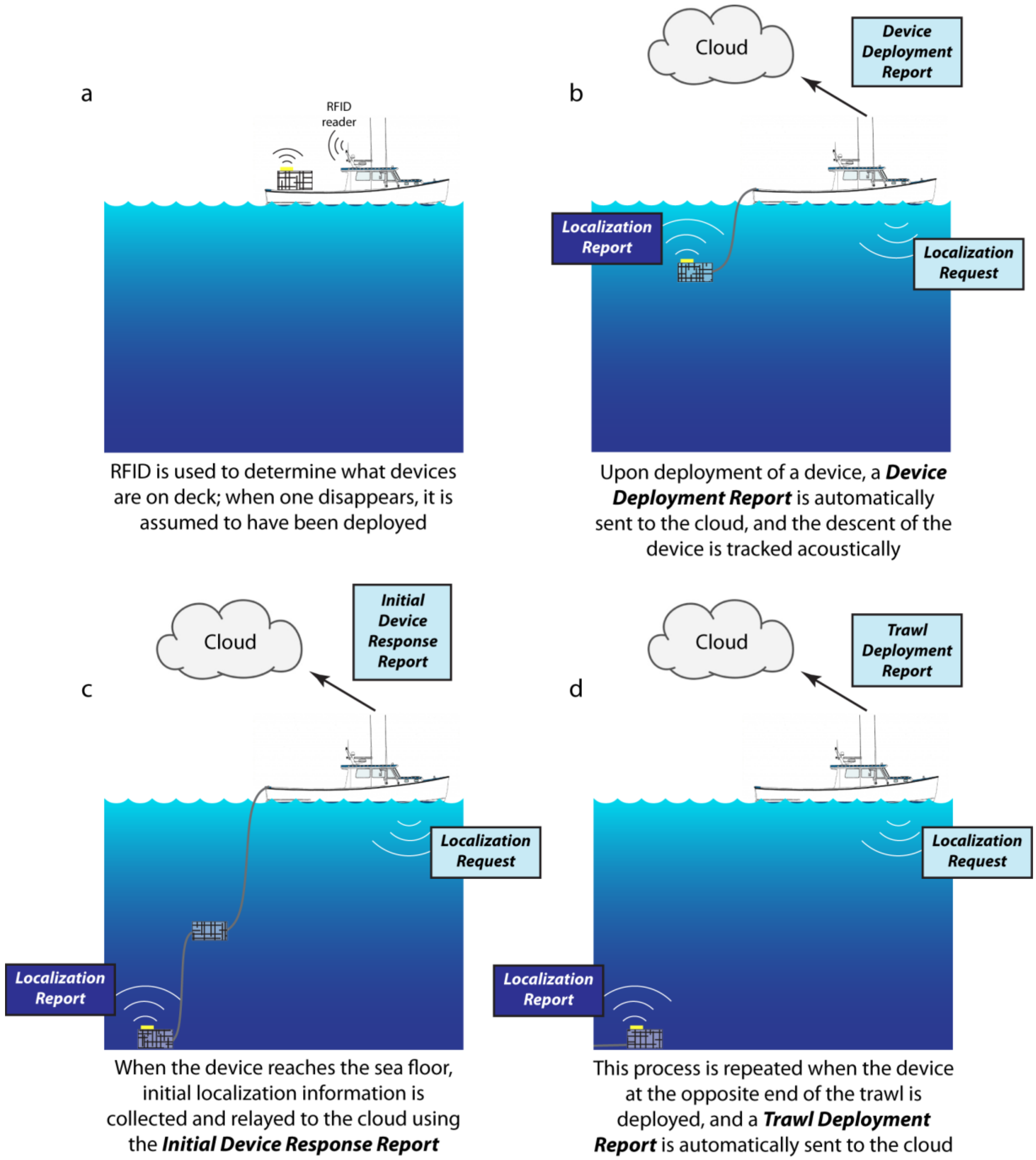


*Figure 4. Cartoons depicting the deployment of a trawl with devices (in yellow) affixed to each end of the trawl.*

The CCU will use the GPS to associate dates, times and positions to the device deployment and recovery events.

Once a device has been deployed, the CCU will notify the cloud with a ***Device Deployment Report*** (Figure 4b, 5) and the cloud will establish a record for this device with its

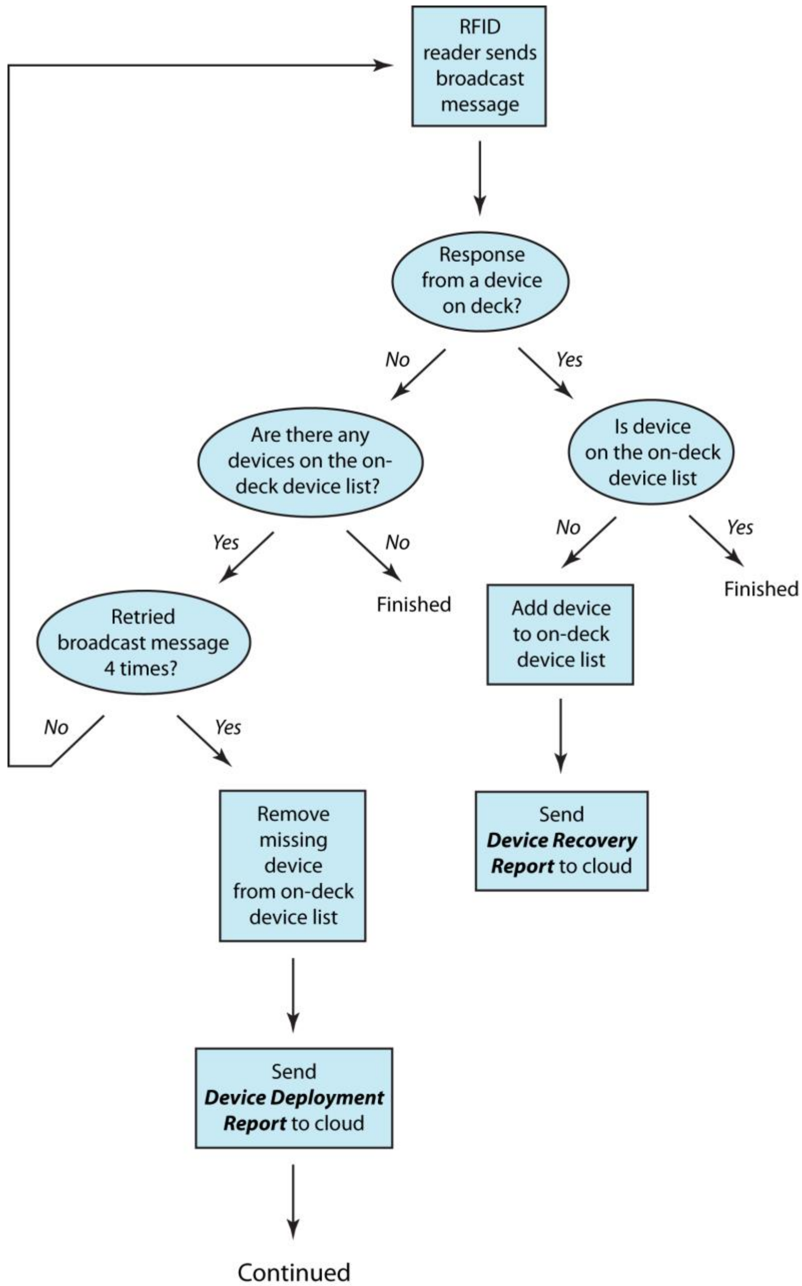


*Figure 5. Flowchart of automatic reporting of deployment and recovery of gear. All of the procedures described here are controlled by the ship's command and control unit (CCU). The purpose of these procedures is to automatically detect the deployment and recovery of devices, and to collect initial localization information once a device has settled on the sea floor. Figure 5 continues on the next page.*

ID, date, time and ship's position upon deployment. The CCU will then direct the acoustic modem to send a ***Localization Request*** to the ship once every 10 seconds, and the reported depth of the device contained in each ***Localization Report*** received in response will be monitored until the depth no longer changes, indicating that the device has reached the sea floor (Figure 4b, 5). At this time, the CCU will collect initial localization information in the form

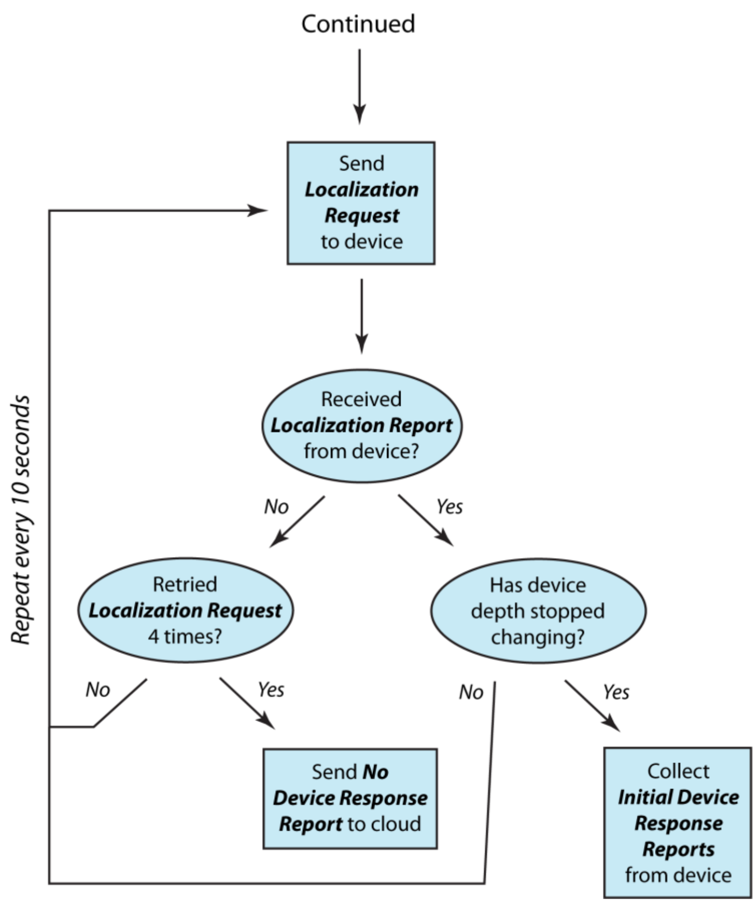


*Figure 5 continued.*

of 3 ***Localization Reports***, and each of these will be sent to the cloud using the ***Initial Device Response Report*** (Figure 4c, 5, 6). The cloud will add this localization information to the device's record, which will be later used to improve the estimated location of the device (see Section 1d). Immediately after deployment, the ship's position upon deployment will be used by the cloud as the initial (and last known) location of the device.

Once both ends of a trawl are deployed, a ***Trawl Deployment Report*** will be automatically submitted to the cloud with information required by the relevant authorities, such as owner ID, fishery registration information and the number of traps on the trawl (Figure 4d, 5). The owner's ID will already be associated with the devices that have been deployed and automatically reported to the cloud, so failure to submit a ***Trawl Deployment Report*** can easily be detected by the cloud and the cloud can alert enforcement. The ***Trawl Deployment Report*** is used to "pair" the devices at the two ends of the trawl so that they can be shown as two symbols with a line between them on chart plotters. In practice, the CCU will store information about the gear owner (owner ID, fishery registration information), as well as characteristics about each trawl maintained by a fisher, such as the number of traps and the IDs of the devices on the terminal ends of a trawl. This information would be numbered sequentially for each trawl; for example: Trawl #1 has 8 traps, device ID 4578 on one end, and device ID 8944 on the

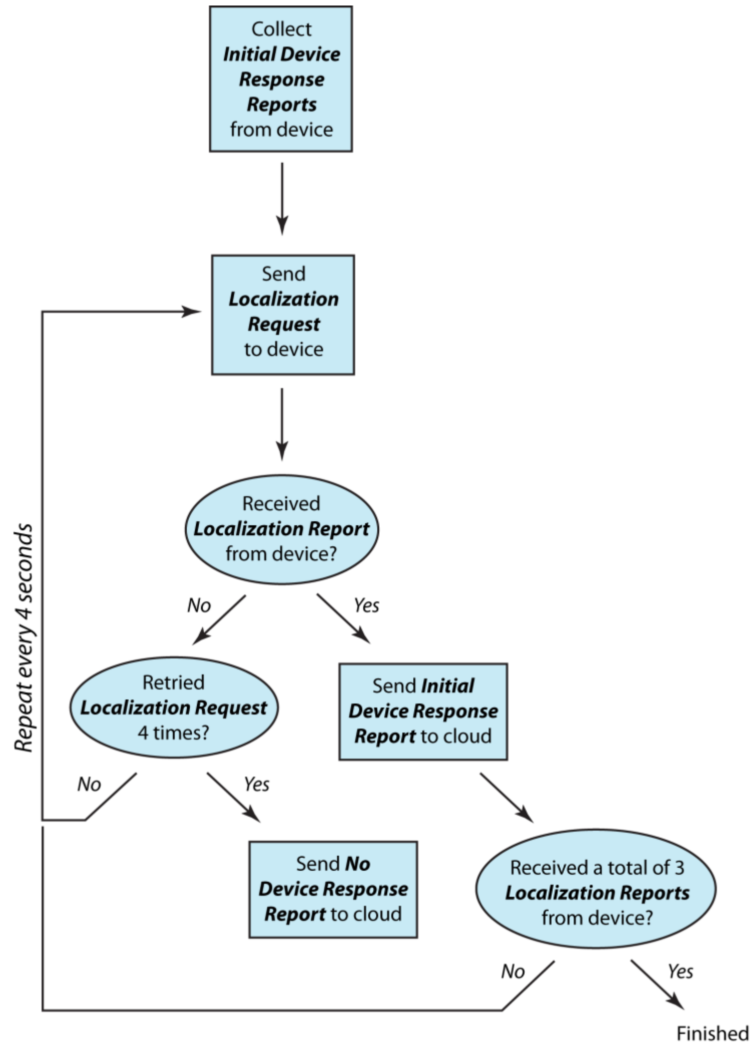


*Figure 6. Flowchart to collect* ***Initial Device Response Reports*** *from a device by the ship. All of the procedures described here are controlled by the ship's command and control unit (CCU). The purpose of these procedures is to collect initial localization information with 3 successive localization requests upon initial deployment, determination that the device has moved, or the discovery of lost gear.*

other end. With this simple database of trawls contained in the CCU, the CCU will detect that device IDs 4578 and 8944 were just deployed (detected by their disappearance to the RFID reader; Figure 4a, 5), and it will automatically send a ***Trawl Deployment Report*** for the trawl to the cloud. Note that if a fisher is fishing single traps/pots, the CCU database of trawls will reflect this by indicating that the "trawl" has only a single trap, and therefore will only have a single device ID associated with it. The cloud can recognize this as well, so that gear locations reported by the cloud (see below) and subsequently delivered to a ship's chart plotter can be appropriately displayed as singles (i.e., with no line between two device locations).

When a device suddenly appears on deck as detected by the RFID reader, the CCU will send a ***Device Recovery Report*** to the cloud (Figure 5, 7a,b). With its user-entered trawl database, the CCU can recognize that a specific trawl is being recovered. In the example above,

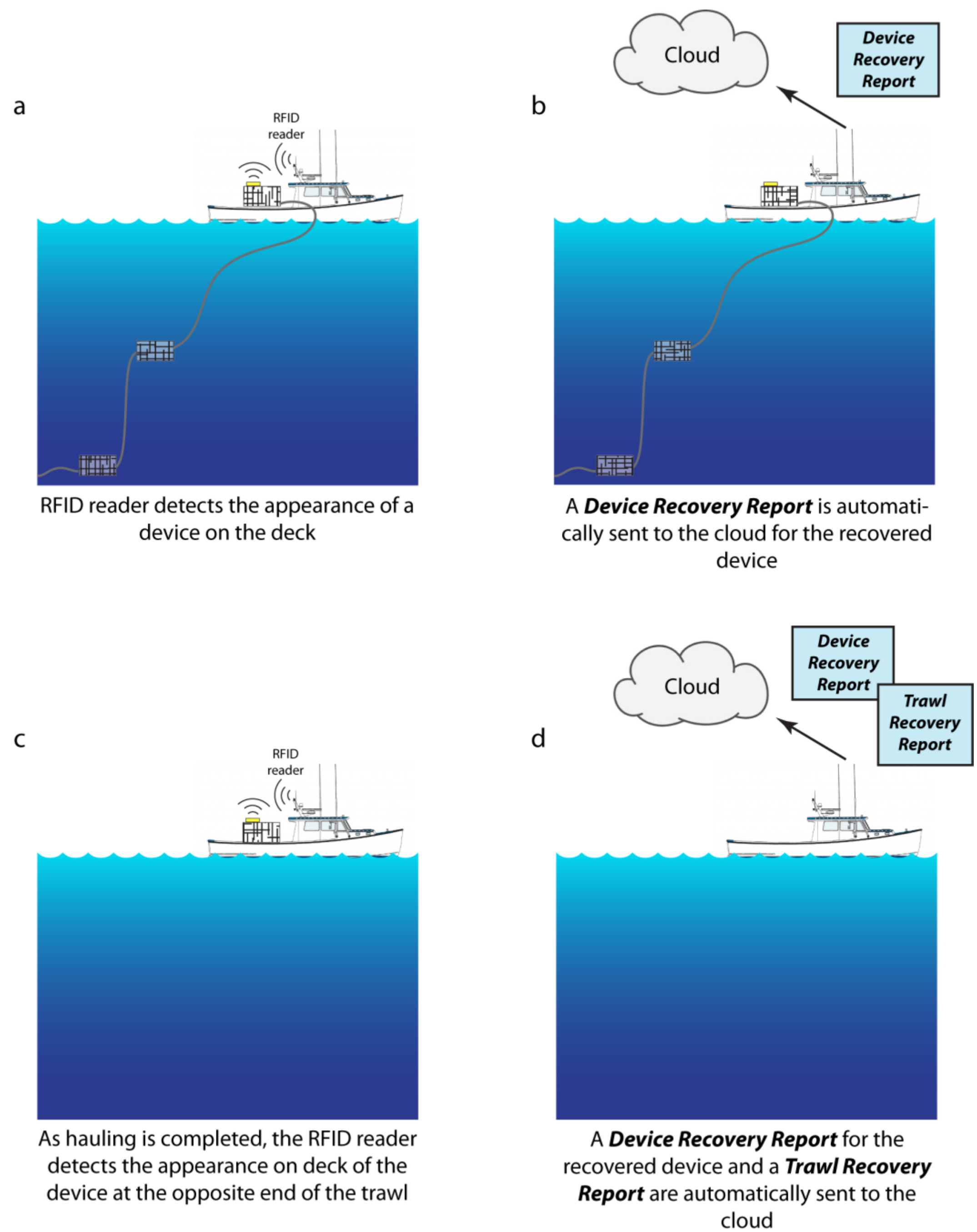


*Figure 7. Cartoons depicting the recovery of a trawl with devices (in yellow) affixed to each end of the trawl.*

if device ID 4578 appears on deck, the CCU will recognize that trawl #1 is being recovered. As soon as device ID 8944 is detected on deck, the CCU can automatically send a ***Trawl Recovery Report*** to the cloud, indicating that this trawl has been recovered (Figure 7d). As with the deployment procedure described above, the fisher need not do anything; this would all happen automatically in the background.

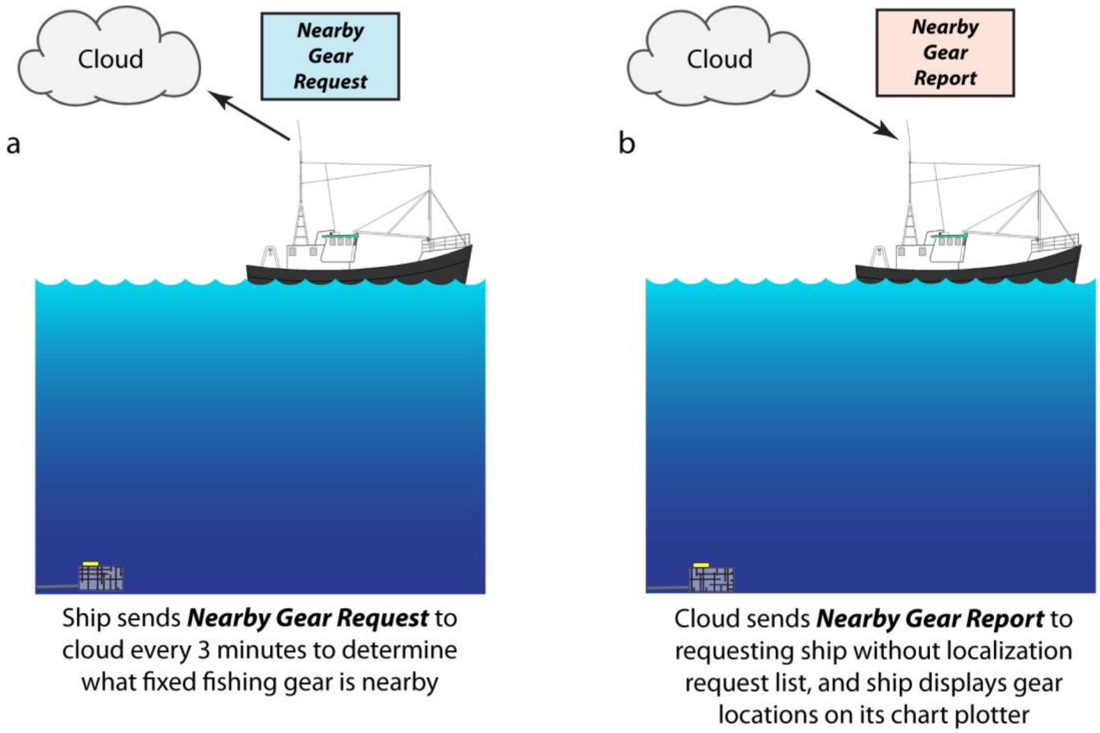


*Figure 8. Cartoons depicting a ship fishing mobile gear discovering and visualizing the location of nearby fixed fishing gear.*


*Figure 9. Flowchart initiated by **Nearby Gear Request** sent from a mobile fishing vessel (without an acoustic modem) to the cloud. The procedure used by the cloud to form the **Nearby Gear Report** is shown in Figure 10. The **Nearby Gear Request** is sent every 3 minutes from all ships. All of the procedures described here are controlled by the ship's command and control unit (CCU). The purpose of these procedures is to make available to a mobile vessel the location of fixed fishing gear in its immediate vicinity.*

*Determining the location of gear near a ship for display on the ship's chart plotter*

For any ship to learn of the location of nearby fixed gear, that ship must query the cloud using a ***Nearby Gear Request*** (Figure 8a, 9). To be updated regularly, this request will be issued automatically by the CCU once every 3 minutes. The request will include the ship's position, and upon receiving the request, the cloud will determine what devices are within 2 miles of the ship (Figure 10). For ships that do not carry an acoustic modem (i.e., mobile fishing vessels), the list of nearby device locations as well as pairing information (i.e., which devices are on the end of the same trawl) will be sent to the requesting ship in the form of a ***Nearby Gear Report***

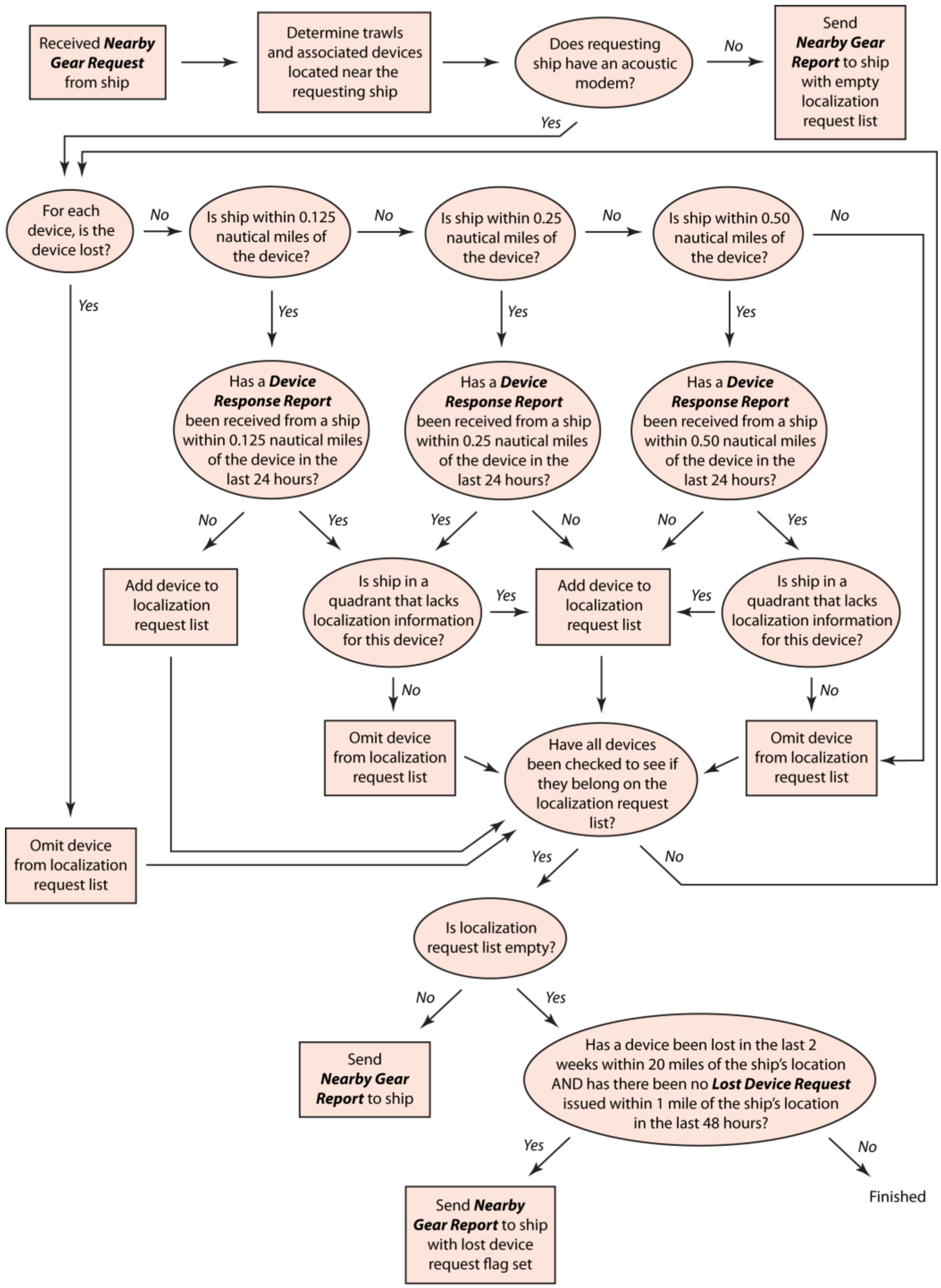


*Figure 10. Flowchart initiated by **Nearby Gear Request** received by the cloud. Note that the **Nearby Gear Report** contains locations of all gear near the requesting ship (for display on the ship's chart plotter) as well as a list of devices for which a **Localization Report** is needed (called the localization request list). The **Nearby Gear Request** is sent every 3 minutes from all ships. All of the procedures described here are controlled by the cloud. The purpose of these procedures is to (1) provide the requesting ship with the locations of all of the fixed gear near it, (2) for ships with acoustic modems, provide a list of devices whose position requires verification/updating, and (3) for ships with acoustic modems, to help discover and re-locate lost devices.*

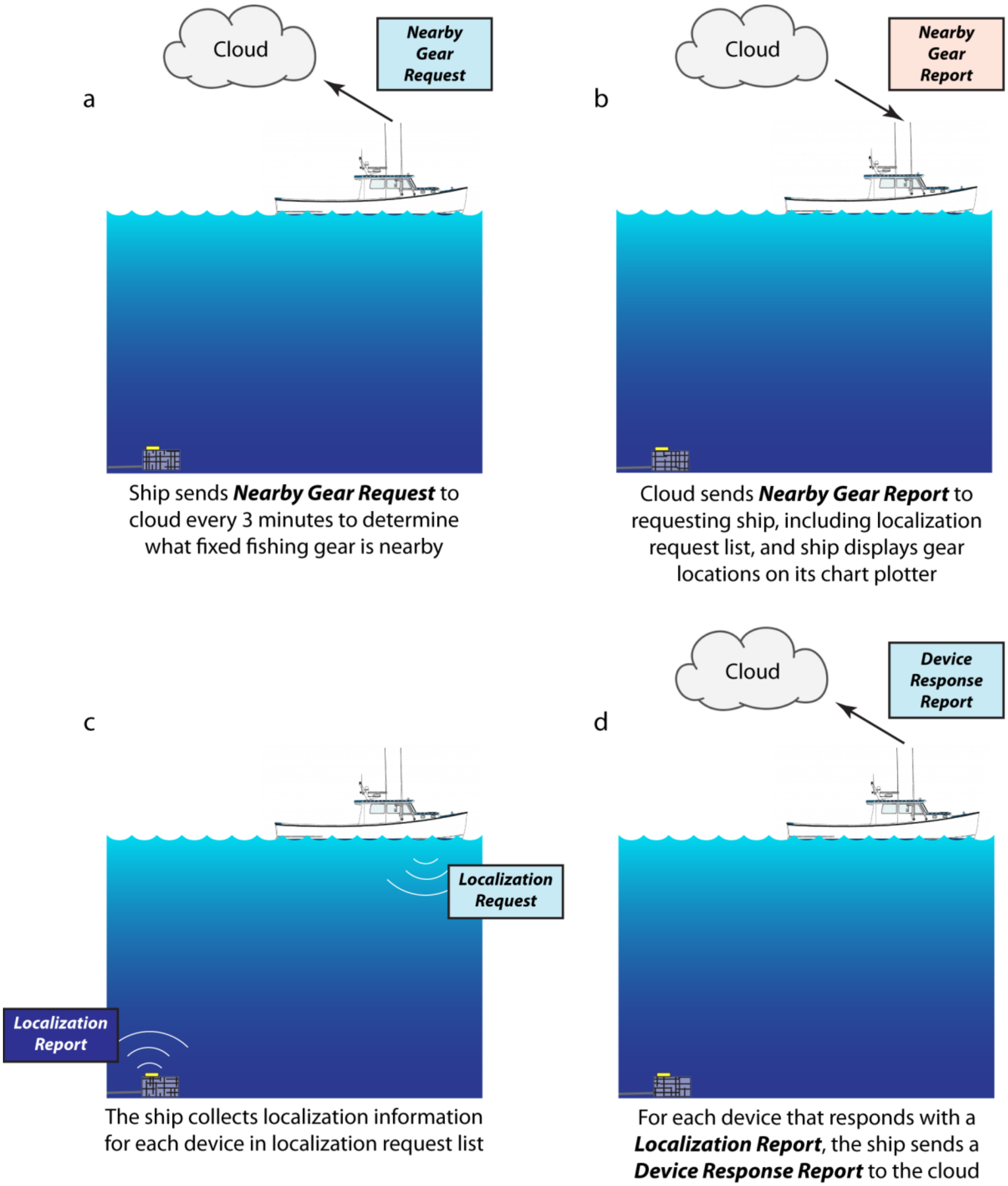


*Figure 11. Cartoons depicting a ship equipped with an acoustic modem discovering and visualizing the location of nearby fixed fishing gear, and then collecting localization information for devices on the sea floor.*

(Figure 8b, 9, 10). This report will not only contain the locations of the terminal ends of each trawl within 2 miles of the ship, but it will also contain information about which of the reported trawls are owned by the requesting fisher (note in Table 2 that the owner ID is sent with the

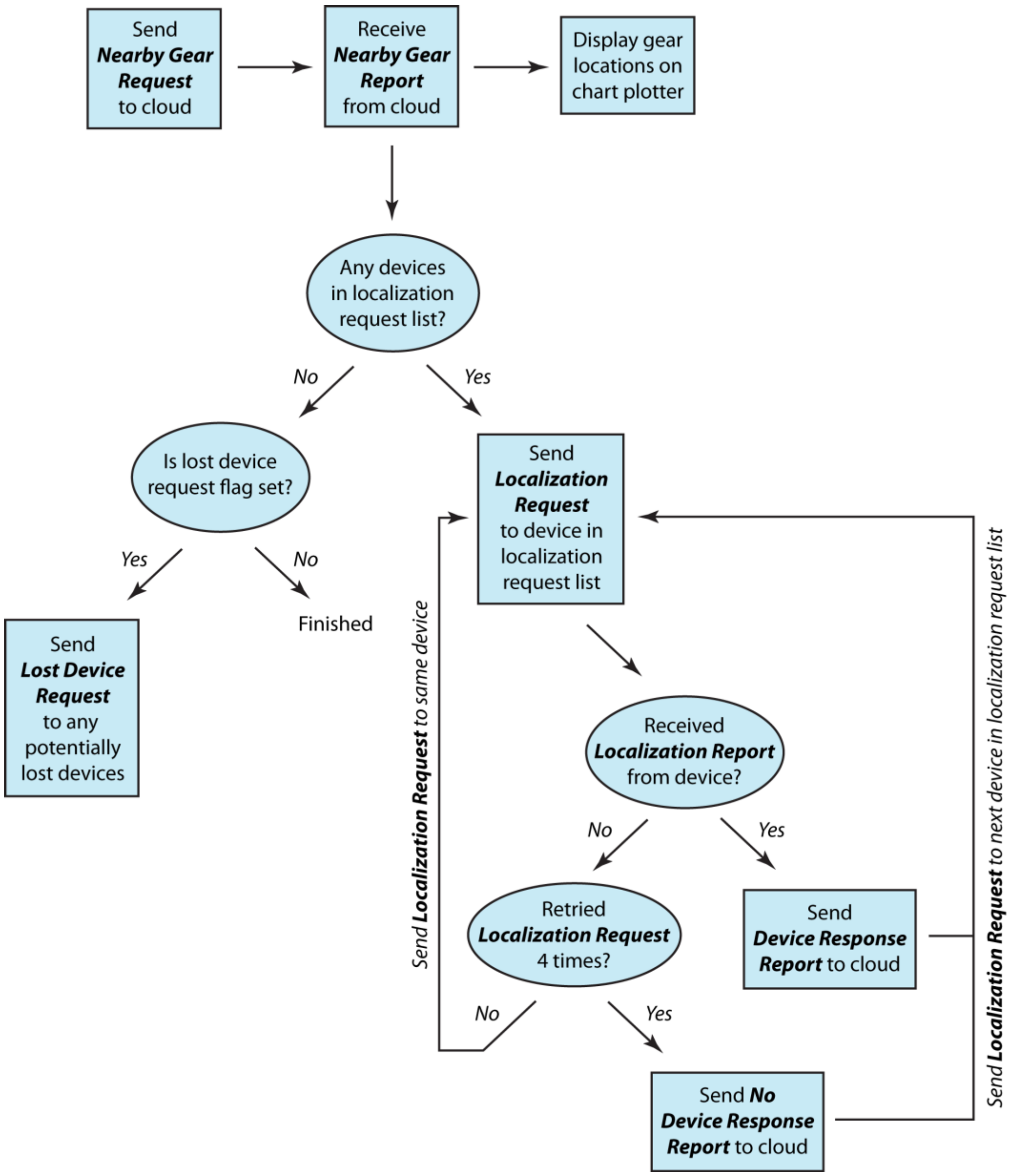


Figure 12. Flowchart initiated by ***Nearby Gear Request*** sent from the ship to the cloud. The procedure used by the cloud to form the ***Nearby Gear Report*** is shown in Figure 10. The ***Nearby Gear Request*** is sent every 3 minutes from all ships. All of the procedures described here are controlled by the ship's command and control unit (CCU). The purpose of these procedures is to (1) make available to a fixed fishing vessel the location of fixed fishing gear in its immediate vicinity, (2) to collect localization information from nearby devices to update those devices' positions in the cloud, to detect whether the devices have moved, and to initiate a relocation process if a device has moved, and (3) to facilitate the discovery and re-location of lost devices.

***Nearby Gear Request***) as well as information about those owned trawls, such as the date/time each owned trawl was deployed. The information in this report will be parsed by the CCU and NMEA messages containing position information for each trawl will be passed from the CCU to the vessel's chart plotter for display (Figures 9 and very top of Figure 12).

To maximize utility, it is highly recommended that the NMEA message contain a field designed to color code the trawls displayed on the chart plotter in a way that is most useful for the gear owner. For example, displaying the owner's gear as a separate color from all other gear owners would be desirable, and even allowing multiple colors for an owner's gear, each indicating the date when the gear was deployed (so the owner can keep track of soak time), would be helpful. The NMEA message could include a color-code field, and the CCU could fill that color code however the fisher wishes based on the owned-trawl information contained in the ***Nearby Gear Report***.

*Verifying and/or updating the location of devices*

Once gear is deployed, it is important to continue to check the location of the gear to make sure it has not moved, and in many cases, it is desirable to improve the location accuracy beyond what the surface deployment position provides (depending on depth and currents, the position of the ship upon deployment and the location of the gear once it lands on the sea floor can be very different). To do this, the cloud will request localization information from acoustic modem-equipped ships that pass near devices on the sea floor when responding to the ***Nearby Gear Request*** (Figure 10, 11 and 12). After identifying each device near the ship that sent the ***Nearby Gear Request*** (Figure 11a), the cloud will decide whether to direct the ship to issue a ***Localization Request*** to one or more of those devices based on the ship's horizontal range and


*Figure 13. Ranges and quadrants around a device in which localization information should be collected for the best localization accuracy.*

bearing relative to the devices (Figure 11b-d; note that henceforth, horizontal range will be referred to as “range,” whereas slant range will be referred to as “slant range”). The goal of the logic depicted in Figure 10 is to gather localization information from a variety of ranges and bearings around the device, since this distribution of observations (referred to as the “geometry” of observations) will produce the best accuracy. Localization information will be collected within 3 rings around the device defined by the following ranges: 0-0.125, 0.125-0.25 and 0.25-0.50 nautical miles (Figure 13) once every 24 hours. If localization information in one of the rings has been collected within the last 24 hours, the cloud will not direct the ship to issue a ***Localization Request*** to that device unless the ship is in a quadrant for which no localization information exists yet for the device (Figure 13). The latter rule is designed to attempt to improve the geometry of observations, which will dramatically improve localization accuracy (see Appendix B). Any device that is determined to need a ***Localization Request*** will be put on the localization request list, and this list will be part of the ***Nearby Gear Report*** sent to the requesting ship (Figure 11b).

When an acoustic modem-equipped ship receives the ***Nearby Gear Report***, it will examine the transmitted localization request list and begin sending ***Localization Requests*** to

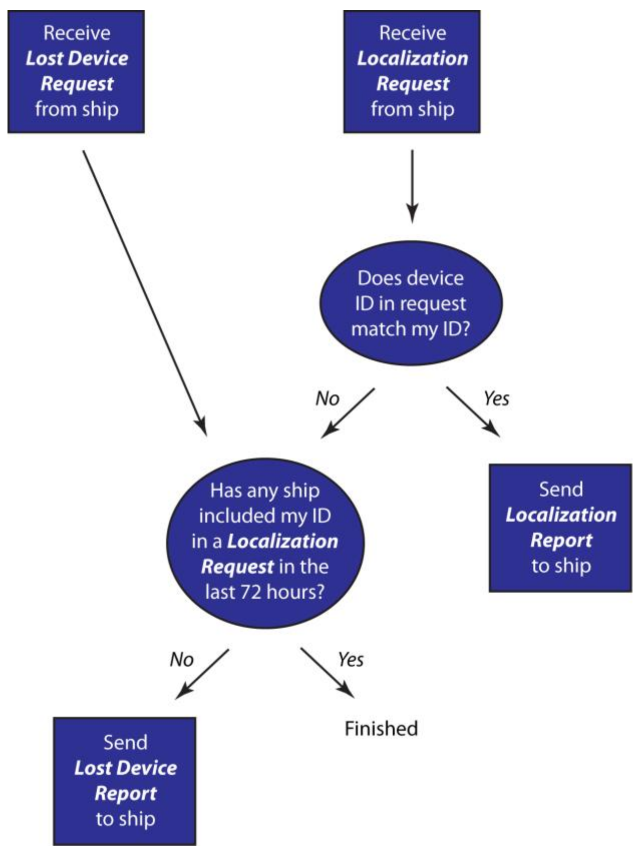


*Figure 14. Flowchart initiated by **Localization Request** or **Lost Device Request** received by a device on the sea floor. Note that the **Localization Request** will contain the ID of the device to which the request is directed. All of the procedures described here are controlled by the device on the sea floor. The purpose of these procedures is to (1) allow the position of the device to be determined by the cloud and (2) to alert passing ships that the device may be lost (i.e., moved very far from its last known position).*

each of the devices on the list (Figures 11c, 12). The ***Localization Request*** contains a single device ID indicating the device that is intended to respond (note that there are ways to compress device IDs so that multiple IDs can be sent in a single ***Localization Request*** to minimize transmissions, and the order of those IDs can be used to manage multi-access; however, for simplicity and immediacy, the currently proposed system will only transmit a single device ID with each ***Localization Request***). It is likely that many devices on the sea floor will successfully detect and decode this message. Each of these devices will examine the device ID contained in the ***Localization Request***, and the device whose own ID matches the transmitted ID will respond back to the ship with a ***Localization Report*** (Figures 11c, 14). The ***Localization Report*** will contain the ship ID to which the report is directed, device ID, device depth, and the delay between receiving the ***Localization Request*** and transmitting the ***Localization Report*** (the latter is used by the acoustic modem to estimate 1-way travel time). When the ***Localization Report*** is detected and decoded by the ship's acoustic modem, the ship will send a ***Device Response Report*** to the cloud with the device ID, the ship's position when it sent the ***Localization Request***, the measured 1-way travel time between the ship and the device, and, if measured by an attached USBL array, the bearing from the ship to the device (Figures 11d, 12). It is quite possible that the ship will not receive a ***Localization Report*** for the following reasons: (1) the device has moved out of the detection range of the system, (2) the device did not successfully detect and decode the ***Localization Request***, or (3) the ship did not successfully detect and decode the ***Localization Report***. In such cases, the ship will retry the ***Localization Request*** 4 times, and if there is still no received ***Localization Report***, the ship will send a ***No Device Response Report*** to the cloud (Figure 12), whereupon the cloud will include information about the lack of response in the device's record. This could be an early clue that the device has moved. After receiving 3 ***No Device Response Reports***, the cloud will consider the device lost and the owner is automatically notified.

When the cloud receives a ***Device Response Report***, it will first compare the new localization information to all of the previously collected localization information, which includes localization information from the 3 ***Initial Device Response Reports*** collected upon deployment, as well as any subsequent ***Device Response Reports*** collected by passing ships (Figure 15). If the new localization information provided in the latest ***Device Response Report*** is inconsistent with all of the previously collected localization information, the device will be considered to have moved from its previous location. In this case, all of the previous localization information will be deleted, the newest localization information will be saved, and the cloud will direct the ship to collect 3 new ***Initial Device Response Reports*** by sending the ***Moved Gear Request*** to the ship (Figure 15, 16). However, if the device is determined not to have moved, the new localization information will be added to the previous localization information and the position of the device will be updated using the procedure described in Appendix B (Figure 15). If the newly estimated position is more than 4 m different from the previous position, the ship will be alerted with an ***Updated Gear Report*** message, which will be treated by the ship identically to a ***Nearby Gear Report*** with an empty localization request list.

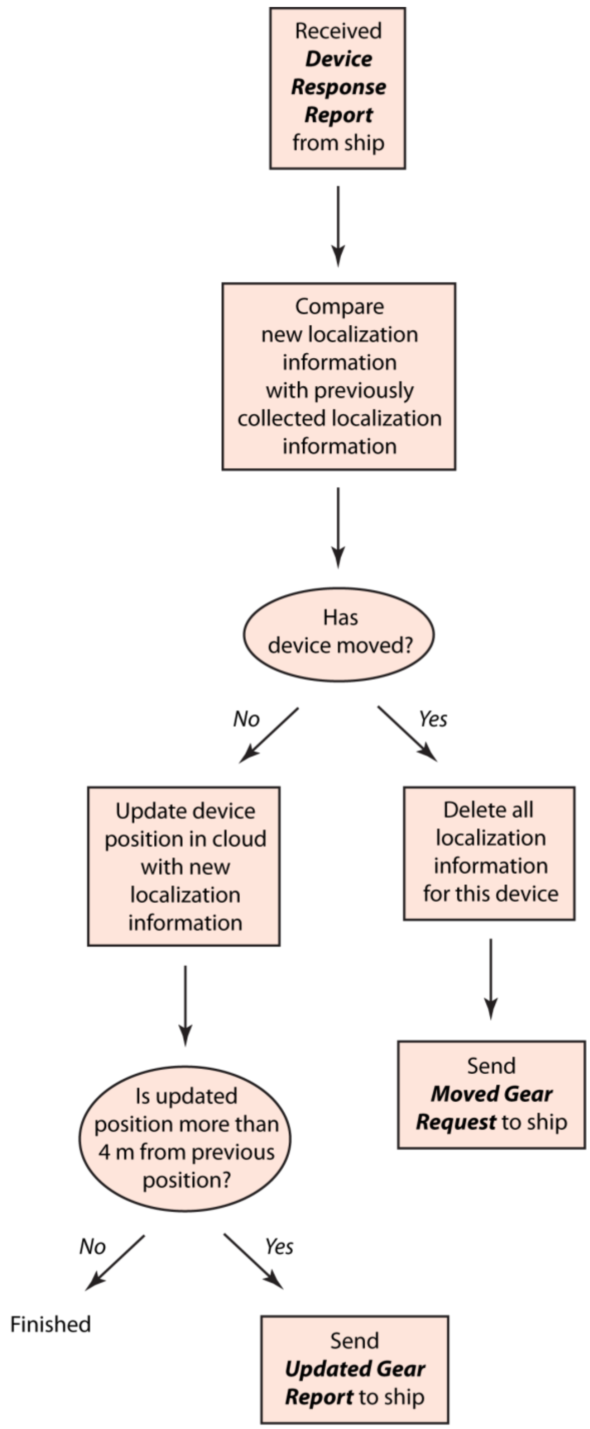


*Figure 15. Flowchart initiated by **Device Response Report** received by the cloud. All of the procedures described here are controlled by the cloud. The purpose of these procedures is to detect whether the device on the sea floor has moved, and if so, to collect new initial localization information via the **Moved Gear Request**. If the device has not moved, then the device's position in the cloud is updated with the new localization information, and if the new (presumably more accurate) position is more than 4 m from the previously estimated position, the cloud will notify the ship with an **Updated Gear Report** and the ship will plot the new gear location on the ship's chart plotter.*

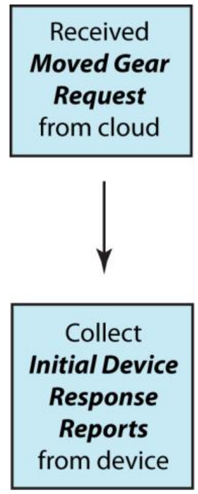


*Figure 16. Flowchart initiated by* ***Moved Gear Request*** *sent from cloud to the ship. All of the procedures described here are controlled by the ship's command and control unit (CCU). The purpose of these procedures is to collect initial localization information after a device has moved from its previously known location.*

*Discovering, reporting and recovering lost gear*

Although the lack of a response to a ***Localization Request*** may indicate that a device has been lost, neither the ship issuing the ***Localization Request*** nor the cloud can determine on their own where the lost gear has gone. It is up to the lost device to report itself lost, and there are two ways that the device can do this. Each ***Localization Request*** is intended to be addressed to a single device, but in fact will likely be detected and decoded by many devices within the acoustic detection range of the ship. For most of these devices, they are not lost and will ignore this request, but for a device that has determined that it is lost, this represents an opportunity to make its presence known to a nearby ship. When the device receives the ***Localization Request*** intended for another device (Figure 17a), it can compare the current time to the last time that it received a ***Localization Request*** that was addressed to it. If this elapsed time is greater than 72 hours, the device will consider itself lost, and it will send a ***Lost Device Report*** to the ship with an appropriate delay so as not to interfere with the transmission of the ***Localization Report*** from the device that was addressed in the ***Localization Request*** (Figure 17b). If the ship successfully receives the ***Lost Device Report***, it will send a ***Localization Request*** to the lost device to collect localization information from it via a ***Localization Report*** sent by the device in response to the ***Localization Request*** (Figure 17c, 18). The ship will then send a ***Found Device Report*** to the cloud (Figure 17d, 18), and the cloud will use the localization information to determine if the device has really moved from its last known position; if it has not moved, the cloud will do nothing, but if the device really has moved, the cloud will delete all of the localization information previously collected, send a ***Moved Gear Request*** to the ship to collect new localization information (Figure 18), and will automatically notify the gear owner that their device (trawl) has been found. With the new initial localization information, the next ship that

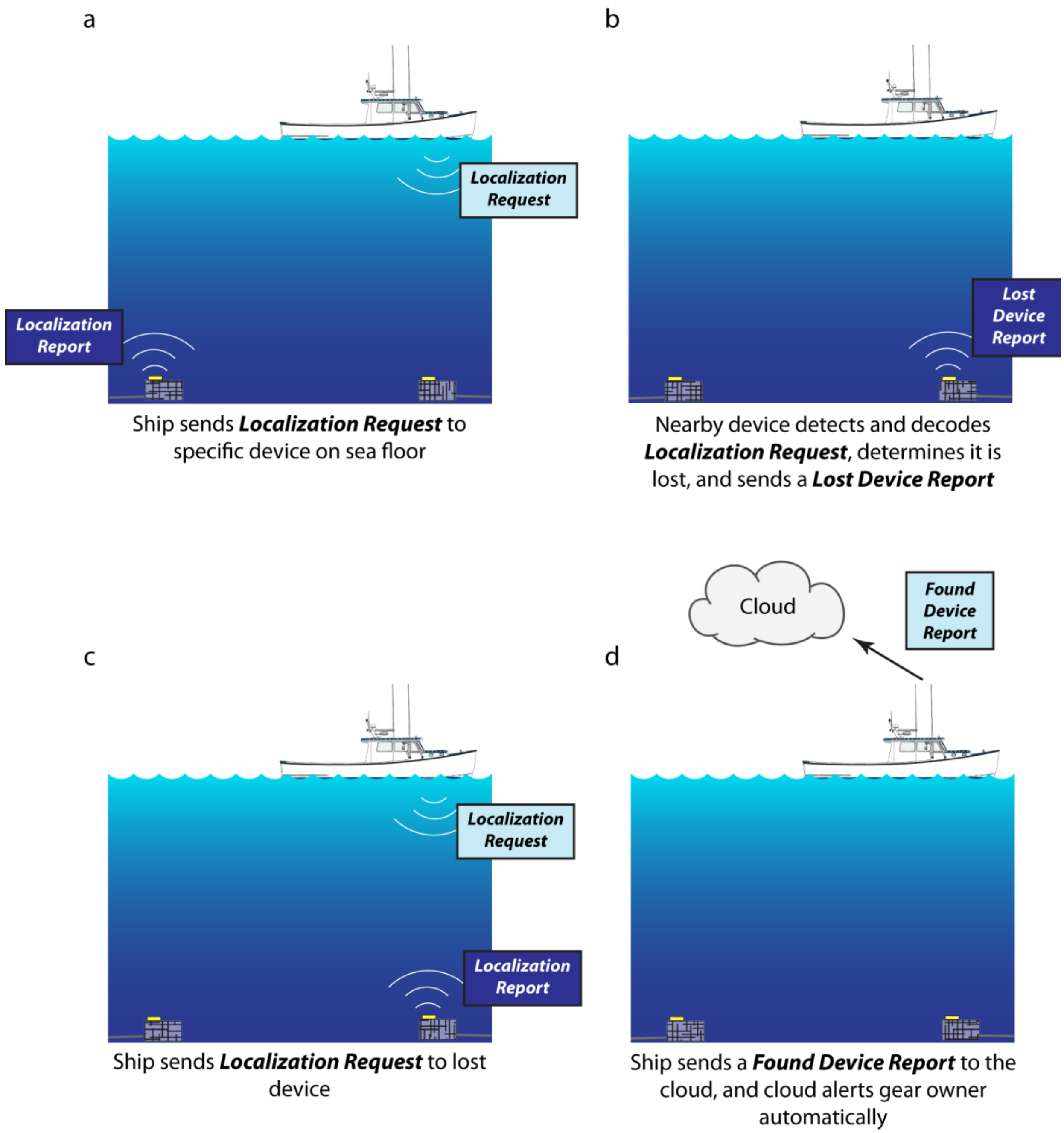


*Figure 17. Cartoons depicting a lost device making itself known to a passing ship after receiving a **Localization Request** not addressed to it.*

passes the device will successfully localize it, and this location can be shared automatically with the gear owner.

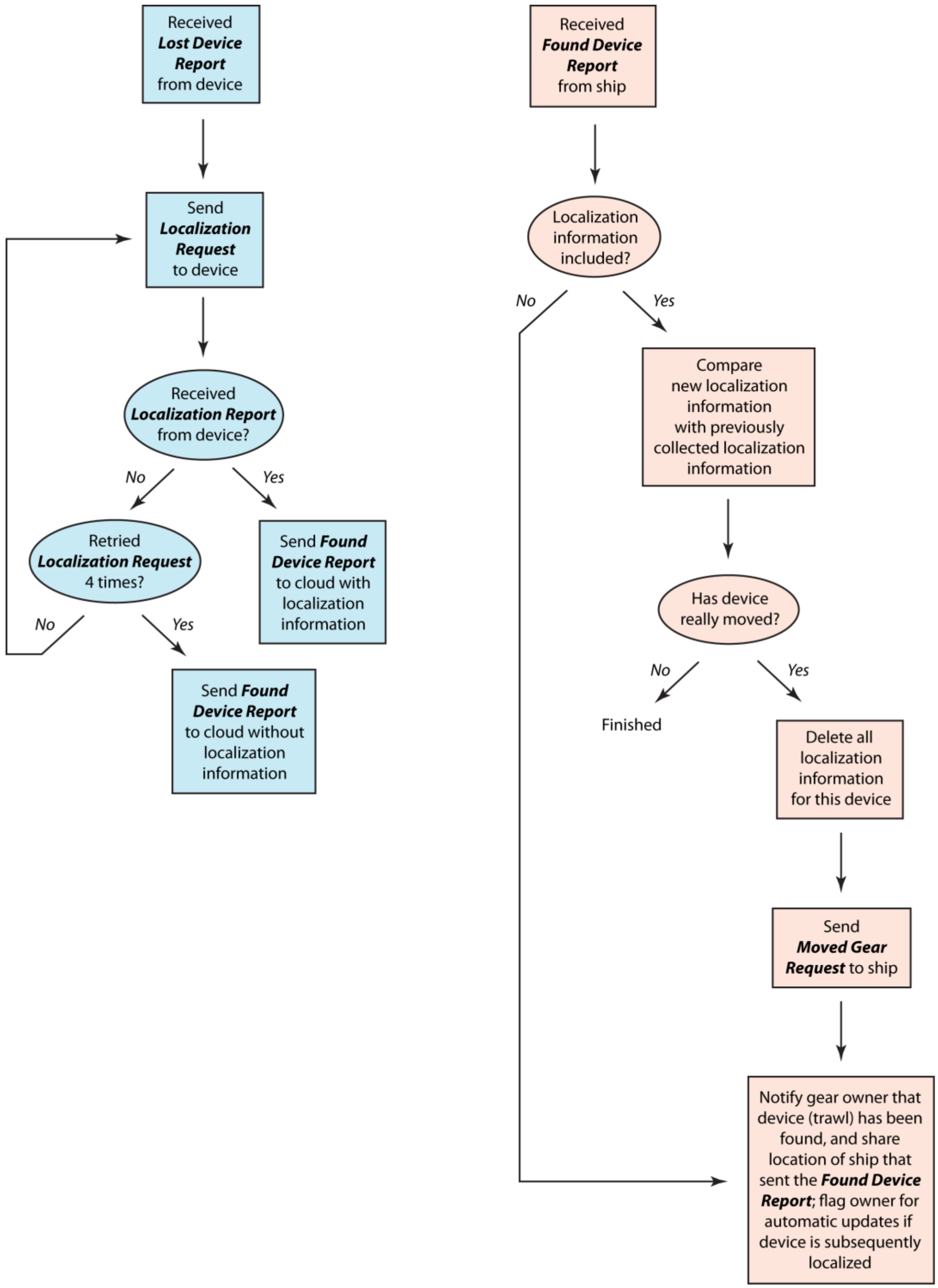


*Figure 18. Flowchart initiated by* ***Lost Device Report*** *sent from a device to the ship. The procedures on the left (in blue) are controlled by the ship's command and control unit (CCU), whereas the procedures on the right (in tan) are controlled by the cloud. The purpose of these procedures is (1) to notify a gear owner that their previously lost trawl has been found and where (approximately) they can go to retrieve it, and (2) to collect initial localization information to aid in relocating the device and helping the owner in recovering their gear.*

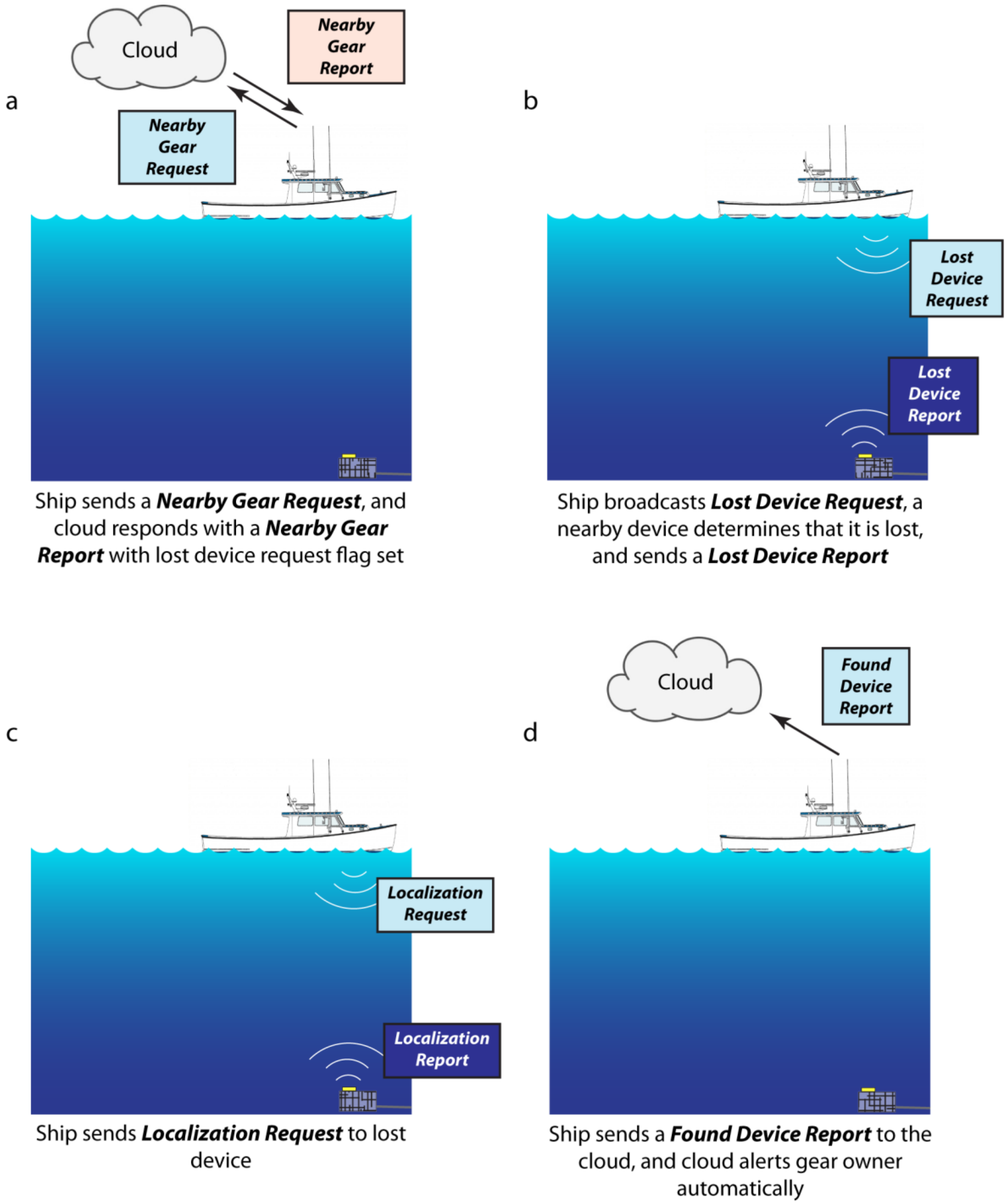


*Figure 19. Cartoons depicting a lost device making itself known to a passing ship after receiving a* ***Lost Device Request****.*

The second method for lost gear to be found is for ships to issue a ***Lost Device Request***, to which any lost device can respond (Figure 19). This is intended to allow devices that have been moved to areas with no nearby gear to be discovered. When a ***Nearby Gear Request*** is received by the cloud from a ship equipped with an acoustic modem (Figure 10), and no devices nearby the ship are identified as requiring localization information (i.e., the localization request list is empty), the cloud will check if any devices have been lost within the last 2 weeks and 20 nautical miles of the ship's location (i.e., if a recently lost device may be nearby) and whether any ***Lost Device Requests*** have been issued within 1 nautical mile of the ship in the last 48 hours (i.e., if any other ship recently checked this area already for lost devices) (Figure 10). If a nearby device has been recently lost and no one has recently checked for lost gear in the area, then the cloud will set the lost device request flag field in the ***Nearby Gear Report***, and will send the report to the ship (Figure 10, 19a). The cloud will record the date/time and ship's location when/where a ***Lost Device Request*** was issued via the lost device request flag in the ***Nearby Gear Report*** and hold those records for at least 48 hours. When a ship receives a ***Nearby Gear Report*** with the lost device request flag set, it will issue a ***Lost Device Request*** via the acoustic modem (Figure 12, 19b). When a device receives this request, it will determine if it has received a ***Localization Request*** in the last 72 hours, and if not, it will respond with a ***Lost Device Report*** using a random delay to mitigate any multi-access issues (Figure 14, 19b). As described above, the ship will respond to the ***Lost Device Report*** with a ***Localization Request*** (Figure 19c), and after receiving a ***Localization Report*** in response from the lost device (Figure 19c), it will notify the cloud with a ***Found Device Report*** (Figure 18, 19d) and the cloud will notify the gear owner automatically if it determines the device is truly lost (i.e., it has moved from its last known location).

*Triggering the on-demand release mechanism and querying the status of devices*

Of course, one of the most important functions of the device is to trigger the activation of the on-demand release mechanism when one is attached (Figure 3). Note that the system described above to mark the location of the gear does not need to be attached to an on-demand release system; the device can be used to mark the terminal ends of trawls that will be recovered via grappling or time-release mechanisms (e.g., a galvanic link). When an on-demand system is attached to the device, an ***Owner Release Request*** can be issued by the ship to trigger activation of the on-demand release mechanism, which in turn will release stowed rope or initiate the inflation of a lift bag to facilitate retrieval. This request must be authenticated by the device on the sea floor so that on-demand systems cannot be triggered for release by non-owners; hence, the request will include a passkey that is encrypted using public-key cryptography and can only be decrypted by the device to which the request is directed. Once the release is activated, the device can send a ***Release Report*** to the ship to confirm that the release has been triggered. On approach, an owner can also issue an ***Owner Status Request*** to the device, prompting the device (upon authentication with the passkey) to respond with an ***Owner Status Report***, which will contain relevant information about the status of the device as well as information needed to estimate the horizontal range from the ship to the device (i.e., device depth and response delay to allow a 1-way travel time to be estimated). The ***Owner Status Report*** may also contain status information that is proprietary to the specific manufacturer's gear; the data returned with the ***Owner Status Report*** should have a private payload to accommodate this proprietary information.

Just as owners will need to release and query the status of their own gear, enforcement will need the capability to do the same for all gear within their jurisdiction. The enforcement requests and reports will be identical in function to the owner requests and reports, but instead of providing owner credentials, the enforcement requests and reports will provide enforcement credentials to gain access to the release and status functions. Through this mechanism, enforcement will be able to release gear using the ***Enforcement Release Request*** and request status information with an ***Enforcement Status Request***, which upon authentication, will elicit a ***Release Report*** and an ***Enforcement Status Report***, respectively.

On shore, it is envisioned that gear owners will be able to query the cloud database for information on their gear in an application of some sort (ideally these applications will be available on desktop computers, web browsers, smart phones and tablets), and that queries from these applications will take the form of an ***Owner Query Request***. After authentication, the cloud will respond with the requested information in an ***Owner Query Report***. Similarly, enforcement will be able to access information for any deployed gear in their jurisdiction using an ***Enforcement Query Request***, and the cloud will respond after authentication with the requested information in an ***Enforcement Query Report***.

### *d. Localization procedure*

The localization procedure used when a ***Device Response Report*** is received in the cloud takes advantage of localization information contributed by many ships that pass by the device. Using these multiple observations yields a more accurate estimate of a device's position than any one ship can likely collect on its own because the geometry (i.e., the distribution of observations around the device) is nearly always going to be better with multiple ships than with a single ship, particularly when that single ship's sole purpose is fishing, not surveying (i.e., localizing) device positions. The localization seeks to estimate the position of the device and the average speed of sound in seawater based on multiple observations of the following measurements: the latitude, longitude and depth of the ship's transducer, depth of the device, 1-way travel time of sound between the transducer and the device, and, optionally, the bearing from the ship to the device measured with a USBL array. These measurements are what are referred to as "localization information" in this document. Note that 1-way travel time is measured as the 2-way travel time (i.e., the difference in time between the acoustic modem transmitting the ***Localization Request*** and receiving the ***Localization Report*** from the device minus the response delay reported by the device) divided by 2. Sound speed is estimated because measuring it is impractical (it would require measuring temperature and salinity throughout the water column, and fishers definitely do not have time to do that).

The localization procedure is provided in detail in Appendix B and is briefly described here. It uses a non-linear least-squares iterative refinement procedure that is straightforward in concept. An initial guess for the device's position and the sound speed is chosen; the deploying ship's position when the device left the deck and 1500 m $s^{-1}$ are good initial guesses. The procedure then iteratively changes the estimated position for the device and the sound speed in such a way that the squared difference between the measurements and their estimated quantities is minimized. The changes in position and sound speed from one iteration to the next are chosen carefully based on the rate of change (i.e., derivative) of the measurements with respect to changes in the position of the device and the sound speed. Simulations can be used to estimate the error in the position estimates given errors in the measurements (see Appendix B for such simulations).

The localization procedure developed for this application has the advantage of being able to use either 1-way travel times alone (i.e., observations from ships without a USBL array), 1-way travel times with bearing estimates (i.e., observations from ships with a USBL array), or a combination of both. For example, if the deploying ship has a USBL, but the next 3 passing ships that collect localization observations do not have a USBL, all observations from all ships can be used in the same localization procedure to improve the accuracy of the estimated position of the device. The simulations presented in Appendix B indicate that if the deploying ship is equipped with a USBL array and collects 3 sets of localization information immediately after the device reaches the sea floor, any approaching ship will be able to collect sufficient localization information to achieve the required 8-m location accuracy (Requirement 2) before that ship reaches the device (i.e., before it can create gear conflict). In areas of low gear density, these same simulations suggest a USBL array is not needed, as the location accuracy requirement can be relaxed in such areas and localization using 1-way travel times will be sufficient.

***e. Justification***

Developing a system for gear location marking, gear retrieval, lost gear recovery and enforcement involves many tradeoffs to meet the requirements set out in Baumgartner et al. (2021). The system described above meets all of those requirements while attempting to minimize cost as much as possible. Below, justifications are provided for the choices that have been made. The justifications are written as answers to questions that a reasonably skeptical reader might have.

*Why use a cloud database?*

There is no doubt that an at-sea real-time connection to the internet to enable ship-cloud communication comes with an economic cost, just as having a real-time connection to the internet on shore at a private home or business comes with an economic cost. However, there are many benefits to using such a connection if it is available that may very well outweigh this cost. Those benefits are detailed here:

- Deployment information is immediately available to other marine users and enforcement (Requirement 5a).
- Location and information about deployed gear is available to gear owners and enforcement on shore (Requirement 5d).
- Mobile fishers (or other authorized marine users with a legitimate interest in knowing what is on the sea floor) can access fixed gear location information without having to install an acoustic modem and transducer (Requirement 5a)
- Without having access to on-demand gear locations on shore, enforcement would need to conduct at-sea surveys to discover the location of gear without any prior information about where to search for gear. Enforcement can currently use aerial surveys to locate where buoyed gear is deployed, but with on-demand gear, no such remote surveillance would be possible.

- All fishers can discover the location of fixed fishing gear at greater distances than what is reasonably feasible with acoustics. Without the cloud, achieving a detection distance of 2 nautical miles for offshore fisheries (Requirement 1b), where trawl lengths are quite long, would be very difficult using acoustics alone. Without knowing the location of the two ends of a trawl (e.g., because the acoustic system can't locate one end), the orientation of the trawl would not be known, leading to an increase risk of gear conflict. Using the cloud avoids this problem altogether.
- When using the cloud in the manner described above, most acoustic communications will be performed at close range (less than 0.5 nautical miles), greatly increasing the probability that transmissions will be detected and decoded successfully the first time; without this, devices will respond at the edge of their acoustic detection range, and many transmissions will likely need to be repeated to be detected and decoded successfully. These repeated transmissions needlessly increase the amount of sound the system puts into the water, which does not meet the requirement to minimize acoustic noise (Requirement 7b).
- By controlling the range at which localization information is collected, the cloud allows much more useful localization information to be collected for the purposes of improving the accuracy of device positions. This is particularly true of USBL-based observations, since the position error increases with the distance between the ship and device because of bearing error. If the range at which localization information is collected is not controlled by the cloud, localization information will be collected at greater distances and the USBL bearing information will be imprecise and unhelpful.
- The cloud allows localization information to be collected from a single device at a time for the purposes of verifying or updating its position by addressing that device by its ID. If the ship simply put out a broadcast message to determine the location of nearby gear without the aid of the cloud, then multiple devices may respond to this broadcast message simultaneously and the ship will have difficulty detecting and decoding these multiple responses because they will interfere with one another (imagine many people talking to you all at once; it may be difficult to understand all of them simultaneously). This is a well-known issue called the multi-access problem. By using the cloud to direct the ship to address one device at a time, the multi-access problem is solved (instead of many people talking to you all at once, imagine calling on each person individually, after which they alone talk to you; in this way, all of the speakers can be perfectly understood).
- By restricting the collection of localization information from devices to once every 24 hours, devices on the sea floor will need to transmit very few times a day. After localization information is collected from a device, all ships passing that device will discover its position from the cloud, not from sending/receiving an acoustic transmission. This has two important consequences: (1) the battery life of the device is extended significantly, since transmitting from the device draws a great deal of power from the batteries (Requirement 8a), and (2) the number of acoustic transmissions is decreased significantly (Requirement 7b).

- The cloud allows localization information collected from many different ships that pass by a device to be used in the localization procedure, which results in a more accurate position estimate than from localization information collected by a single ship alone.
- The process of discovering lost gear minimizes acoustic transmissions since the cloud will manage when and where a ship will broadcast the ***Lost Device Request*** (i.e., not all ships everywhere will broadcast this message to find lost devices). If other gear is nearby, then the discovery of lost gear will occur in the normal process of collecting localization information from that nearby gear (i.e., the device will send a ***Lost Device Report*** in response to its ID not being addressed by any passing ships in their ***Localization Request*** messages). ***Lost Device Requests*** will only be sent when ships have no devices for which they need to collect localization information (i.e., the localization request list is empty in the ***Nearby Gear Report***; Figure 12), and only in areas that have recently had a device go missing and have not had a ***Lost Device Request*** issued in the last 48 hours (Figure 10). This management of the lost device discovery process by the cloud reduces acoustic transmission (Requirement 7b).
- The cloud can pass parameters to the ship and to devices (via ships) that it can use for all functions, reducing the need to update the ship (CCU) or device software. There are many parameters that could be tuned over time as more experience is gained with the entire system, such as the number of ***Localization Requests*** to send when a device is initially deployed (= 3), how long a device should go without a ***Localization Request*** addressed to it before sending a ***Lost Device Report*** to a passing ship (= 72 hours), and how many times to retry sending a ***Localization Request*** to a device before sending a ***No Device Response Report*** to the cloud (= 4). Without the cloud, gear owners would need to update software on their ship and in each device they own to change these parameters.
- The cloud has much more powerful computing power available, so doing all of the management and localization there is more efficient. There is an endurance cost to having a device do advanced computations for localization (i.e., such computations could deplete batteries faster). A ship has no power limitations, but any advancements in localization or data management would need to be implemented with a software update to all CCUs. By implementing these functions in the cloud, they are available to all users immediately without any software updates.
- One of the great advantages of using the cloud is its ability to recognize and notify owners when gear is lost and when gear is found. The cloud keeps track of where all gear is located, and if a passing ship cannot verify the presence of a device at the location where it is supposed to be, then the cloud can alert the owner that the trawl to which the device is attached may be lost. When a device determines that it is lost because it has not been addressed in the last 72 hours (Figure 14), it will send a ***Lost Device Report*** to the next passing ship, the ship will send a ***Found Device Report*** to the cloud, and the gear owner can be immediately notified of the location where the device was re-discovered.

*Why not have each ship discover the location of gear acoustically themselves?*

Without real-time access to a cloud database, every fisher who wishes to know where fixed fishing gear is located on the sea floor will need to have an acoustic modem attached to their ship's CCU, including mobile fishers. Each ship will need to discover where devices attached to fixed fishing gear are located on the sea floor by sending acoustic transmissions to the devices and then performing the localization process on the CCU to determine the device locations. Such an approach would likely require a USBL array so that position estimates can be derived with a single acoustic request and response (however the accuracy of this approach is insufficient to meet Requirement 2 at all but the closest ranges; see below). For example, if 8 ships pass by a device on the sea floor in a day, each of those ships will have to send acoustic transmissions to the device to collect localization information, and the device will need to respond each of those 8 times so that each ship can go through the same localization procedure to determine the device's position. If the device responds to these passing ships when it first detects the ship's acoustic transmissions (i.e., at the edge of the detection range), the likelihood that the ship will successfully detect and decode the device's transmissions is low, owing to the long range over which these transmissions are being sent; thus, there will very likely need to be repeated transmissions. Moreover, if there is no implemented solution to the multi-access problem, multiple devices on the sea floor will likely respond to the ship's localization information request nearly simultaneously, making it difficult for the ship to detect and decode the responses and necessitating additional repeated transmissions.

With the cloud approach described above, only one of the 8 passing ships will collect localization information from the device on the sea floor; the other 7 ships will get the device's location from the cloud. Furthermore, the one ship that collects localization information will do so within 0.5 nautical miles of the device, greatly increasing the chances that the request/report acoustic transmissions will be successfully detected and decoded on the first try. With such dramatically reduced acoustic transmissions, less sound is put into the ocean (Requirement 7b) and the battery life of the device is maximized (Requirement 8a). If the localization methodology is ultimately improved, the cloud-based approach allows those changes to be implemented immediately for all users, whereas the acoustics-only approach would require each ship's CCU to undergo a software upgrade. Finally, the cloud-based approach allows localization information collected by different ships to be shared in the localization procedure, which will result in a much more accurate position estimate for the device; with the acoustics-only approach, the ship's CCU can only localize the device's position using localization information that it alone has collected.

*Why use RFID?*

RFID uses very little power, so will not be a drain on device batteries. For short-range RFID systems, the power to respond to a broadcast RFID message is actually harvested from the energy in the broadcast RFID message itself, so theoretically, it requires no power at all for a device to respond to an RFID broadcast message. This same technology is used in automatic toll collection systems. This seems like the best technology to fulfill Requirements 5b and 5c (real-time information must mirror reality and the ends of trawls must be marked in a way that is not voluntary). The system cannot rely on a fisher voluntarily pushing a button to have other fishers and enforcement become aware that gear has been deployed or recovered; the process of deployment and recovery notification must be automated and verifiable. By having a system that detects the disappearance of a device from the ship's deck (via RFID; Figure 4a) and then very shortly thereafter detects that same device underwater (via the ***Localization Request***; Figure 4b) provides this automation and verification. Note that device deployments and recoveries are made automatically using the RFID subsystem (via the ***Device Deployment Report*** and the ***Device Recovery Report***), and with the appropriate trawl data pre-loaded in the CCU, ***Trawl Deployment Reports*** and ***Trawl Recovery Reports*** can be sent automatically as well, requiring no fisher input at the time of deployment or recovery.

*Why not use SART?*

Localization of devices on the sea floor can only be done using acoustics, and there are three methods that can be applied to the on-demand gear location marking problem: (1) 1-way travel time only, (2) 1-way travel time and bearing, and (3) successive acoustic receive time (SART; Baumgartner and Partan 2021). 1-way travel time and bearing are measured at the ship when it issues a ***Localization Request*** and then receives a corresponding ***Localization Report*** from a device on the sea floor; the ship measures aspects of the acoustic properties of the ***Localization Report*** transmission to measure 1-way travel time and bearing, and it can then use that information to localize the device (either with the assistance of the cloud or using bearing and range derived from the 1-way travel time and reported device depth to directly estimate the device's position). Hence, the localization process happens at the ship or in the cloud. SART uses successive transmissions from an acoustic modem on a moving vessel to provide localization information to the device on the sea floor, and after collecting this information from at least two passing ships, the device on the sea floor can estimate its own position. SART was designed to limit the amount of transmitting required by the device (hence minimizing noise and maximizing battery life); instead of having to respond multiple times to each passing ship so the ship can localize the device's position, the device would simply listen to the regular transmissions of passing ships, localize its own position, and share that position once with each passing ship.

Because including a real-time satellite or cellular connection between the ship and the cloud provides so many benefits (such as having the cloud direct when and where ***Localization Requests*** are issued, aggregating localization information across many ships, and performing the localization process in the cloud), relying on SART for gear location marking makes less sense than the system described above for several reasons. SART would ultimately increase the overall number of transmissions both from ships to devices and from devices to ships. With SART, the device on the sea floor would need to transmit its position to every passing ship, yet with the system described above, the device would need to only transmit at most a few ***Localization Reports*** to one passing ship a day to verify or update its position in the cloud; all other ships would obtain the device's location from the cloud, not by acoustically communicating with it. Moreover, to facilitate SART localization by a device, ships would need to be transmitting localization information regularly. By using the cloud to direct when and where to issue ***Localization Requests*** and ***Lost Device Requests***, ship transmissions will be minimized and the need for regular transmissions (as would be needed for SART) is eliminated. Finally, using SART would substantially increase the complexity of the device on the sea floor. In the system described above, all of the complexity associated with measuring localization information and conducting the localization procedure is pushed to the ship and cloud, respectively, where there are no power limitations and comparatively unlimited computing resources. This makes the device relatively simple in design and function, which will speed development and manufacturing.

*Why collect 3 localization observations upon deployment?*

The localization procedure for a device attempts to estimate 3 properties: latitude of the gear, longitude of the gear, and the speed of sound in the ocean (see Appendix B). Very generally, to estimate 3 properties like this, at least 3 observations are needed, and depending on the observations and where they are collected, more observations will almost surely be needed. More observations, particularly when collected all around the device (in what is referred to as a good “geometry”), will result in better position estimates. When the gear is deployed, this is an outstanding opportunity to collect initial localization information, as the ship is close by the devices on either end of the gear (in many cases, closer than any other ship will ever get to the devices). Multiple observations taken at this time may not result in a very good position estimate for the device, as the locations where the observations are taken are not distributed around the device, but instead are located along a line proceeding away from the device (this is a poor “geometry”). However, these observations ensure that the next ship to pass near the device and collect localization information will very likely allow the localization procedure to estimate the device’s position with accuracy that meets Requirement 2 (see simulation results in Appendix B). Without multiple localization observations collected upon deployment, the localization procedure would not be able to derive an accurate position for the device as quickly; instead, it would need to collect information from several passing ships before being able to estimate a sufficiently accurate position estimate.

*With USBL, can’t we localize gear with just one set of request/report transmissions?*

With the acoustic modem, the 1-way travel time of sound between the ship’s transducer and the device on the sea floor can be measured, and with a USBL array, the bearing between the ship and the device can also be measured. If the speed of sound and the depth of the device is known, the horizontal range between the ship and the device can be calculated with the measured 1-way travel time. With this range, the measured bearing, and the ship’s GPS-derived location, the latitude and longitude of the device can be estimated. But how accurate is this position estimate and does it meet Requirement 2? This depends largely on (1) how well we know the speed of sound and (2) what is the error in the bearing estimate (other factors that affect the localization include the error in the 1-way travel time measurement, device depth, and GPS-derived position of the ship, but these will be ignored for now).

Without explicitly measuring it (which would be extremely impractical for commercial fishing operations), the speed of sound is completely unknown and a typical value of 1500 m $s^{-1}$ is often used in these types of calculations. As a simple example, Table 3 shows position errors (in the direction aligned with the bearing between the ship and the device) when estimating the horizontal range using an incorrect sound speed; in this case, a sound speed of 1500 m $s^{-1}$ is used when the true sound speed is actually 1480 or 1460 m $s^{-1}$. These values were derived by calculating the true slant range (from true horizontal range and device depth), the true 1-way travel time, and then calculating the estimated horizontal range with the incorrect sound speed, the true 1-way travel time and the device depth. The difference between the estimated range and the true range is provided as the along-bearing error. These errors grow with range, device depth and the difference between the true sound speed and the sound speed used in the calculations. Depending on how deep the device is and the difference in sound speeds, many of the along-bearing errors are outside of the allowable maximum error of 8 m (Requirement 2).

*Table 3. Error in horizontal range estimates when an incorrect sound speed is used. For each calculation of error, a sound speed of 1500 m $s^{-1}$ is used, when in fact the sound speed (c) is actually 1480 or 1460 m $s^{-1}$. Results are shown for device depths of 30 or 200 m. Errors are aligned in the direction of the bearing between the ship and the device; hence, they are termed "along-bearing errors". Note that Requirement 2 indicates a maximum allowable error of 8 m.*

| **Range between ship and device (nautical miles)** | **Range between ship and device (meters)** | **Along-bearing error (m)** |
|---|---|---|
| *c = 1480 m $s^{-1}$, depth = 30 m* | | |
| 0.125 | 232 | 3.2 |
| 0.250 | 463 | 6.3 |
| 0.500 | 927 | 12.5 |
| *c = 1480 m $s^{-1}$, depth = 200 m* | | |
| 0.125 | 232 | 5.4 |
| 0.250 | 463 | 7.4 |
| 0.500 | 927 | 13.1 |
| *c = 1460 m $s^{-1}$, depth = 30 m* | | |
| 0.125 | 232 | 6.5 |
| 0.250 | 463 | 12.7 |
| 0.500 | 927 | 25.4 |
| *c = 1460 m $s^{-1}$, depth = 200 m* | | |
| 0.125 | 232 | 11.0 |
| 0.250 | 463 | 15.0 |
| 0.500 | 927 | 26.5 |
| | | |

A similar example is shown in Table 4 to consider the position errors imposed by the bearing error of the USBL array. For this exercise, bearing errors of $\pm 2$, 5 and 10° were used to calculate position errors in the direction perpendicular to the bearing between the ship and the device (cross-bearing errors; this is the direction perpendicular to the along-bearing errors discussed above). Cross-bearing errors are simply calculated as R $\times$ tan($\theta_e$) where R is the range (in meters) and $\theta_e$ is the bearing error (here $\pm 2$, 5 and 10°). Even at close ranges with a very good USBL array with $\pm 2°$ bearing error, the cross-bearing error is just over $\pm 8$ m (Requirement 2), and all other cross-bearing errors are considerably greater than that.

*Table 4. Error in horizontal range estimates as a function of bearing error. Errors are aligned perpendicular to the direction of the bearing between the ship and the device; hence, they are termed "cross-bearing errors". Note that Requirement 2 indicates a maximum allowable error of 8 m.*

| **Range between ship and device (nautical miles)** | **Range between ship and device (meters)** | **Cross bearing error (m) with ± 2° bearing error** | **Cross bearing error (m) with ± 5° bearing error** | **Cross bearing error (m) with ± 10° bearing error** |
|---|---|---|---|---|
| 0.125 | 232 | ± 8.1 | ± 20.3 | ± 40.8 |
| 0.250 | 463 | ± 16.2 | ± 40.5 | ± 81.7 |
| 0.500 | 927 | ± 32.4 | ± 81.1 | ± 163.4 |

What seems to be clear from Tables 3 and 4 is that when USBL arrays are used to estimate the position of a device using a single set of localization observations (i.e., one localization request from the ship and one corresponding localization report from the device in response that allows 1-way travel time and bearing to be measured), they will have sufficient accuracy to satisfy Requirement 2 only at very close ranges (less than 0.125 nautical miles) and only with USBL arrays with small bearing errors (note that cost of a USBL array generally scales inversely with the bearing error, meaning USBL arrays with small bearing errors are generally more expensive than ones with large bearing errors). Even the deployment ship may be challenged to collect localization observations of sufficient accuracy with a single set of localization observations from a modem and USBL array under some circumstances because fishing vessels typically continue to steam away as the gear sinks from the surface, and by the time the gear arrives at the sea floor, the ship may be beyond 0.125 nautical miles for a sufficiently accurate position estimate of the device on the sea floor.

These range restrictions suggest that using a single set of localization observations to accurately estimate the position of a device on the sea floor will require rapid repetition of localization information requests from the ship. For example, a ship travelling at 5 knots traverses a distance of 0.125 nautical miles in 1.5 minutes, so the ship would need to be issuing a localization information request to devices on the sea floor at or faster than once every 1.5 minutes to ensure the ship was within a range of the device in which the system would be sufficiently accurate. This approach implies that the ship as well as the devices on the sea floor would be transmitting very often, which does not meet the requirements to minimize acoustic noise (Requirement 7b) and maximize device battery life (Requirement 8a).

*Why collect localization information when the ship is within 0.50 nautical miles of a device?*

By using the cloud to restrict the range at which the ship issues a ***Localization Request***, the chances that acoustic transmissions from the ship to the device and from the device to the ship will be successfully detected and decoded increase substantially. The successful detection of an acoustic transmission depends on range; an example of this is shown in Figure 20, which depicts the rate of transmission detection (number of detections per minute) as a function of range for a commercial pinger that is transmitting at roughly once per second (i.e., ~60 transmissions per minute; data from Baumgartner et al. 2008). As the range between the pinger and receivers (mounted on four different buoys) increases, fewer and fewer of the pinger's transmissions are detected, meaning that the chances of successfully detecting the pinger's transmissions decline markedly with range. Figure 20 is only an example to illustrate this phenomenon of decreasing probability of detection with range. If all acoustic transmissions can be restricted to when the ship and the device are relatively close to one another (i.e., within 0.5 nautical miles), then the chances of having to repeat the transmission because of a failed reception are kept low, which fulfills the requirements to minimize acoustic noise (Requirement 7b) and maximize device battery life (Requirement 8a). At greater range, this chance of needing to repeat transmissions because of failed receptions increases.

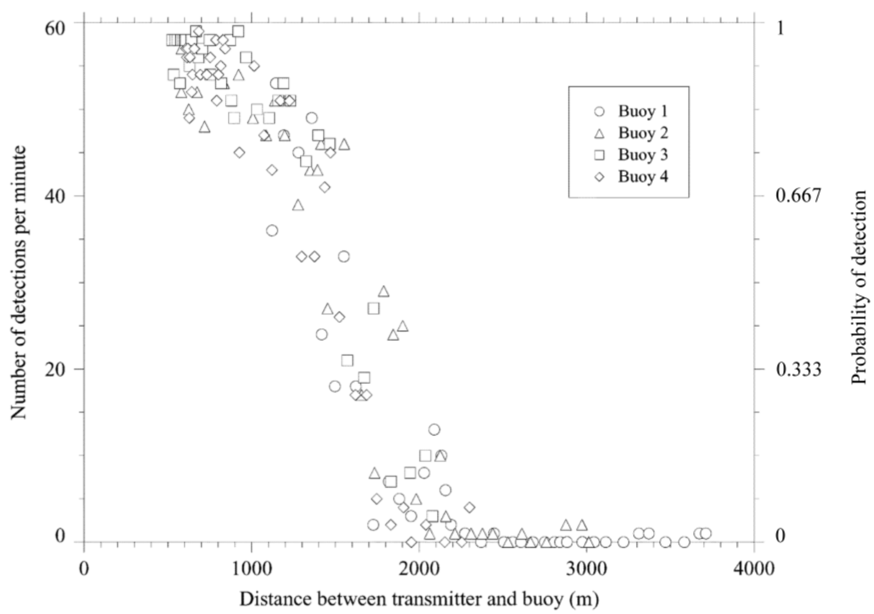


*Figure 20. Detection rates (number of detections per minute) and probability of detection for 4 buoys equipped with acoustic receivers when simultaneously exposed to an acoustic transmitter transmitting roughly once per second. Figure from Baumgartner et al. (2008) and shown only as an example of how the probability of detection decreases with the range between the transmitter and the receiver. This figure is not intended to represent the probability of detection for acoustic modems used in the system described in this document.*

It is important to note that while the ***Localization Requests*** are issued within 0.5 nautical miles of devices, devices that consider themselves lost can respond to either ***Localization Requests*** or ***Lost Device Requests*** (Figure 14) at any range as long as they can successfully detect and decode these requests from passing ships. It is possible that these devices will need to repeat transmission for the ship to successfully detect and decode the ***Lost Device Report*** sent from the device because the device is far from the ship. However, once the ship successfully receives the ***Lost Device Report***, it will send a ***Localization Request*** addressed to the lost device, which partly functions as an acknowledgement of the ***Lost Device Report*** and the device will stop transmitting the ***Lost Device Report***.

*Why try to collect localization information in quadrants?*

The cloud has the advantage of being able to aggregate localization information collected by several ships at different times in the localization process to yield a very accurate position estimate for a device. The best localization occurs when the ships collecting these observations are distributed around the device. When this occurs, it is said that the "geometry" (i.e., distribution) of the observations is good. If all of the observations are collected, say, along the same bearing relative to the device (definitely not distributed all around the device), the geometry would be poor and the localization results would be inaccurate. The use of quadrants by the cloud is designed to achieve a good geometry for the best localization results.

*Why not just have everyone use USBL; isn't it more accurate?*

It is not clear that the complexity and cost of a USBL array is justified for all fishing conditions, particularly those where gear density is low. When deployed fixed gear is separated by distances of hundreds of meters, the accuracy requirement (Requirement 2) can be relaxed and need not be 8 m. In such cases, devices on the sea floor can be localized (with potentially reduced accuracy) using 1-way travel time alone (i.e., without bearing estimates provided by a USBL array; see Appendix B). One of the advantages of the localization procedure described in Appendix B is that it will work for localization observations collected both with and without a USBL array, so if some fishers in an area use a USBL array and others do not, the localization procedure will use all of their observations seamlessly to localize devices on the sea floor.

*How would this work if I was grappling or using a release timer?*

Aside from not being able to actively facilitate recovery of your gear by triggering a release mechanism, the devices will work identically for gear location marking, lost gear recovery and enforcement as they would for devices that are attached to a gear retrieval mechanism (e.g., stowed rope or lift bag). That is, you would still use a device on each of the terminal ends of your trawl, and it would allow your gear to appear on the chart plotters of other fishers and enforcement and allow your gear to be found if lost.

*Why spend so much effort on finding lost gear?*

Fishers lose fixed fishing gear, which represents a loss of time, effort, equipment and money. Some estimates suggest that as much as 10% of fixed fishing gear is lost every year. This is a substantial loss, as well as a major source of marine debris. With the addition of acoustic devices and on-demand release mechanisms, the value of that lost gear will increase. To facilitate gear location marking, gear retrieval and enforcement, the gear will already have the necessary technology to relocate the gear, and the procedures above outline an approach to using that technology to automatically notify gear owners when gear is both lost and found. This approach is expected to reduce permanent gear loss substantially.

*Can I choose the color of the trawls that show up on my chart plotter?*

Hopefully yes. The CCU receives information about nearby gear, including the owner's gear, from the cloud in the ***Nearby Gear Report***, and it has the potential to use that information to color code trawls on the chart plotter. For example, the gear owner may wish all non-owned gear to appear as gray, and each owned trawl to have a different color based on the date it was deployed (to track soak time; e.g., trawls deployed yesterday are yellow, trawls deployed 2 days ago are blue, trawls deployed 3 days ago are red, and so on). The CCU should allow the owner to configure all of this so that a color code can be sent along with gear location information from the CCU to the chart plotter via an NMEA message. The NMEA message must be defined in a way that allows this color code, and defines the color table that the chart plotter will use with the color code field.

*Does everyone have to get a USBL array for their ship?*

No. Appendix B presents simulations that help to answer this question. The simulations are designed to estimate the error in device locations when the 1-way travel time and bearing measurements (and other measurements, such as GPS-derived positions and device depth) have errors of a known magnitude. These simulations suggest that USBL arrays are needed to obtain the location accuracy specified in Requirement 2 (8 m accuracy or less). While 1-way travel times alone can often produce sufficient accuracy, they cannot do so when the distribution of observations (i.e., geometry) is poor. The only way to ensure that Requirement 2 is met is to use a USBL array. However, not all fishing conditions warrant the location accuracy specified in Requirement 2. In areas where fixed fishing gear density is low, a USBL array is likely unnecessary if the device location errors associated with collecting only 1-way travel time measurements (i.e., without bearing information) are less than the minimum distance between deployed trawls.

*Does anyone have to get a USBL array for their ship?*

Yes. USBL arrays are needed to achieve the location accuracies specified in Requirement 2 for the worst-case scenario of a fisher approaching a trawl shortly after it has been deployed with the intention of setting their own trawl close by (i.e., no other localization information is available other than that from the deploying and approaching ship; see Appendix B). The localization accuracy specified in Requirement 2 is for areas where the density of fixed fishing gear is very high, so USBL arrays will be needed in these areas to meet this requirement.

*How will a gear owner find out if their gear has been lost or found?*

Email or text message from the cloud. The cloud will know when a device is lost, because nearby ships that are directed to send it a ***Localization Request*** will get no response.

In such cases, the cloud can automatically send the gear owner an email or text, reporting the device ID and the owner's own trawl ID (reported in the Trawl Deployment Report) that has been lost. The cloud will also know when a device has been found, because it will receive a ***Found Device Report*** from a ship that has been in acoustic contact with the device (via the ***Lost Device Report*** and the subsequent ***Localization Request/Report***). The owner can be immediately and automatically notified by email or text, letting them know that the device and the associated trawl has been found, as well as the location of the ship that made contact with the formerly lost device. The gear owner can use this information to retrieve their device (and likely when they approach the device, the cloud will direct their ship to collect localization information, and they will get a very accurate position for the lost device).

*Why do we need an acoustic communication standard to make all of this happen?*

Many of the functions of the system described in this document rely on fishers' shipboard subsystems to acoustically communicate (i.e., send/receive requests and reports) with devices that they do not own. Those devices that they don't own may be manufactured by a different company or perhaps by many different companies. If all of the manufacturers' devices do not acoustically communicate in the same way, and use the same data formats when they do communicate, functions like gear location marking, localizing devices, finding lost gear, and having enforcement interrogate and haul gear, cannot work, and without these functions, the federal governments of the U.S. and Canada will not permit commercial on-demand fishing.

## 2. Acoustic communication methodology

### a. Challenges

An easy way to conceptualize two computers that communicate data between one another is to think of two people that can send text messages back and forth to one another via their cellphones. One person composes a message on their cellphone, and then their cellphone encodes the message and transmits it using electromagnetic waves sent through the atmosphere. The other cellphone receives this message, decodes it, and then displays it for the recipient to view (note that cell phone towers and other communication pathways are involved, but for this simple exercise, imagine that the cell phones communicate directly with one another). Data is sent acoustically between two computers in the ocean in an analogous way. One computer (person) forms a data packet (text message), and an acoustic modem (cellphone) encodes the message and transmits it using acoustic waves (electromagnetic waves) sent through the ocean (atmosphere). The other acoustic modem (cellphone) receives the data packet (message), decodes it, and then presents it to the other computer (person). Unlike electromagnetic waves traveling largely unimpeded at nearly the speed of light through the atmosphere, acoustic waves travel slowly and can be altered by many processes in the ocean. Much effort has gone into studying these processes and the challenges they present to reliable underwater data communications. The five principal challenges are background noise, transmission loss, multi-path, multi-access and range rate, and each of these will be discussed briefly below. Any acoustic communication system for on-demand fishing must take into consideration these challenges and provide solutions to overcome them.

Just as it is difficult to understand a person speaking to you in a crowded room, background noise can interfere with the successful detection and decoding of acoustic transmissions. Noises can come from a variety of sources, including biological (e.g., snapping shrimp) and anthropogenic sources (e.g., ship noise), but they have the same effect: to reduce the signal-to-noise ratio, making the signal (i.e., transmission) harder to distinguish from the noise. There are several ways to accommodate this noise, such as choosing an acoustic frequency with which to transmit data that is outside of the major sources of noise, or increasing the source level of the transmitter (akin to simply talking louder in a crowded room).

Transmission loss very simply refers to how the energy in sound is attenuated by the medium it is traveling through so that the loudness of the sound decreases with distance from the source. Transmission loss, background noise and how loudly a sound is produced affect how far away that sound can be successfully detected and the information contained therein understood (commonly referred to as the detection range). This can be imagined as someone talking to you and how well you understand what they are saying. If the person is speaking softly, for example, you may not even hear them, or perhaps you hear the sound of their voice, but you can’t understand them. One reason you cannot understand them is because the sound is attenuated by the atmosphere (absorbed and scattered such that the loudness of the speaker’s voice is decreased), and this attenuation increases with distance; if the person is far away from you, your chances of understanding them are decreased because of this attenuation. Another reason you may not understand them is because your hearing is not very good. These same phenomena occur in the ocean during acoustic communications between modems; the ability of an acoustic modem to detect and decode a transmission from another modem depends on how loud the transmission is, how much the ocean attenuates the signal and how well the receiver performs in detecting and decoding the transmission. As in the case of overcoming background noise, one solution to the problem of poor detection range is increasing the source level of the transmission (akin to the speaker talking louder). Because attenuation varies with frequency in the ocean (higher frequencies attenuate more than low frequencies), another solution is to transmit sound at a lower frequency. By knowing the desired detection range for a particular application, the source level and acoustic frequency of transmissions can be chosen to account for transmission loss and ensure reliable acoustic communications.

As described in Section 1, the multi-access problem involves several sources attempting to communicate with a single receiver at once, such as when several children answer a teacher's question simultaneously. With multiple sources, the chances of understanding what each source is communicating is diminished. There are numerous ways to handle multi-access; in the example above, the teacher may insist that each child raise their hand so that they can be called upon one at a time to respond. Any system of acoustic communication between ships and devices must implement a solution for multi-access, since many devices will be able to detect and decode transmissions from a nearby ship and will therefore have the potential to interfere with one another if they respond simultaneously.

Multi-path refers to the fact that sound has many ways (paths) to get from a transmitter to a receiver, and some paths take longer than others such that the receiver experiences many arrivals of the same sound, all differing a bit in the time that they arrive. A common example of this is yelling "Hello" in a canyon, and hearing several "Hellos" echoed back to you as the sound of your voice bounces off rock faces farther and farther from you. Multi-path goes by many names, including reverberation and echoes. In the ocean, sound can bounce (i.e., reflect) off the sea surface, off the sea floor, and sometimes off interfaces between different water masses in the interior of the ocean. Multi-path can play havoc with the acoustic communication process (specifically demodulation), so using approaches like broadband frequency hopping is needed to overcome it (see below).

The challenge of range rate (which refers to the rate of change in range between the source and receiver over time) encompasses two phenomena that occur when sound is produced or received by a moving platform: (1) the shifting of frequency (commonly known as Doppler shift), and (2) the perceived compression or dilation of time. Doppler shift can be experienced by listening to a train whistle or police siren as it passes by you; the sound increases in pitch (frequency) as the sound source approaches you and decreases in pitch as it recedes away from you. To understand compression or dilation of time, consider a person who yells "Hello there" to you while riding a bike quickly toward you. When the person says "Hello", they are 30 feet away from you, but when they say "there", they are only 25 feet away. The word "there" has less distance to travel to reach your ear than if the person were stationary, so it will seem to you as if the gap in time between the "Hello" and the "there" is just a bit shorter than normal. Conversely, if they did the same while pedaling away from you, the gap between the words would seem a bit longer than usual (this phenomenon is actually exploited for underwater localization in SART by Baumgartner and Partan [2021]). Range rate is critical to address for on-demand fishing because fishing vessels rarely stand still; most operations are conducted while the vessel is moving, and any system that requires the fisher to regularly stop their vessel to improve acoustic communications is infeasible.

These challenges were considered when developing the acoustic communication methodology for the on-demand standard described in general in this section and in detail in Appendix C. The goal of the standard is to ensure as reliable communications as possible so that ships and devices do not need to repeat transmissions, thus minimizing acoustic noise (Requirement 7b) and maximizing battery life of the devices on the sea floor (Requirement 8a). The open standard documented here is intended as a proposal for how acoustic communication should be accomplished between devices produced by different manufacturers to enable the gear location marking, lost gear recovery, enforcement and gear retrieval functions described in Section 1. The proposed standard represents the authors' independent and expert opinion on the methodology that will achieve the most reliable acoustic communications, and while we expect the foundational structure of the standard (i.e., frequency hopping with binary frequency-shift keyed modulation) will remain the same, we anticipate that some details of the standard may be refined and clarified in the near future through a process of community input. We very much welcome and look forward to that input.

**b. Overview**

The proposed acoustic communication standard is simple, robust and loosely based on the open acoustic communication standard JANUS. As mentioned above, we call the new standard FONTUS because of its relationship to JANUS, as Fontus was a child of the Roman god Janus. The standard allows data to be sent between two acoustic modems in packets. Each packet consists of (1) an initial synchronization signal, (2) a fixed preamble, and (3) the encoded data message. An optional encoded cargo message is included in the standard if the size of the data to be sent is larger than 56 bits, the specified size of the un-encoded data message portion of the packet. Frequency hopping (described below) over a 7,520 Hz band centered at 25 kHz is utilized for all packet components except the initial synchronization signal. Data messages delivered to or generated by an acoustic modem for communication to another modem (e.g., a ***Localization Request*** message generated by the CCU and sent from the ship to a device on the sea floor via the ship's acoustic modem, or a ***Localization Report*** sent from the device to the ship) are transformed in two steps, encoding and modulation, prior to being transmitted into the ocean via the transducer.

The encoding step provides a means to account for the changes in the transmitted signal caused by the ocean (including from the challenges described in Section 2a) that will cause multiple errors in reception. An analogue to this step is a speaker slowing their speech, enunciating words carefully and repeating some of their message in a very noisy room to ensure that the person to whom they are speaking can understand exactly what they are saying. The listener may not perfectly decipher each syllable spoken, but they will understand the message. In the same way, the encoding step provides redundancy (repetition) that allows the receiving system to successfully recover the original data message despite transmission errors. The standard uses convolutional forward error correction coding and interleaving to provide data redundancy and to facilitate error identification and correction upon reception. Additionally, a cyclic redundancy check (CRC) is used so that the receiver can verify that the decoding process successfully removed all errors and the received data message is identical to the one that was originally sent.

The modulation step converts the encoded data message into an acoustic signal that can be transmitted into the ocean via the transducer. The encoded message is binary and therefore consists simply of a list of zeros and ones. A short tone (sinusoidal signal with constant frequency) lasting 12.5 milliseconds is created for each binary value in the list. The tone's frequency relative to a central frequency indicates whether the binary value is a 0 or a 1: if the frequency is offset below the central frequency, the binary value is 0, but if the frequency is offset above the central frequency, the binary value is 1 (see Figure 21b below). This way of representing the binary data is called binary frequency-shift keyed (BFSK) modulation. The modulation also employs frequency hopping (FH) to account for the challenges of multi-path, multi-access and narrowband background noise (see section 2c for a detailed explanation of why frequency hopping is used in the standard). Frequency hopping simply means that the central frequency for each entry in the list of binary values changes in a predictable pattern that is known to both the source and the receiver. Thus, if the encoded data message consists of 100 bits (i.e., 100 binary values), then the acoustic signal for that encoded data message will consist of one hundred contiguous 12.5-millisecond tones lasting 1.25 seconds, and the central frequencies of the tones will be distributed over the entire bandwidth of the system (over 7,520 Hz centered at 25 kHz). The acoustic signal is then converted from digital to analog voltage, amplified and transmitted into the ocean via the transducer.

At the acoustic modem receiving the message, the acoustic signal will be sensed by the transducer, converted from an analog voltage signal to a digital signal, and de-modulated to retrieve the bits making up the encoded data message. De-modulation requires the receiver to know exactly when in the acoustic signal each tone is produced, and at what frequency to expect each binary value. To do so, the receiver needs to detect the very beginning of the message (see below) and to know the frequency hopping pattern of central frequencies. With these, the receiver can compare each detected tone with the expected central frequency, and if the detected tone is offset below that central frequency, it will assign a binary value of 0 and if above, it will assign a binary value of 1. In this way, the encoded message is recovered from the acoustic signal, and it can now go through the decoding process, which will recover the original data message from the encoded message. This process involves de-interleaving and decoding (with error correction) using a maximum likelihood decoder. The final step utilizes the CRC to verify that the decoded data message is identical to the original data message encoded by the source.

To successfully de-modulate the acoustic signal, the demodulator needs to know the exact time when the first tone occurs. To do so, the modulator prepends 32 tones to the modulated acoustic signal in a frequency hopping pattern known to both the source and the receiver (this 32-tone sequence is referred to as the "preamble"). The modulated binary values represented by these tones are fixed; they never change, and are therefore amenable to detection by the receiver to synchronize the demodulation. The acoustic signal immediately following these initial 32 tones comprises the modulated data message, so once the demodulator identifies the 32 tones, the 12.5 milliseconds of acoustic data immediately following the preamble will contain the first tone of the modulated data message.

While the process of demodulation and decoding is likely robust to range rates of about 5 knots, it will begin to fail above that range rate because of Doppler effects and time compression/dilation. To account for this, a hyperbolic frequency-modulated (HFM) waveform is prepended to the acoustic signal (prior to the 32-tone preamble described above) to facilitate the detection of the beginning of the acoustic signal. The HFM waveform is insensitive to range rate, and therefore is a good signal to serve this purpose. The demodulator uses a matched filter to detect the HFM waveform, and because it now knows where the 32-tone preamble begins in the acoustic signal (following the HFM waveform), it can then perform an analysis of the preamble to estimate the range rate. This analysis again uses a matched filter to compare the measured preamble to what the preamble would look like under many hypothesized range rates. The range rate associated with the best match is now used to correct the rest of the acoustic signal (i.e., the part of the acoustic signal that contains the encoded data message). Once this correction is complete, the acoustic signal can be demodulated and decoded as described above.

Appendix C provides all of the details of the proposed acoustic communication standard, as well as references to Matlab code to implement and test the standard, so the reader is referred to Appendix C for a more detailed description.

### c. Justification

*Is this standard a form of broadband communication?*

Yes, the fact that the central frequency of the tones “hops” over a broad range of frequencies is what makes it a broadband communication method.

*What is the difference between broadband and narrowband communication?*

As the name implies, narrowband communication occurs over a much narrower band of frequencies than broadband. Although there are many forms of narrowband modulation, an example of one narrowband communication method is shown in Figure 21 alongside a FH-BFSK broadband method that is nearly identical to the one used in the FONTUS standard (the broadband method shown in Figure 21 uses a wider frequency range than FONTUS just to improve the visualization). Figure 21a shows a spectrogram (a visualization of how the frequency of sound changes over time) of a narrowband signal transmitting binary values (ones and zeroes) using BFSK and a single central frequency of 25 kHz. As in FONTUS, the binary value is modulated as a short tone whose frequency is either offset below the central frequency (representing a zero) or offset above the central frequency (representing a one). A short time gap is introduced between the tones to accommodate multi-path (i.e., reverb or echoes). Figure 21b shows the exact same binary sequence modulated with frequency-hopping (FH) BFSK, where the central frequency for each tone changes in a predictable pattern known to both source and receiver.

Figures 21c and 21d show these two acoustic communication signals in the presence of significant multi-path, which causes the tone to be extended in duration beyond the 12.5 milliseconds of the original tone (i.e., the tone bounces off the sea surface, sea floor or other structures, causing different paths of the sound to arrive later and extending the duration of the tone). The narrowband signal is much more susceptible to multi-path than the broadband signal, since the broadband signal is spread out over many frequencies and the reverberation (extension of the tone) does not interfere with succeeding tones. In contrast, reverberation of

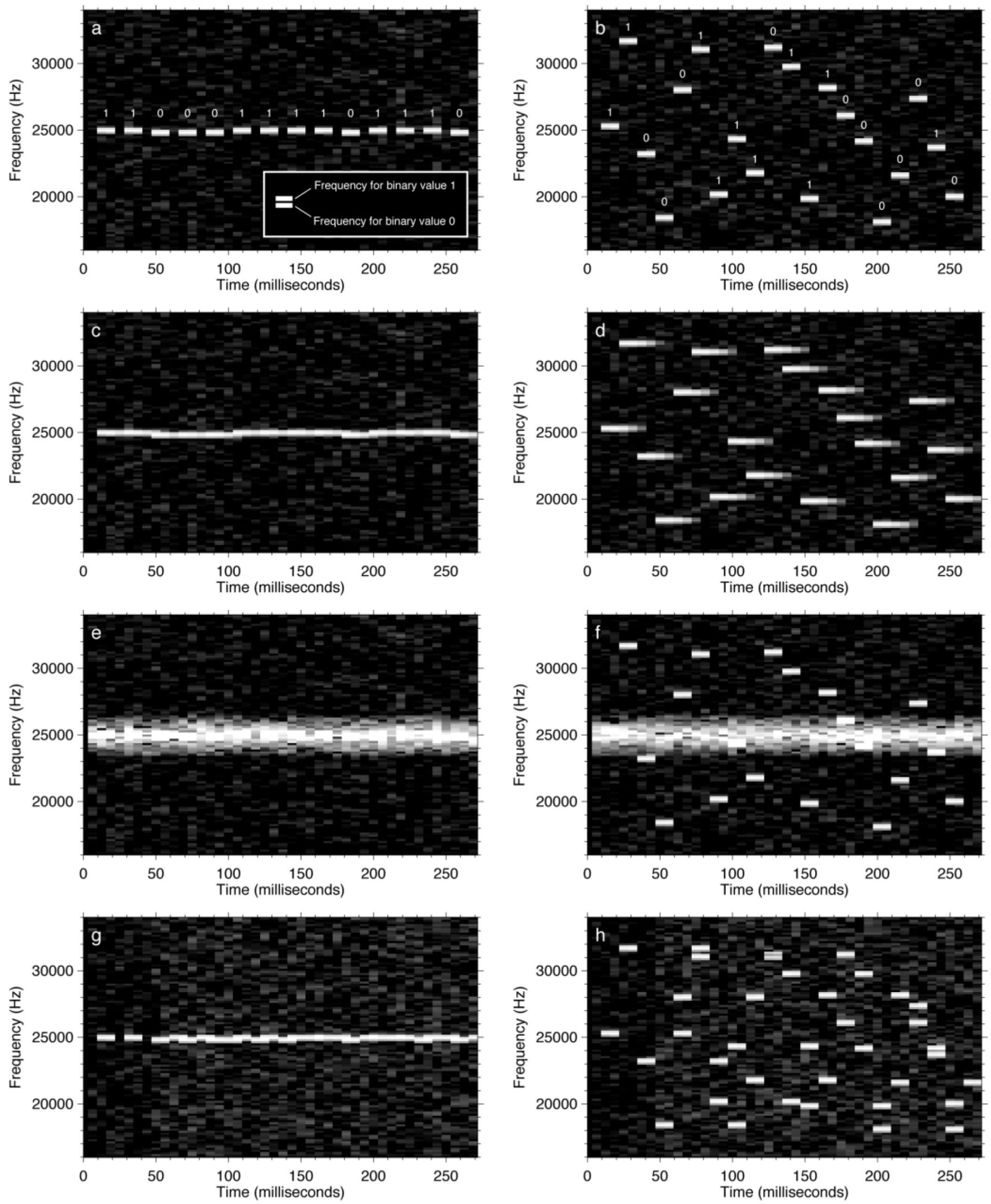


*Figure 21. Example spectrograms of acoustic communication tones used for (a) a narrowband modulation and (b) broadband modulation. Light areas indicate loud sounds, dark areas indicate background noise. For each modulation (narrowband or broadband), a binary value of 0 or 1 is represented by a short acoustic tone at one of two frequencies offset below (for binary value 0) and above (for binary value 1) a central frequency (e.g., in the plots above, binary values 0 and 1 are ±80 Hz around a central frequency). For narrowband modulations, the central frequency is fixed, but for broadband modulations, the central frequency changes (hops) for each transmitted value in a pattern known to both the transmitter and receiver. Note that the narrowband modulation in (a) includes a short pause between transmitted values to accommodate multi-path; no pause is needed for broadband modulation. Finally, the frequency range (i.e., bandwidth) of the broadband modulation in (a) is wider than what is proposed for Fontus; it was widened only to improve the visualization. The influence of multi-path (c, d), narrowband noise (e, f), and multi-access (g, h) on the narrowband and broadband modulations is shown.*

one tone can interfere with succeeding tones for a narrowband transmission, making the tones more difficult to detect and successfully demodulate. The narrowband transmission method illustrated in Figure 21a includes a time gap between tones in an attempt to accommodate a modest level of multi-path, but this has the drawbacks of (1) reducing the data communication rate (fewer tones are sent per second) and (2) if the multi-path produces reverberations that are longer than the gap, those reverberations will affect the succeeding tones. The need for the time gap in narrowband communications is why broadband communications can achieve higher transmission rates, which means transmissions are shorter in duration when compared to narrowband communications.

Figures 21e and 21f show the effect of a narrowband background noise (i.e., noise that occurs persistently in a narrow range of frequencies) on both of the communication signals. Narrowband transmissions can be very susceptible to interference with this kind of background noise; in Figure 21e, the communication signal is completely obscured. By including tones that occur over a broad range of central frequencies, only a portion of a broadband transmissions would be affected by such noise (Figure 21f). Because FONTUS includes data redundancy (i.e., duplication of data bits) as part of the error correction scheme, losing some of the tones to interference by narrowband noise does not preclude the successful decoding of the message.

Finally, Figures 21g and 21h demonstrate the effects of multi-access on the two communication methods, namely, two messages being sent simultaneously, one 50 milliseconds after the other (4 times the tone length). In the case of a narrowband transmission, the two messages interfere completely with one another, making neither message decipherable. With the broadband transmission, the frequency hopping approach allows the messages to be easily distinguished from one another. As with the background noise example shown in Figure 21f, if some tones from the two messages do happen to interfere with one another, the built-in data redundancy and error correction capabilities of FONTUS will still allow the first message to be successfully demodulated and decoded. By way of example, if the two transmissions shown in Figure 21h were being sent from a device on the sea floor to a ship (e.g., both are ***Lost Device Reports*** sent in response to a ***Lost Device Request*** from the ship), the ship will successfully demodulate and decode the first message, but the second message may need to be repeated unless the ship's modem is capable of demodulating and decoding more than one acoustic message at a time (to reduce complexity, it is recommended that the standard not include detection, demodulation and decoding of multiple messages simultaneously at this time). This is why it is important to provide additional multi-access protection by increasing and randomizing the response delay between receiving a ***Lost Device Request*** and sending a ***Lost Device Report***, which should greatly reduce the chances of needing to repeat transmissions.

*Why not use both narrowband and broadband in the standard?*

There are already many different acoustic systems available among on-demand manufacturers, most of which were designed for triggering a release mechanism and not for the other acoustic functions described in Section 1 (e.g., gear location marking, recovering lost gear, enabling enforcement to query and trigger the release of on-demand gear). While some of these systems use narrowband and others use broadband communications, there are important additional differences among these systems beyond narrowband vs. broadband, including the use of different frequency bands and different encoding and modulation methods. Simply making transmission and receiving systems that can accommodate narrowband and broadband signals is insufficient; these systems would also have to be able to accommodate multiple frequency bands and multiple encoding/modulation methods as well (likely requiring multiple transducers, too). Even if such a system were feasible, each manufacturer will still need to do substantial development work to adapt their acoustic systems to incorporate the functionality described in Section 1 to enable gear location marking, lost gear recovery and enforcement operations. Because narrowband communications are not suitable for the on-demand application because of the challenges of noise, multi-path and multi-access (described above and in Figure 21), it is more efficient to develop, easier to regulate, and easier to maintain an open communication standard based on the most reliable acoustic communication method for the on-demand application.

*Why use frequency hopping?*

By moving (hopping) the central frequency after a tone is transmitted, any reverberation (multi-path) that extends the duration of the received tone beyond the 12.5 millisecond transmitted duration won't interfere with the reception of the next tone, since it will occur at a different frequency (Figure 21d). Frequency hopping also provides protection from narrowband noise by transmitting tones at central frequencies that are outside the noise band (Figure 21f). Even if some of the tones fall in the noise band, the data redundance and error correction methods used by FONTUS will allow the transmission to be successfully decoded. Finally, the frequency hopping approach makes the system robust to the multi-access problem; if two modems are communicating at the same time, but are offset in time by just a bit, they will likely be transmitting tones at different frequencies and therefore won't interfere with one another (Figure 21h; this is a type of code-division multiple access or CDMA method, commonly used in mobile phone communication standards). Any interference that might occur if the two modems happen to transmit at the same frequency at the same time should be remedied by the data redundancy and error correction procedure. This is why frequency hopping is characterized as robust to multi-path, noise and multi-access. In practice, the system described in Section 1 uses the cloud to manage the multi-access problem by addressing each device individually when sending ***Localization Requests***; however, responses from ***Lost Device Reports*** do not have foolproof system-level multi-access protection, so this feature of frequency hopping may be useful for successfully detecting and decoding ***Lost Device Reports*** when multiple devices respond together.

*Why use a 25-kHz center frequency; why not a lower or higher frequency?*

The U.S. International Traffic in Arms Regulations (ITAR) specifies that any device communicating with "an acoustic carrier frequency outside the range from 20 kHz to 60 kHz" is considered a controlled item (ITAR is designed to prevent sensitive technologies or methods from being used by potential military adversaries). As such, we have chosen the lower end of this allowable frequency range because (1) the acoustic detection range at 25 kHz (roughly 2 km) is appropriate for gear location marking, recovery of lost gear, and gear retrieval, (2) addressing the range rate problem is much easier at 25 kHz than at higher frequencies, and (3) audio sampling rates and associated processing load for both acoustic communications and bearing estimation with a USBL array are comparatively low at 25 kHz than at higher frequencies, which reduces the power consumption of the modem's digital signal processor (which, in turn, extends battery life). A center frequency of 25 kHz with a bandwidth of 7,520 Hz means that frequency hopping will occur between 21,240 – 28,760 Hz, the lower of which is at the highest end of the hearing range of right whales (Parks et al. 2007) and most other baleen whales. As such, the acoustic transmissions of the acoustic modems will be inaudible to baleen whales.

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# Workshop on Buoyless Fishing Gear Location Marking Methods

*Report on Stakeholder Engagement Meetings*

*August 2021*

Mark Baumgartner (Woods Hole Oceanographic Institution), Leah Baumwell (The Pew Charitable Trusts), Elizabeth Baker and Sean Brillant (Canadian Wildlife Federation)

A report to the Ropeless Consortium

ropeless.org

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### Abstract

Identifying the location of fixed fishing gear on the sea floor to avoid gear conflict is one of the principal technical challenges in the development of buoyless fishing. Agreement on a single gear location marking method that can be developed by multiple manufacturers is needed, so a workshop will be convened in September 2021 to allow fishers, enforcement, regulators, and other stakeholders to (1) agree on a list of requirements for a gear location marking system for buoyless fishing, (2) evaluate various methods with respect to those requirements, and (3) choose a method that best meets the requirements. Interviews were conducted with stakeholder groups between August 2020 and March 2021 to develop a list of preliminary requirements, and an initial assessment of the four methods of gear location marking with respect to the preliminary requirements was completed. This report describes the workshop goals and process, stakeholder interviews, preliminary requirements, gear location marking methods, and the initial assessment of those methods. The report is intended to facilitate discussion and efficient decision making during the September 2021 workshop.

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## 1. Introduction and purpose

Buoyless (also called ropeless or on-demand) fishing systems eliminate the need for persistent surface buoys and vertical end lines from trap/pot fishing gear. For buoyless fishing systems to be suitable for commercial fisheries, they must replace the role that persistent surface buoys play in marking the location of fishing gear on the seafloor.

Since 2018, there has been considerable progress in the development of buoyless fishing systems (e.g., bottom-stowed rope, lift bags). There has, however, been less progress in the development of technology to mark the location of buoyless fishing systems on the seafloor. Gear location marking is required to prevent conflict between fishers using buoyless systems, and between different fisheries (e.g., mobile and fixed-gear). NOAA Fisheries identified gear location marking as the principal challenge to advancing buoyless fishing in 2010, and it remains largely unsolved today.

The greatest obstacle to developing a commercially viable gear location marking system is the universal adoption of a single method to locate gear on the seafloor. There are several proposed methods, including the use of GPS marking, acoustic ranging, directional acoustic ranging, and acoustic self-localization. GPS marking has been implemented by several manufacturers of buoyless fishing systems, but none of the proposed methods have been rigorously reviewed to determine if they meet the needs of industry, enforcement, and regulators. Furthermore, there has been no formal comparison of the various gear location marking options to determine which best meets those needs.

The decision of which gear location marking method to adopt must be made as a community of fishers, enforcement, and regulators, with input from engineers, scientists, conservationists, and gear manufacturers. It is unlikely that any government agency will impose a specific method in the near term. Moreover, it is undesirable for any single manufacturer to choose and implement a proprietary method for their gear alone, because cross-communication among different buoyless systems is crucial for preventing gear conflict and for keeping the technology affordable for fishers through manufacturer competition. Choosing an appropriate gear location method is the joint responsibility of fishers, enforcement, regulators and other interested stakeholders (e.g., manufacturers, conservationists, scientists, engineers).

In September 2021, we will host a workshop for members of this community to discuss and select a single gear location marking method that will meet the needs of fishers, enforcement and regulators and can ultimately be developed by technology companies for use in buoyless fishing. Prior to the workshop, we conducted 17 interviews with groups of stakeholders to understand the requirements of a gear location marking system. These interviews focused on how buoy-based gear location marking works today for fishers and enforcement, as well as how buoyless gear location marking might work in the future. This report (1) explains the workshop process, (2) summarizes the interviews, (3) provides a preliminary list of requirements for gear location marking based on the results of the interviews, (4) describes the available gear location marking methods, and (5) offers an initial assessment of these gear location marking methods relative to the preliminary requirements.

## 2. Workshop

Workshop goals

The Workshop on Buoyless Fishing Gear Location Marking Methods is intended to be an opportunity for the community to discuss and to decide which gear location marking method will work best. Through this Workshop, we seek to gather fishers, enforcers, regulators, engineers, scientists, conservationists, and gear manufacturers from the U.S. and Canada to:

- **(1)** Discuss and agree upon the requirements for gear location marking
- **(2)** Evaluate various gear location marking methods to decide which method best meets the requirements identified by users and stakeholders
- **(3)** Form a technical working group to formally develop and document the specifications for the adopted method

Workshop process

*Preliminary requirements*

Prior to the workshop, a preliminary list of requirements has been compiled through interviews with stakeholder groups. **This report describes the preliminary requirements identified during these interviews.**

*Final requirements*

The preliminary requirements will be collectively reviewed and discussed at the workshop to establish a final list of requirements for a gear location marking system for buoyless fishing.

*Evaluation of gear location marking methods*

Each method of gear location marking (described in Section 5 of this report) will be presented and examined with respect to the final requirements. The evaluation will use a matrix identical in format to Table 4 in Section 6 of this report. Based on the results of this evaluation, workshop participants will decide which method best meets the requirements.

*Technical working group*

The last task of the workshop is to form a small technical working group. The purpose of this group is to develop detailed specifications for devices that can meet the final requirements using the agreed-upon gear location method. It is expected that the working group will enlist the help of technology experts to complete the specifications.

> The specifications will be documented and circulated to the workshop participants for feedback, and once approved by the workshop participants, these will be made publicly available for manufacturers to begin research and development (R&D) activities.

The workshop is intended to spur innovation and development of a gear location marking solution, but it is recognized that this may take several years and an investment of time and resources to design, prototype and test. As a result, it is also expected that interim gear location marking solutions that may not meet all of the community's requirements will be necessary in the short-term to allow continued development and testing of buoyless systems in small-scale experimental fisheries. The workshop is intended to focus solely on the long-term solution for buoyless gear location marking.

## 3. Stakeholder engagement meetings

To develop the preliminary list of requirements for a gear location marking system, 17 meetings were held between August 2020 and March 2021 with stakeholder groups that included fishers from different sectors (e.g., inshore, offshore, lobster, snow crab, mobile), fisheries associations, fisheries regulators, enforcement, scientists, engineers, non-governmental organizations and gear manufacturers from both Canada and the United States. A total of 76 people participated in the interviews. The meetings were held virtually, and participants were informed that the organizers were not acting on behalf of any government agency nor being funded for their effort.

A set of standard questions were posed to each group (Table 1), recognizing that some groups may not have the ability to answer all questions. Participants were encouraged to reflect on the fisheries with which they were most familiar, but to also give responses appropriate for a gear location marking solution that could be used for all fisheries. Participant names can be found in Appendix 1. Notes from the interviews (Appendix 2) are available upon request from the report authors; no participant names have been attributed to any comments in the notes.

Table 1. Questions posed during stakeholder interviews.

| Function | Question |
|---|---|
| Detection distance | At what distance away from gear do you want/need to be able to detect it? |
| Location accuracy | What location accuracy is needed for localizing the position of the gear? How far apart is gear typically set in your area? How far apart does gear need to be to avoid gear conflict among fixed fishers in your area? |
| Data display at sea | When at sea, how do you want to view the location of gear on the sea floor (e.g., chart plotter, separate fixed display, tablet, smartphone)? |
| Additional information to collect and share | What information do you want/need from a marking system besides the location of gear? |
| Data sharing | Should information about currently set gear be available in a shore-side database? If information about currently set gear was available in a shore-side database, who should have access to that information? Do you want/need access to gear location information when not at sea? If you are a fisher, do you want/need information on the location of your gear when not at sea? |
| Lost gear | Do you want/need the marking system to assist in locating lost gear? If so, how? |
| Environmental impacts | What environmental impacts of a gear location marking system are acceptable? Which impacts are not acceptable? What impacts, if any, should be minimized? |
| Battery endurance | For gear location marking devices that are attached directly to trawls/traps, how long do you need/want them to work before the batteries need to be replaced or recharged? |

## 4. Preliminary requirements

The following briefly summarizes what we learned from each set of interview questions, and reports the preliminary requirements we developed based on participant responses. The preliminary requirements are summarized in Table 2.

We have not included cost as a preliminary requirement, as that is very difficult to assess at this early stage of development. Additionally, most gear retrieval devices use an acoustic device to trigger the release of stowed rope or a lift bag. This acoustic device can be used for gear location marking, and the additional cost of including a localization method in this device may be minimal.

### Detection Distance

*Discussion:* Fishers need to detect both ends of a trawl simultaneously to understand the entire trawl's location and orientation, so detection distance is related to the trawl length.

*Requirements:*

- For inshore fisheries where trawl lengths are shorter (e.g., 0.25 miles), a minimum detection distance of 0.5 nautical miles is required.
- For offshore fisheries where trawl lengths can reach 1.5 miles, a minimum detection distance of 2 nautical miles is required.

*Alternatives:* Some offshore fishers suggested a detection distance of 3 miles would be best, but current detection distances of buoys, high fliers or radar reflectors are sometimes less than 3 miles.

*Potential Solutions:* For acoustic-based gear location marking, source level (i.e., the loudness of the acoustic transmissions) could be user-configurable so that in areas with longer trawls, the source level could be increased to increase detection range.

### Location Accuracy

*Discussion:* Requirements for location accuracy are related to the density of fishing effort (i.e., the number of trawls in a given area, or equivalently, the distance between trawls). The denser the fishing effort, the higher the accuracy required. Mobile fishers do not need any higher accuracy for a fixed gear location marking system than required by fixed fishers. In some of the densest areas, fishers are setting trawls within tens of feet of other trawls.

*Requirements:*

- Location accuracy of at least 25 feet (~8 meters) is required.

*Alternatives:* In areas with low gear density, lower accuracy (50-100 feet) is likely acceptable; however, setting different accuracy standards in different zones may be difficult to manage.

<u>Data Display at Sea</u>

*Discussion:* All fixed fishers expressed a preference to see gear location information at sea on their chart plotter.

*Requirements:*

- Gear location information, including location and orientation of trawls, must be displayed on a chart plotter.

*Alternatives:* There was very modest support among fishers for displaying gear location data on a computer, and almost no support for viewing these data on a smart phone or tablet (although other groups, such as enforcement, may like to have the option of displaying data on a computer or tablet).

<u>Additional Information to Collect and Share</u>

*Discussion:* The gear location marking system should transmit not only gear location information, but other information important to gear owners, enforcement, and regulators.

*Requirements:*

- The gear location marking system must provide ownership information (state/federal permit/license numbers, owner identity), gear type, unique system identifier, number of traps on trawl, length and orientation of trawl, and date/time gear was deployed (from which soak time can be calculated).

*Alternatives:* Some fishers expressed interest in collecting and transmitting environmental data, such as information on water temperature and ocean currents.

<u>Data Sharing</u>

*Discussion:* The gear location marking system will collect data on gear location, ownership, configuration, etc., that will be helpful for gear owners, enforcement and fishery regulators. Fishers and enforcement need access to some or all of these data when at sea and when on shore as well. Fishery regulators will want access to some form of these data on shore, but they do not require immediate access, and anonymized and summarized versions will likely suffice for them. Clear distinctions between public (e.g., gear location, trawl orientation) and private data (e.g., owner name) should be made, with private data encrypted for access only by gear owners and enforcement.

*Requirements:*

- Gear location information must be available to fishers and enforcement in real time on scene at sea (i.e., within the detection distance of the system) to avoid gear conflict.
- Real-time location information must mirror reality (i.e., locations must be associated with actual gear on the sea floor, and a lack of locations must be associated with no gear on the sea floor).
- The ends of trawls must be marked in a way that is not voluntary.
- All data (including location, state/federal permit/license numbers, owner identity, gear type, unique system identifier, number of traps on trawl, length and orientation of trawl, and date/time gear was deployed) must be available to enforcement in real time on scene at sea (i.e., within the detection distance of the system) as well as shared in near real time (within some prescribed time after deployment; e.g., 18 hours) with enforcement on shore (e.g., in an enforcement-accessible cloud database).

*Alternatives:* Some (but not all) fishers expressed an interest in seeing the location of their gear while they are on shore (note that providing location information access to gear owners is required for recovering lost gear; see “Lost Gear” section below).

Some fishers expressed an interest in knowing where their and others’ gear was located while on shore prior to going to sea to save time and fuel when planning where to set/move gear. However, most fishers had serious reservations about making the location of their gear accessible to other fishers.

Some fishers expressed an interest in knowing the owner’s identity of other fishers’ gear to resolve gear conflicts or territoriality issues, and some fishers expressed a willingness to provide that information.

*Potential Solutions:* Layers of access together with encryption should be implemented so that data is only shared with appropriate parties. For example, all data is to be shared with gear owners and enforcement, whereas gear location and trawl length/orientation information is to be shared with all users when on scene at sea. Encryption can be used to keep owner data private and accessible only by the owner and enforcement.

A solution to fishers sharing gear ownership or location data with other fishers is to make sharing voluntary (default is no sharing, but fishers can "opt in" to sharing their ownership data).

Lost Gear

*Discussion:* Buoyless fishing causing an increase in the amount of ghost gear was a concern raised by most stakeholders. For some fishers, losing gear is not a serious problem in their area, so having a means to locate and recover lost gear was not a priority. For other fishers, lost gear and lost catch was a significant problem and a significant cost. Some fishers also suggested that the elimination of buoy lines would greatly reduce the chances of gear moving, so lost gear would become less of a problem. Enforcement agencies recover derelict gear; with a means for owners to relocate and recover their own gear, this may relieve enforcement of this task and free up resources for other tasks. The rate of gear loss is frequently quoted to be 10% per year, and at the very least, a suitable gear location marking system should be no worse than this.

*Requirements:*

- The gear location marking system must be able to provide an accurate location for gear even if the gear has moved (e.g., because of storms or being dragged by a mobile fisher).
- The gear location marking system should provide a means for gear that has moved to be relocated and retrieved by the owner.

*Potential Solutions:* An on-shore cloud database that makes gear location data accessible to gear owners in near real time would allow owners to be alerted if their gear was encountered by other fishers in someplace other than the location at which it was deployed.

Environmental Impacts

*Discussion:* Concern was expressed by most stakeholders over the introduction of noise into the environment by acoustic-based gear location marking systems. Concerns were also expressed over potential pollution from plastics, batteries, toxic components and heavy metals if gear was lost (this concern is addressed in the "Lost Gear" section above).

*Requirements:*

- The gear location marking system should (1) minimize the use of disposable plastics, (2) minimize acoustic noise, (3) choose acoustic frequencies and source levels that minimize effects on marine mammals, fish, and shellfish.

<u>Battery endurance</u>

*Discussion:* Devices attached to the ends of trawls will need to be serviced, and in particular, batteries will need to be replaced or recharged. Interviewed fishers provided a range of values for minimum battery life, from 3 months to over a year (depending on their fishing seasons). Battery life is likely going to be a feature with which device manufacturers compete against one another (similar to battery life on smartphones).

*Requirements:*

- Any gear location marking device that is affixed to submerged fishing gear must have an endurance of at least 6 months.
- Battery condition (e.g., voltage, charge status) of the gear location marking device must be easily interrogated.

*Alternatives:* Endurance of over a year would be preferred.

<u>Other</u>

*Discussion:* Other requirements emerged from the interviews that were not part of the original question list.

*Requirements:*

- Acoustic-based gear location marking devices must be able to activate whatever gear retrieval mechanism to which the device is attached (e.g., lift bag, bottom-stowed rope).
- The gear location marking system must be capable of sharing data in real time across international boundaries to avoid gear conflict and assist enforcement in these sensitive areas.
- A manufacturer's gear location marking device must be able to communicate with all other manufacturers' gear location marking devices using adopted standards.

*Alternatives:* Ultimately a registry for gear location marking devices will likely be needed so that their ownership can be tracked for enforcement purposes.

Table 2. Summary of preliminary requirements for a gear location marking system.

| **Function** | **Preliminary requirement** |
|---|---|
| Detection distance | For inshore fisheries where trawl lengths are shorter, a minimum detection distance of 0.5 nautical miles is required.<br><br>For offshore fisheries where trawl lengths can reach 1.5 miles, a minimum detection distance of 2 nautical miles is required. |
| Location accuracy | Location accuracy of at least 25 feet (~8 meters) is required. |
| Data display at sea | Gear location information, including location and orientation of trawls, must be displayed on a chart plotter. |
| Additional information to collect and share | The gear location marking system must provide ownership information (state/federal permit/license number, owner identity), gear type, unique system identifier, number of traps on trawl, length and orientation of trawl, and date/time gear was deployed. |
| Data sharing | Gear location information must be available to fishers and enforcement in real time on scene at sea (i.e., within the detection distance of the system) to avoid gear conflict.<br><br>Real-time location information must mirror reality (i.e., locations must be associated with actual gear on the sea floor, and a lack of locations must be associated with no gear on the sea floor).<br><br>The ends of trawls must be marked in a way that is not voluntary.<br><br>All data (including location, ownership information, etc.) must be available to enforcement in real time on scene at sea (i.e., within the detection distance of the system) as well as shared in near real time (within some prescribed time after deployment; e.g., 18 hours) with enforcement on shore (e.g., in an enforcement-accessible cloud database). |
| Lost gear | The gear location marking system must be able to provide an accurate location for gear even if the gear has moved (e.g., because of storms or being dragged by a mobile fisher).<br><br>The gear location marking system should provide a means for gear that has moved to be relocated and retrieved by the owner. |

| Function | Preliminary requirement |
| --- | --- |
| Environmental impacts | The gear location marking system should (1) minimize the use of disposable plastics, (2) minimize acoustic noise, (3) choose acoustic frequencies and source levels that minimize effects on marine mammals, fish, and shellfish. |
| Endurance | Any gear location marking device that is affixed to submerged fishing gear must have an endurance of at least 6 months.<br><br>Battery condition (e.g., voltage, charge status) of the gear location marking device must be easily interrogated. |
| Other | Acoustic-based gear location marking devices must be able to activate whatever gear retrieval mechanism to which the device is attached (e.g., lift bag, bottom-stowed rope).<br><br>The gear location marking system must be capable of sharing data in real time across international boundaries to avoid gear conflict and assist enforcement in these sensitive areas.<br><br>A manufacturer's gear location marking device must be able to communicate with all other manufacturers' gear location marking devices using adopted standards. |

## 5. Gear location marking method descriptions

A gear location marking system must fulfill two primary functions: (1) provide gear location information to fixed fishers to help them avoid laying trawls over one another and to mobile fishers to help them avoid trawling or dragging through fixed fishing gear and (2) provide gear location, ownership and other pertinent information to enforcement for monitoring and at-sea inspection. Depending on how the gear location marking system is designed, another possible function may be to provide fishing effort information to fishery managers.

Currently, there are four methods of gear location marking that have the potential for application in buoyless fishing: (1) GPS marking, (2) acoustic ranging, (3) directional acoustic ranging and (4) successive acoustic receive time (SART) self-localization. To provide a base of understanding of the available methods, we include a brief explanation of each of the gear location marking methods below as well as their pros and cons. A comparison among the different methods is provided in Table 3.

GPS marking

*System requirements:* (1) A GPS, (2) real-time at-sea data communications (e.g., cellular, satellite) and (3) on-shore data system to collect, store and distribute location, ownership, and enforcement data.

*Localization principle:* The location of each end of the trawl is measured as the GPS locations of the vessel when each end of the trawl is deployed (i.e., the surface location when they leave the vessel's deck). That location data must be transmitted to the on-shore data system along with ownership and enforcement data so that the location data is immediately accessible to other fishers, and ownership and enforcement data is accessible to enforcement.

*Pros:*

- Very simple and makes use of a well-understood technology (GPS).
- Produces no acoustic noise whatsoever.
- No device is attached to the ends of the trawl, so no maintenance of a trap marker is required (e.g., there are no batteries to replace).

*Cons:*

- No actual marker or physical device is attached to the gear to communicate its location; the marker is virtual and must rely on some other means of communicating the location of the gear in real time (e.g., an at-sea internet connection).
- If GPS data acquisition is not automatic for marking (i.e., marking is user-controlled), this method can be "gamed" such that virtual markers are set for gear that is not present, or virtual markers are absent for gear that is present.
- The initial accuracy of the location information will vary by depth and current, since the end of the trawl will drift laterally with the current as it descends to the sea floor.
- If the gear moves (e.g., because of a storm or dragger), its location will be unknown and it will contribute to increased gear conflict.
- If the gear moves beyond the acoustic range of the retrieval mechanism trigger (e.g., because of a storm or dragger), it will be impossible to relocate and retrieve the gear.
- This method alone does not transmit any information, so an on-shore data system capable of collecting, storing and sharing (with appropriate parties) data, including gear location, ownership information, gear type, number of traps per trawl and other essential information, is needed.
- Delivery of location information to avoid gear conflict requires real-time at-sea data communications (e.g., cellular or satellite internet connection).

Ranging

*System requirements:* (1) An acoustic device, called here the vessel transponder, affixed to a vessel's hull, (2) a complementary transponder (called here the trap transponder) affixed to one end of a trawl, (3) a vessel's GPS, (4) a computer or microprocessor to carry out the localization calculations, and (5) an on-shore data system to collect, store and distribute ownership and enforcement data.

*Localization principle:* The vessel transponder regularly (e.g., once a minute) emits a sound and records the exact time and location when the sound was emitted. When the trap transponder detects the sound, it immediately emits a sound of its own. When the vessel transponder detects this sound, it records the exact time of detection. A two-way travel time is calculated by subtracting the emission time from the detection time, and this two-way travel time is used to estimate the slant range to the trap transponder using the speed of sound in seawater. When slant ranges are collected at several different locations distributed around the trap transponder, the position of the trap transponder can be calculated. Accuracy largely depends on the spatial distribution of slant ranges measured around the trap transponder.

*Pros:*

- This is a common localization method for high-value equipment deployed on the sea floor, so is well known by many acousticians and acoustic release manufacturers.
- Several retrieval mechanisms (e.g., stowed rope or lift bag) are designed to be triggered acoustically, so including an acoustic gear location marking method in the same acoustic device that triggers the retrieval mechanism is feasible.

*Cons:*

- The vessel transponder needs to collect two-way travel times at locations distributed 270-360 degrees around the trap transponder (a process called "surveying"). Fishing vessels do not have the time to survey every trap transponder they encounter, so will not be able to localize every trap transponder they encounter.
- The trap transponder emits a sound every time a vessel emits a sound so the vessel system can measure the two-way travel time. This method produces the most sound of any of the other gear location marking methods, and since sound emission consumes power, this method will cause the trap transponder to use up batteries more quickly than other methods.
- This method alone does not transmit any information in the sound emission, so another method would be required to capture ownership and enforcement information as well as to identify both ends of a trawl to allow trawl orientation to be viewed by passing vessels.
- Without a capability to transmit information, this method cannot facilitate relocation of gear that has moved further away from the original deployment location than the detection range of the system.

## Directional Ranging

*System requirements:* (1) An acoustic device (called here the vessel directional transponder) affixed to a vessel's hull, (2) a transponder (called here the trap transponder) affixed to one end of a trawl, (3) a vessel's GPS, (4) a computer or microprocessor to carry out the localization calculations, and (5) an on-shore data system to collect, store and distribute ownership and enforcement data.

*Localization principle:* The vessel transponder is attached to a hull-mounted directional transducer (also known as an ultra-short baseline, or USBL, transducer). The vessel and trap transponders produce sounds in exactly the same manner as for ranging to estimate the slant range (described above). Additionally, the vessel transponder measures a bearing to the sound produced by the trap transponder using the directional transducer. Using the position of the vessel, the estimated slant range, the bearing, and an estimate of the trap transponder's depth, the position of the trap transponder can be calculated.

*Pros:*

- This is a localization method often used for high-value equipment or divers, so is well known by several acoustics manufacturers.
- The position of the trap transponder can be calculated with a single transmission from the trap transponder.
- Several retrieval mechanisms (e.g., stowed rope or lift bag) are designed to be triggered acoustically, so including an acoustic gear location marking method in the same acoustic device that triggers the retrieval mechanism is feasible.

*Cons:*

- The accuracy of the calculated trap transponder position varies with range (i.e., the distance between the vessel directional transponder and the trap transponder) such that the error in the position estimate is larger at long ranges and smaller at short ranges. Because the accuracy changes with range, a vessel will likely need to emit sounds several times as it approaches a trap transponder to achieve sufficient accuracy to avoid gear conflict.
- Because multiple sound emissions are required to improve accuracy, this method produces more sound than the SART method, but less sound than the ranging method. Consequently, the battery drain (i.e., power consumption) from sound emission will be more than the SART method and less than the ranging method.
- This method alone does not transmit any information in the sound emission, so another method would be required to transmit ownership and enforcement information as well as to identify both ends of a trawl to allow trawl orientation to be viewed by passing vessels.
- Without a capability to transmit information, this method cannot facilitate relocation of gear that has moved further away from the original deployment location than the detection range of the system.

Successive acoustic receive time (SART) self-localization

*System requirements:* (1) An acoustic device (called here the vessel modem) affixed to a vessel's hull, (2) a complementary acoustic device with included microprocessor to carry out localization calculations (called here the trap modem) affixed to one end of a trawl, and (3) a vessel's GPS.

*Localization principle:* The vessel modem is attached to a hull-mounted transducer which regularly (e.g., once a minute) emits a series of sounds in which the following data are encoded: location of the vessel's transducer at the time of the sound emission and the time of the sound emission. The trap modem detects and decodes these sounds and stores the information about where and when the sounds were sent from the vessel in a table. Each successive difference in transmission time and each successive difference in acoustic receive time is then calculated from the data in the table, and from these differences, the position of the trap modem can be calculated[1]. Hence, the trap modem can self-localize simply by listening for and decoding the transmissions from passing vessels. The trap modem communicates its calculated position to a passing vessel in a single message that contains unencrypted public data and encrypted private data; the public data might include a unique identifier, the location of the trap modem and the unique identifier of the trap modem located at the other end of the trawl, while the private data might include ownership information, permit/registration number, deployment date/time and number of traps on the trawl.

*Pros:*

- Communicating information is built into this method, so relocating lost gear by transmitting ownership information is feasible.
- The SART method creates the least amount of noise and uses the least amount of battery capacity to transmit sound of any other method since it localizes by listening to vessel modem transmissions (i.e., not transmitting sound itself).
- Several retrieval mechanisms (e.g., stowed rope or lift bag) are designed to be triggered acoustically, so including an acoustic gear location marking method in the same acoustic device that triggers the retrieval mechanism is feasible.

*Cons:*

- The localization method is new, so is therefore unfamiliar to nearly all acousticians and acoustic release manufacturers.
- Because SART requires acoustic time differences to be measured 270-360 degrees around the trap modem, the first vessel to approach the trap modem would receive the surface deployment location in lieu of a SART-derived location. After the first vessel passes the trap modem, the trap modem will be able to self-localize and send self-localized positions to all other passing vessels.

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[1] Baumgartner, M.F. and J. Partan. 2021. Self-localization of buoyless fishing gear and other objects on the sea floor. JASA Express Letters 1, 086001. https://doi.org/10.1121/10.0005739. Also available at ropeless.org.

Table 3. Comparison of gear location marking methods.

| Characteristic | GPS marking | Ranging | Directional ranging | SART |
|---|---|---|---|---|
| *Detection range* | Unlimited[1] | Depends on acoustic source level, frequency, and ocean conditions | Depends on acoustic source level, frequency, and ocean conditions | Depends on acoustic source level, frequency, and ocean conditions |
| *Accuracy* | Accuracy decreases with increasing water depth and currents | Can be high if a complete survey is done | Varies with distance; low at long range, higher at close range | High (independent of range, water depth or currents) |
| *Requires survey?*[2] | No | Yes | No | No |
| *Acoustic noise* | None | High | Medium | Low |
| *Can buoyless systems be relocated if moved beyond detection range?* | No | No, unless device has the capability to transmit data acoustically[3] | No, unless device has the capability to transmit data acoustically[3] | Yes |
| *Other information required for localization* | None | Device depth | Device depth | Device depth |
| *Other requirements for gear conflict resolution* | Requires an on-shore data system and real-time at-sea data communications (e.g., cellular, satellite) to provide location information | Requires capability to transmit data acoustically to identify device at other end of trawl and thereby share trawl orientation | Requires capability to transmit data acoustically to identify device at other end of trawl and thereby share trawl orientation | None |
| *Other requirements for locating lost gear and facilitating enforcement* | Requires an on-shore data system to provide ownership and enforcement data[4] | Requires capability to transmit data acoustically as well as an on-shore data system to provide ownership and enforcement data[4] | Requires capability to transmit data acoustically as well as an on-shore data system to provide ownership and enforcement data[4] | None; encrypted ownership and enforcement data are delivered locally by device attached to trawl |

[1] Range will likely be limited in software so that only gear within some fixed radius around a vessel's current position can be viewed by a fisher.

[2] A survey is when the fishing vessel must travel in a circle around the device on the sea floor to determine its position.

[3] With the capability to transmit data acoustically, the trap transponder could send a unique identifier to the vessel, and this identifier could be used to access ownership data in an on-shore data system to alert the owner that the gear has moved.

[4] Data such as unique system identifier, state/federal permit/license numbers, owner identity, gear type, number of traps on trawl, and date/time gear was deployed must be accessible to appropriate parties.

## 6. Preliminary assessment of gear location marking methods

We have conducted an initial assessment of the four gear location marking methods relative to the preliminary requirements (Table 4). This assessment will be discussed and updated during the workshop to determine how each of the gear location marking methods compares to the agreed-upon final requirements. Methods that meet a requirement are indicated with a check mark, while methods that do not meet a requirement are indicated with an "X". Additional capabilities needed for a method to meet a requirement are included where appropriate.

Table 4.  Matrix of preliminary requirements and the capability of each gear location marking method to meet those requirements.

| Function | Preliminary requirement | GPS marking | Ranging | Directional Ranging | SART |
|---|---|---|---|---|---|
| Detection distance | For inshore fisheries where trawl lengths are shorter, a minimum detection distance of 0.5 nautical miles is required. | ✓ | ✓ | ✓ | ✓ |
| Detection distance | For offshore fisheries where trawl lengths can reach 1.5 miles, a minimum detection distance of 2 nautical miles is required. | ✓ | ✓ | ✓ | ✓ |
| Location accuracy | Location accuracy of at least 25 feet (~8 meters) is required. | Depends on depth, currents and if gear moves | If survey is completed | ✓ | ✓ |
| Data display at sea | Gear location information, including location and orientation of trawls, must be displayed on a chart plotter. | N/A | N/A | N/A | N/A |
| Additional information to collect and share | The gear location marking system must provide ownership information (state/federal permit/license number, owner identity), gear type, unique system identifier, number of traps on trawl, length and orientation of trawl, and date/time gear was deployed. | Requires on-shore data system and real-time at-sea communications | Requires acoustic communication capability and on-shore data system | Requires acoustic communication capability and on-shore data system | ✓ |
| Data sharing | Gear location information must be available to fishers and enforcement in real time on scene at sea (i.e., within the detection distance of the system) to avoid gear conflict. | Requires on-shore data system and real-time at-sea communications | Requires acoustic communication capability and on-shore data system | Requires acoustic communication capability and on-shore data system | ✓ |

| Function | Preliminary requirement | GPS marking | Ranging | Directional Ranging | SART |
|---|---|---|---|---|---|
| Data sharing | Real-time location information must mirror reality (i.e., locations must be associated with actual gear on the sea floor, and a lack of locations must be associated with no gear on the sea floor). | Marker is virtual | ✓ | ✓ | ✓ |
| Data sharing | The ends of trawls must be marked in a way that is not voluntary. | Depends on implementation | N/A | N/A | N/A |
| Data sharing | All data (including location, ownership information, etc.) must be available to enforcement in real time on scene at sea (i.e., within the detection distance of the system). | Requires on-shore data system and real-time at-sea communications | Requires acoustic communication capability, on-shore data system and real-time at-sea communications | Requires acoustic communication capability, on-shore data system and real-time at-sea communications | ✓ |
| Data sharing | All data (including location, ownership information, etc.) must be shared in near real time (within some prescribed time after deployment; e.g., 18 hours) with enforcement on shore (e.g., in an enforcement-accessible cloud database). | N/A | N/A | N/A | N/A |
| Lost gear | The gear location marking system must be able to provide an accurate location for gear even if the gear has moved (e.g., because of storms or being dragged by a mobile fisher). | X | Requires acoustic communication capability and on-shore data system | Requires acoustic communication capability and on-shore data system | ✓ |

| Function | Preliminary requirement | GPS marking | Ranging | Directional Ranging | SART |
|---|---|---|---|---|---|
| Lost gear | The gear location marking system should provide a means for gear that has moved to be relocated and retrieved by the owner. | X | Requires acoustic communication capability and on-shore data system | Requires acoustic communication capability and on-shore data system | Requires on-shore data system |
| Environmental impacts | The gear location marking system should (1) minimize the use of disposable plastics, (2) minimize acoustic noise, (3) choose acoustic frequencies and source levels that minimize effects on marine mammals, fish, and shellfish. | Produces no acoustic noise | Produces highest amounts of acoustic noise | Produces moderate amounts of acoustic noise | Produces lowest amounts of acoustic noise |
| Endurance | Any gear location marking device that is affixed to submerged fishing gear must have an endurance of at least 6 months. | N/A | Uses most power for acoustic transmission | Uses moderate power for acoustic transmission | Uses least power for acoustic transmission |
| Endurance | Battery condition (e.g., voltage, charge status) of the gear location marking device must be easily interrogated. | N/A | N/A | N/A | N/A |
| Other | Acoustic-based gear location marking devices must be able to activate whatever gear retrieval mechanism to which the device is attached (e.g., lift bag, bottom-stowed rope). | N/A | ✓ | ✓ | ✓ |
| Other | The gear location marking system must be capable of sharing data in real time across international boundaries to avoid gear conflict and assist enforcement in these sensitive areas. | N/A | N/A | N/A | N/A |

| Function | Preliminary requirement | GPS marking | Ranging | Directional Ranging | SART |
|---|---|---|---|---|---|
| Other | A manufacturer’s gear location marking device must be able to communicate with all other manufacturers’ gear location marking devices using adopted standards. | N/A | N/A | N/A | N/A |

**Appendix 1: List of participants**

| Participant | Affiliation |
|---|---|
| Matt Abbott | Conservation Council of New Brunswick |
| Terry Alexander | Fisher (ME), NEFMC |
| Shannon Arnold | Ecology Action Centre |
| Regina Asmutis-Silvia | Whale and Dolphin Conservation USA |
| Peter Baker | Pew Charitable Trusts |
| Major Robert Beal | Maine state enforcement |
| Andre Bezanson | Ashored Innovations |
| Kurt Blanchard | Rhode Island Division of Law Enforcement |
| Diane Borggard | NOAA Fisheries |
| Catherine Boyd | Clearwater Seafoods |
| Remi Brine | DFO NCR |
| Billy Brophy | Fisher (GoSL NS) |
| Lt. Delayne Brown | New Hampshire state enforcement |
| Lisa Bujold | DFO Gulf - Resource Mgmt |
| Erin Burke | Massachusetts Division of Marine Fisheries |
| David Capotosto | DBV Technology |
| Colleen Coogan | NOAA Fisheries |
| Leslie Coolan | DFO Conservation & Protection |
| Jane Davenport | Defenders of Wildlife |
| Marco Flagg | Desert Star |
| Erica Fuller | Conservation Law Foundation |
| Caroline Good | NOAA Fisheries |
| Brian Guptill | Fisher (GM/BoF NB) |
| CT Harry | International Fund for Animal Welfare |
| Sean Hayes | NOAA Fisheries |
| Tim Hayman | DFO Maritimes - Resource Management |
| Cormac Hondros-McCarthy | LobsterLift |
| Mary Hudson | Maine Coast Fishermen’s Association |
| Adam Kenney | Fisher (South shore Nova Scotia) |
| Christin Khan | NOAA Fisheries |
| Amy Knowlton | New England Aquarium |
| Melissa Landry | DFO NCR |
| Scott Landry | Center for Coastal Studies |
| Mike Lane | Fisher (MA) |
| Cole MacLellan | Fisher (Northern CB) |
| Ben Martens | Maine Coast Fishermen’s Association |
| Rob Martin | Fisher (MA)/NOAA |

| Participant | Affiliation |
|---|---|
| Eric Matzen | NOAA Fisheries |
| Stormy Mayo | Center for Coastal Studies |
| James McFarlane | FioMarine |
| Kim McKown | NY Department of Environmental Conservation |
| Bill Mclellan | UNC Wilmington |
| Cathy Merriman | DFO NCR |
| Henry Miliken | NOAA Fisheries |
| Vanessa Mitchell | Maritime Aboriginal People’s Council |
| Kristen Monsell | Center for Biological Diversity |
| Michael Moore | Woods Hole Oceanographic Institution |
| Lt. Colonel Patrick Moran | Massachusetts state enforcement |
| Rob Morris | EdgeTech |
| Bonnie Morse | Grand Manan Fisherman's Association |
| Allison Murphy | NOAA Fisheries |
| Martin Noel | Fisher (GoSL NB) |
| Mathieu Noel | Fisher (GoSL NB) |
| Darlene Norman-Brown | Fundy North Fisherman's Association |
| Scott Olszewski | Rhode Island Department of Environmental Management |
| Marc Palumbo | Fisher (MA/RI) |
| Cheri Patterson | New Hampshire Fish and Game |
| Sean Reilly | New York state enforcement |
| Meghan Rickard | New York Natural Heritage Program |
| Rich Riels | SMELTS |
| Allison Rosner | NOAA Fisheries |
| Hubert Saulnier | Fisher (BoF NS) |
| Kim Sawicki | Sustainable Seas Technology |
| Geoff Shester | Oceana |
| Andy Spaulding | Fisher (ME) |
| Aaron Stevenson | Ashored Innovations |
| Erin Summers | Maine Department of Marine Resources |
| Kim Theriault | DFO Gulf - Resource Mgmt |
| Ed Trippel | DFO NCR |
| Alexis Van Bemmel | DFO NCR |
| Alex Vance | Oceana Canada |
| Kris Vascotto | Atlantic Groundfish Council |
| Harold (Bud) Vincent | DBV Technology |
| Jim Violet | Fisher (RI) |
| Corey Webster | Conservation & Protection NCR |
| Tim Werner | OAI Consulting |

## Appendix B:  Procedure for localizing devices on the sea floor

# FONTUS: Localizing devices on the sea floor

We will use a non-linear least squares approach for localizing devices on the sea floor with observations of 1-way travel times alone, 1-way travel times with associated bearings or a combination of both. One-way travel times are measured with an acoustic modem as the 2-way travel time (i.e., the difference in time between the acoustic modem transmitting the ***Localization Request*** and receiving the ***Localization Report*** from the device minus the response delay reported by the device) divided by 2. Bearing is measured with an ultra-short baseline (USBL) array that estimates the direction of arrival of the ***Localization Report*** from the device. To start, we define slant range ($S$) and horizontal range ($R$) as follows:

$$S_i = \sqrt{(x - X_i)^2 + (y - Y_i)^2 + (z_i - Z_i)^2} \tag{1}$$

$$R_i = \sqrt{(x - X_i)^2 + (y - Y_i)^2} \tag{2}$$

where ($x$, $y$, $z$) is the position of the device on the sea floor and ($X_i$, $Y_i$, $Z_i$) is the position of the ship's transducer in Cartesian coordinates (i.e., eastings and northings with units of meters). We also define $c$ as the water-column averaged sound speed, $\Delta t_i$ as the 1-way travel time between ($X_i$, $Y_i$, $Z_i$) and ($x$, $y$, $z$), $\theta_i$ as the bearing between ($X_i$, $Y_i$) and ($x$, $y$), respectively. Note the following:

$$\Delta t_i = \frac{S_i}{c} \tag{3}$$

$$sin(\theta_i) = \frac{x - X_i}{R_i} \tag{4}$$

$$cos(\theta_i) = \frac{y - Y_i}{R_i} \tag{5}$$

We will define an observation as a set of the following measurements: $X_i$, $Y_i$, $Z_i$, $z_i$, $\Delta t_i$ and, if available, $\theta_i$ (note that $z_i$, the depth of the device, is measured). Measurements will be subscripted with the letter "$i$" in the equations here. The goal of the non-linear least squares iterative refinement is to estimate $x$, $y$, and $c$; these variables lack subscripts in the equations here to indicate that they are estimated (i.e., calculated). There is a total of $n$ observations and $n = n_\theta + n_0$ where $n_\theta$ is the number of observations with a bearing measurement (i.e., $\Delta t_i$ and $\theta_i$ are available because the ship making the observations has a USBL array) and $n_0$ is the number of observations without a bearing measurement (i.e., only $\Delta t_i$ is available because the observations come from a ship without a USBL array).

We will solve for $x$, $y$ and $c$ by specifying a measurement equation ($m$) and an equivalent estimation equation ($f$) that defines $m$ in terms of the unknown variables (i.e., if the measurements were collected without error and $x$, $y$ and $c$ were estimated perfectly, $f$ would be equal to $m$). We can then estimate $x$, $y$, and $c$ iteratively until $m \approx f$, or equivalently until

$$r_i = m_i - f_i \tag{6}$$

is very small (Foy 1976), where $r_i$ is the residual. To do this, we can write a Taylor series expansion of $f_i$ (ignoring higher order terms) as follows

$$f_i \approx f_i(x, y, c) + \frac{\partial f_i}{\partial x}\delta_x + \frac{\partial f_i}{\partial y}\delta_y + \frac{\partial f_i}{\partial c}\delta_c \tag{7}$$

Rearranging Eq. (7), we have

$$\frac{\partial f_i}{\partial x}\delta_x + \frac{\partial f_i}{\partial y}\delta_y + \frac{\partial f_i}{\partial c}\delta_c = m_i - f_i(x, y, c) - r_i \tag{8}$$

which can be rewritten in matrix notation as

$$J\delta = B - r \tag{9}$$

where $\boldsymbol{J}$ is the Jacobian matrix (matrix of derivatives), $\boldsymbol{\delta}$ is the vector of increments for *x*, *y* and *c* for the iterative refinement, and $\boldsymbol{B}$ is the vector of $m_i$ - $f_i$. If the residuals ($r_i$) are independent with zero means and equal variances, then the solution to Eq. (9) that minimizes the sum of squared residuals is

$$\delta = [J^T J]^{-1} J^T B \tag{10}$$

(Foy 1976) and the estimates of *x*, *y* and *c* are updated as follows:

$$x = x + \delta_x \tag{11}$$

$$y = y + \delta_y \tag{12}$$

$$c = c + \delta_c \tag{13}$$

These estimates are used in Eq. (9) again, and a new set of estimates for *x*, *y*, and *c* is computed. This is repeated until the change in position between iterations (i.e., $\sqrt{\delta_x^2 + \delta_y^2}$) is very small (< 0.01 m).

If the residuals ($r_i$) are independent (uncorrelated), but their variances are not all equal, weighted least squares can be used by replacing Eq. (10) with the following:

$$\delta = [J^T W J]^{-1} J^T W B \tag{14}$$

where W is a square matrix whose off-diagonal elements are set to 0, and whose diagonal elements are set to the following:

$$W_{j,j} = \frac{1}{\sigma^2} \tag{15}$$

where $\sigma^2$ is the variance of the measurement error (see more below). The subscript $j$ indexes the entries in ***J***, ***B*** and ***W*** ($i$ varies from 1 to $n_\theta + n_0$, whereas $j$ varies from 1 to $3n_\theta + n_0$ because 3 rows are entered into ***J***, ***B*** and ***W*** for each observation with a bearing; see below for an explanation of this). By using ***W*** as specified in Eq. (15), the solution becomes the best linear unbiased estimator (BLUE).

For all 1-way travel time observations (from any ship regardless of whether they have a USBL array or not), one row will be entered into ***J***, ***B*** and ***W*** as follows:

$$m_i = \Delta t_i \tag{16}$$

$$f_i = \frac{S_i}{c} \tag{17}$$

$$\frac{\partial f_i}{\partial x} = \frac{x}{cS_i} \tag{18}$$

$$\frac{\partial f_i}{\partial y} = \frac{y}{cS_i} \tag{19}$$

$$\frac{\partial f_i}{\partial c} = \frac{-S_i}{c^2} \tag{20}$$

$$B_j = m_i - f_i \tag{21}$$

$$J_j = \begin{bmatrix} \frac{\partial f_i}{\partial x} & \frac{\partial f_i}{\partial y} & \frac{\partial f_i}{\partial c} \end{bmatrix} \tag{22}$$

$$W_{j,j} = \frac{1}{\sigma_{\Delta t}^2} \tag{23}$$

For observations with both 1-way travel time and bearing (from a USBL array), two additional rows will be entered into ***J***, ***B*** and ***W*** as follows:

$$p_i = \Delta t_i \, sin(\theta_i) \tag{24}$$

$$g_i = \frac{xS_i}{cR_i} \tag{25}$$

$$\frac{\partial g_i}{\partial x} = \frac{x^2 + S_i^2 - \frac{x^2 S_i^2}{R_i^2}}{cS_i R_i} \tag{26}$$

$$\frac{\partial g_i}{\partial y} = \frac{xy\left(1 - \frac{S_i^2}{R_i^2}\right)}{cS_i R_i} \tag{27}$$

$$\frac{\partial g_i}{\partial c} = \frac{-xS_i}{c^2 R_i} \tag{28}$$

$$q_i = \Delta t_i \, cos(\theta_i) \tag{29}$$

$$h_i = \frac{yS_i}{cR_i} \tag{30}$$

$$\frac{\partial h_i}{\partial x} = \frac{xy\left(1-\frac{S_i^2}{R_i^2}\right)}{cS_iR_i} \tag{31}$$

$$\frac{\partial h_i}{\partial y} = \frac{y^2+S_i^2-\frac{y^2S_i^2}{R_i^2}}{cS_iR_i} \tag{32}$$

$$\frac{\partial h_i}{\partial c} = \frac{-yS_i}{c^2R_i} \tag{33}$$

$$B_j = p_i - g_i \tag{34}$$

$$B_{j+1} = q_i - h_i \tag{35}$$

$$J_j = \begin{bmatrix} \frac{\partial g_i}{\partial x} & \frac{\partial g_i}{\partial y} & \frac{\partial g_i}{\partial c} \end{bmatrix} \tag{36}$$

$$J_{j+1} = \begin{bmatrix} \frac{\partial h_i}{\partial x} & \frac{\partial h_i}{\partial y} & \frac{\partial h_i}{\partial c} \end{bmatrix} \tag{37}$$

$$W_{j,j} = \frac{1}{2\sigma^2_{\Delta t\, sin(\theta)}} \tag{38}$$

$$W_{j+1,j+1} = \frac{1}{2\sigma^2_{\Delta t\, cos(\theta)}} \tag{39}$$

where *p* and *q* are measurement equations and *g* and *h* are estimation equations. The coefficient 2 in the denominator of the weights (Eq. 38-39) is included because $\Delta t_i$ and $\theta_i$ are the independent observations, and while 1 row is added to ***J***, ***B*** and ***W*** for the measurement equation involving only $\Delta t_i$ (Eq. 16), 2 rows are added to ***J***, ***B*** and ***W*** for the measurement equations involving $\theta_i$ (Eq. 24, 29); thus, a weight of ½ is included for each of these measurement equations so that the 1-way travel times and the bearings are treated as equivalent independent observations in the calculations. Note that $\Delta t_i$, $\Delta t_i \, sin(\theta_i)$ and $\Delta t_i \, cos(\theta_i)$ are all uncorrelated with one another, and they all have the same units (seconds), so are appropriate for use in the non-linear least squares approach[1].

---

[1] One may be tempted to use bearing or the tangent of bearing directly in the non-linear least squares approach with a single measurement equation instead of separate measurement equations for $\Delta t_i \, sin(\theta_i)$ and $\Delta t_i \, cos(\theta_i)$. However, using $m = \Delta t_i$ and $p = tan(\theta_i)$ as measurement equations does not work well because (1) $\Delta t_i$ and $\tan(\theta_i)$ have different units, (2) $tan(\theta_i)$ behaves poorly as northings approach 0, and (3) $tan(\theta_i)$ does not vary much when

To estimate the variances of the measurement errors ($\sigma^2$ in Eq. 23, 38 and 39), a simulation was conducted by placing a device at the origin of a Cartesian coordinate system and 10,000 ships within this same domain, each at a uniformly random range (1-1000 m) and bearing (0-360°) relative to the device. Constants for the simulations included sound speed (*c*; 1450 m $s^{-1}$), device depth (50 m) and transducer depth (3 m); note that changing the values of these constants does not affect the variances of the measurement errors. The true 1-way travel time was computed from the slant range (*S*) between each ship and the device (Eq. 1 and 3), and the measured 1-way travel time was calculated as the sum of the true 1-way travel time and a uniformly random error term between $\pm$ 0.001 s. Similarly, the true bearing was determined between each ship and the device, and the measured bearing was calculated as the sum of the true bearing and a uniformly random error term between $\pm$ 5°. The error of the measurements $\Delta t_i$, $\Delta t_i\ sin(\theta_i)$ and $\Delta t_i\ cos(\theta_i)$ (i.e., equations *m*, *p* and *q*) were then calculated as the measurement minus the true value:

$$e_i^m = \Delta t_i - \frac{S_i}{c} \tag{40}$$

$$e_i^p = \Delta t_i\ sin(\theta_i) - \frac{X_i S_i}{cR} \tag{41}$$

$$e_i^q = \Delta t_i\ cos(\theta_i) - \frac{Y_i S_i}{cR} \tag{42}$$

Note that the superscript on the error terms refers to the measurement equation from which the errors were derived. The variance of $e_i^m$ was calculated as follows:

$$\sigma_{\Delta t}^2 = \frac{1}{n-1}\sum(e_i^m - \overline{e^m})^2 = \frac{1}{n-1}\sum(e_i^m)^2 \tag{43}$$

Note that the mean of $e^m$ = 0 (there is no bias in the measurement errors of $\Delta t_i$ in the simulation). The variance of the error $e^m$ was only influenced by the specified error term for $\Delta t_i$ in the simulation ($\pm$ 0.001 s), however, the variances of the measurement errors for $\Delta t_i\ sin(\theta_i)$ and $\Delta t_i\ cos(\theta_i)$ ($e^p$ and $e^q$, respectively) were a function of range ($R_i$) (Figure B1). To model these variances, the errors $e_i^p$ and $e_i^q$ were isolated in 25-m range bins (midpoint of each range bin is $R_{bin}$) and the variance of the $n_{bin}$ values in each bin was calculated as follows:

$$\sigma(R_{bin})_{\Delta t\ sin(\theta)}^2 = \frac{1}{n_{bin}-1}\sum\left(e_i^p - \overline{e^p}\right)^2 = \frac{1}{n_{bin}-1}\sum\left(e_i^p\right)^2 \tag{44}$$

$$\sigma(R_{bin})_{\Delta t\ cos(\theta)}^2 = \frac{1}{n_{bin}-1}\sum\left(e_i^q - \overline{e^q}\right)^2 = \frac{1}{n_{bin}-1}\sum\left(e_i^q\right)^2 \tag{45}$$

Note that the mean of $e^p = e^q = 0$ (there is no bias in the measurement errors of $\Delta t_i\ sin(\theta_i)$ or of $\Delta t_i\ cos(\theta_i)$ in the simulation, i.e., there is no bias in $\Delta t_i$ or $\theta_i$). The following quadratic models were then fit to the binned variances using multiple linear regression:

---

bearing is within ±30° of 0° or 180°, so it is therefore not very helpful for the non-linear least squares approach that relies on derivatives (rates of change) for the iterative refinement.

$$\sigma^2_{\Delta t\, sin(\theta)} = \sigma(R_{bin})^2_{\Delta t\, sin(\theta)} = \alpha_1 R_{bin} + \alpha_2 R^2_{bin} \tag{46}$$

$$\sigma^2_{\Delta t\, cos(\theta)} = \sigma(R_{bin})^2_{\Delta t\, cos(\theta)} = \beta_1 R_{bin} + \beta_2 R^2_{bin} \tag{47}$$

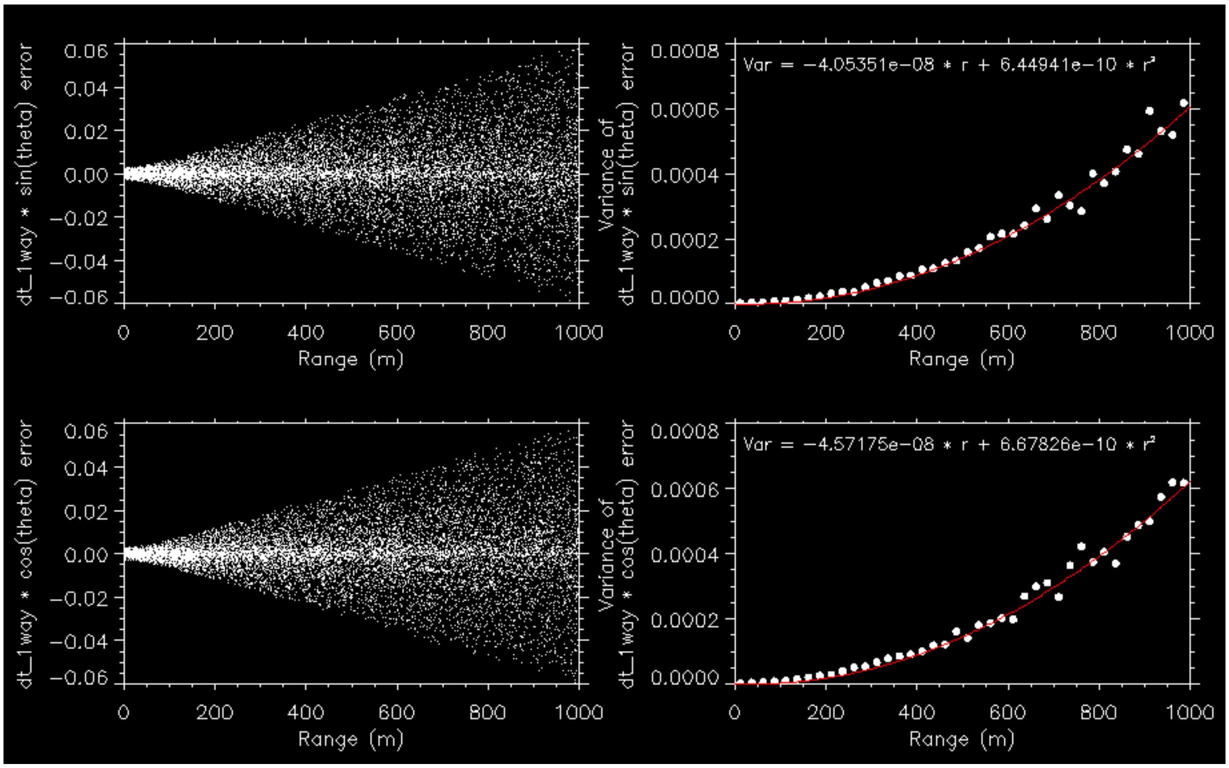


*Figure B1. Measurement error for $\Delta t_i\, sin(\theta_i)$ and $\Delta t_i\, cos(\theta_i)$ from simulations with a 1-way travel time error of $\pm$0.001 s and a bearing error of 5° (left-hand panels), and the variance of the measurement errors as a function of range (calculated in 25-m range bins; right-hand panels). Red lines indicate multiple linear regression fits to the variance data.*

The variances estimated from the simulation and used in the non-linear least squares iterative refinement as weights $W_{j,j}$ (Eq. 23, 38, 39) are shown in Table B1.

*Table B1. Variances or coefficients of modeled variances for simulations with 1-way travel time errors of $\pm$0.001 s and bearing errors of $\pm$5°.*

| Parameter | Value |
|---|---|
| $\sigma^2_{\Delta t}$ | $3.35 \times 10^{-7}$ s$^2$ |
| $\alpha_1$ | $-4.05 \times 10^{-8}$ s$^2$ m$^{-1}$ |
| $\alpha_2$ | $6.45 \times 10^{-10}$ s$^2$ m$^{-1}$ |
| $\beta_1$ | $-4.57 \times 10^{-8}$ s$^2$ m$^{-1}$ |
| $\beta_2$ | $6.68 \times 10^{-10}$ s$^2$ m$^{-1}$ |

As an example, imagine a gear-owner deploys a device on the end of a trawl and takes $n_\theta = 3$ observations as the ship steams away with a USBL array (recall an observation with a USBL array consists of $X_i$, $Y_i$, $Z_i$, $z_i$, $\Delta t_i$ and $\theta_i$). Sometime shortly thereafter, a second ship passes nearby this device, and collects $n_0 = 2$ observations without a USBL array (recall an observation without a USBL array consists of $X_i$, $Y_i$, $Z_i$, $z_i$ and $\Delta t_i$). The ***J***, ***B*** and ***W*** matrices would look as follows (note that W is a square matrix; only the diagonal elements are shown, and all off-diagonal elements are set to 0):

$$J = \begin{bmatrix} \frac{\partial f_1}{\partial x} & \frac{\partial f_1}{\partial y} & \frac{\partial f_1}{\partial c} \\ \frac{\partial g_1}{\partial x} & \frac{\partial g_1}{\partial y} & \frac{\partial g_1}{\partial c} \\ \frac{\partial h_1}{\partial x} & \frac{\partial h_1}{\partial y} & \frac{\partial h_1}{\partial c} \\ \frac{\partial f_2}{\partial x} & \frac{\partial f_2}{\partial y} & \frac{\partial f_2}{\partial c} \\ \frac{\partial g_2}{\partial x} & \frac{\partial g_2}{\partial y} & \frac{\partial g_2}{\partial c} \\ \frac{\partial h_2}{\partial x} & \frac{\partial h_2}{\partial y} & \frac{\partial h_2}{\partial c} \\ \frac{\partial f_3}{\partial x} & \frac{\partial f_3}{\partial y} & \frac{\partial f_3}{\partial c} \\ \frac{\partial g_3}{\partial x} & \frac{\partial g_3}{\partial y} & \frac{\partial g_3}{\partial c} \\ \frac{\partial h_3}{\partial x} & \frac{\partial h_3}{\partial y} & \frac{\partial h_3}{\partial c} \\ \frac{\partial f_4}{\partial x} & \frac{\partial f_4}{\partial y} & \frac{\partial f_4}{\partial c} \\ \frac{\partial f_5}{\partial x} & \frac{\partial f_5}{\partial y} & \frac{\partial f_5}{\partial c} \end{bmatrix} \qquad B = \begin{bmatrix} m_1 - f_1 \\ p_1 - g_1 \\ q_1 - h_1 \\ m_2 - f_2 \\ p_2 - g_2 \\ q_2 - h_2 \\ m_3 - f_3 \\ p_3 - g_3 \\ q_3 - h_3 \\ m_4 - f_4 \\ m_5 - f_5 \end{bmatrix} \qquad W_{j,j} = \begin{bmatrix} [\sigma_{\Delta t}^2]^{-1} \\ \left[2\sigma_{\Delta t\, sin(\theta)}^2\right]^{-1} \\ \left[2\sigma_{\Delta t\, cos(\theta)}^2\right]^{-1} \\ [\sigma_{\Delta t}^2]^{-1} \\ \left[2\sigma_{\Delta t\, sin(\theta)}^2\right]^{-1} \\ \left[2\sigma_{\Delta t\, cos(\theta)}^2\right]^{-1} \\ [\sigma_{\Delta t}^2]^{-1} \\ \left[2\sigma_{\Delta t\, sin(\theta)}^2\right]^{-1} \\ \left[2\sigma_{\Delta t\, cos(\theta)}^2\right]^{-1} \\ [\sigma_{\Delta t}^2]^{-1} \\ [\sigma_{\Delta t}^2]^{-1} \end{bmatrix} \tag{48}$$

## Code for implementation

```
; This code estimates xp, yp and cp from obs(*).x, obs(*).y, obs(*).z, obs(*).device_depth,
; obs(*).dt_1way and, optionally, obs(*).bearing using a non-linear least squares iterative
; refinement.  xp, yp and cp are set to initial values before executing the code below.

tolerance = 0.01         ; meters
max_iterations = 50

; empirically derived via simulation with 0.001 s 1-way travel time error and 5 degree bearing error
variance_dt_1way = 3.35D-07
alpha1 = -4.05D-08
alpha2 = 6.45D-10
beta1 = -4.57D-08
beta2 = 6.68D-10

iter = 0
done = 0
repeat begin
  k = 0L
  for i = 0, nobs - 1 do begin
       x = xp - obs(i).x
       y = yp - obs(i).y
       z = obs(i).device_depth - obs(i).z
       x2 = x ^ 2.0D
       y2 = y ^ 2.0D
       s2 = (x ^ 2.0D) + (y ^ 2.0D) + (z ^ 2.0D)
       s = sqrt(s2)
       r2 = (x ^ 2.0D) + (y ^ 2.0D)
       r = sqrt(r2)

       ; all observations include a 1-way travel time...
       m = obs(i).dt_1way                       ; measured values (observations); m is the ONE-WAY travel time
       f = s / cp                               ; what the measured value should be if xp, yp and cp are correct
       zed(k) = m - f                           ; zed is the error computed as measured minus estimated
       jac(0,k) = x / (s * cp)                  ; df/dx
       jac(1,k) = y / (s * cp)                  ; df/dy
       jac(2,k) = -s / (cp ^ 2.0D)              ; df/dc
       weight(k,k) = 1.0D / variance_dt_1way
       k = k + 1

       ; for observations with a bearing...
       if (obs(i).bearing lt 1.0e30) then begin
            p = obs(i).dt_1way * sin(obs(i).bearing)          ; measured values (observations)
            g = s * x / (cp * r)                              ; what the measured value should be
            zed(k) = p - g                                    ; zed is the error computed as measured minus estimated
            jac(0,k) = (x2 + s2 - x2 * s2 / r2) / (cp * r * s) ; dg/dx
            jac(1,k) = x * y * (1.0D - s2 / r2) / (cp * r * s) ; dg/dy
            jac(2,k) = -s * x / (r * (cp ^ 2.0D))             ; dg/dc
            variance_dt_1way_sin_bearing = alpha1 * r + alpha2 * (r ^ 2.0D)
            if (variance_dt_1way_sin_bearing lt variance_dt_1way) then $  ; don't weight bearing more than travel time
                 variance_dt_1way_sin_bearing = variance_dt_1way          ; this can happen if range is very small
            weight(k,k) = 1.0D / (2.0D * variance_dt_1way_sin_bearing)
            k = k + 1

            q = obs(i).dt_1way * cos(obs(i).bearing)          ; measured values (observations)
            h = s * y / (cp * r)                              ; what the measured value should be
            zed(k) = q - h                                    ; zed is the error computed as measured minus estimated
            jac(0,k) = x * y * (1.0D - s2 / r2) / (cp * s * r) ; dh/dx
            jac(1,k) = (y2 + s2 - y2 * s2 / r2) / (cp * s * r) ; dh/dy
            jac(2,k) = -s * y / (r * (cp ^ 2.0D))             ; dh/dc
            variance_dt_1way_cos_bearing = beta1 * r + beta2 * (r ^ 2.0D)
            if (variance_dt_1way_cos_bearing lt variance_dt_1way) then $  ; don't weight bearing more than travel time
                 variance_dt_1way_cos_bearing = variance_dt_1way          ; this can happen if range is very small
            weight(k,k) = 1.0D / (2.0D * variance_dt_1way_cos_bearing)
            k = k + 1
            end
       end

  j = jac(*,0:k-1)                              ; Jacobian matrix
  b = zed(0:k-1)                                ; measured - estimated
  w = weight(0:k-1,0:k-1)                       ; weights
  jt = transpose(j)                             ; transpose of the Jacobian matrix
  delta = invert(jt ## w ## j, /double) ## jt ## w ## b

  xp = xp + delta(0)
  yp = yp + delta(1)
  cp = cp + delta(2)

  diff = sqrt(delta(0) ^ 2.0D + delta(1) ^ 2.0D)
  iter = iter + 1
  if (diff lt tolerance or iter gt max_iterations or diff gt 1.0e6) then $
    done = 1

  end until (done eq 1)
```

Evaluation simulations

To evaluate the position errors associated with the localization method described above, many simulations were conducted with different geometries of observations, different combinations of USBL and non-USBL equipped ships, and different measurement errors (not all simulations are presented here). Simulations were conducted by first specifying the true location at which the device was deployed (the origin of the domain), the true location where it landed on the sea floor after sinking from the deployment location, the true locations of ships that collected observations, and whether these ships had a USBL array or not. All of this true information was calculated with parameters that remained constant during each iteration of the simulation; these parameters are summarized in Table B2. Constants that varied from one iteration to the next are presented in Table B2 with their range; the parameter value used in any one iteration was selected from a uniform distribution bounded by the range in Table B2.

*Table B2. Constants used in the simulations.*

| **Parameter** | **Value** |
|---|---|
| Sound speed | 1440-1520 m $s^{-1}$ |
| Water depth | 50 m |
| Sinking rate | 2 m $s^{-1}$ |
| Current speed | 1 knot |
| Current direction | 315 ° |

For each set of observations, the measured parameters listed in Table B3 were then determined. A measured parameter was determined as the sum of the true parameter value and a measurement error term drawn from a uniform distribution bounded by the error values in Table B3 (i.e., the values following the "±" symbol in the table). One thousand iterations of the simulation were run with only the error terms and the true speed of sound varied between each iteration.

*Table B3. True and measured parameters in the simulations.*

| **Parameter** | **True** | **Measured** |
|---|---|---|
| Ship position | X, Y | $X \pm 3$ m, $Y \pm 3$ m |
| Transducer depth | Z | $Z \pm 1$ m |
| Device depth | z | $z \pm (0.05 \times z)$ m |
| 1-way travel time | $\Delta t$ | $\Delta t \pm 0.001$ s |
| Bearing (if using USBL) | $\theta$ | $\theta \pm 5°$ |

Several geometries of observations were investigated (i.e., the distribution of observations around the device), but the best performance was achieved if the ship that initially deploys a device on the sea floor collects several observations as it steams away from the device. This is the best (and often the only) chance for collecting observations in close proximity to the device, and these observations should be collected automatically as part of the deployment sequence (see section 2). The observations are only collected once the device has landed on the sea floor and is no longer moving laterally with the current. In practice, the deploying ship will interrogate the device many time (e.g., once every 10 seconds) to monitor the device's depth; once the device lands on the sea floor, indicated by the device's depth remaining constant, the observations for localization can be collected. Observations from passing or approaching ships were included in the simulations to determine how many additional observations are needed and from how far away these observations should be collected to improve position accuracy. We assessed position accuracy relative to the 8 m accuracy requirement for on-demand fishing in high gear density areas described in Baumgartner et al. (2021).

For each of the simulations, the performance of 2 different localization methods were compared: (1) localization using only the 1-way travel times and ignoring any available bearing estimates (i.e., only using measurement equation *m*); this method is referred to as "travel time only", and (2) localizations using 1-way travel times and any available bearing estimates (i.e., using measurement equations *m*, *p* and *q*); this method is referred to as "travel time/bearing." These two methods are useful to compare because they indicate (1) how localization performance would change if none of the ships used USBL arrays, and (2) what is the value of including a USBL array in improving localization performance.

The localization methods evaluated in the simulations have varying dependence on the geometry of the observations; geometry greatly influences localizations that only use measurement equation *m* (i.e., travel time only localizations), whereas localizations that use measurement equations *m*, *p* and *q* (i.e., those with bearing measurements) are less influenced by geometry, particularly at close range. To assess this, multiple simulations were conducted where the difference in travel directions between the deploying ship and the approaching ship was varied between simulations (Figure B2). The results of these simulations allowed comparisons of position accuracy between localization methods as a function of changing geometry.

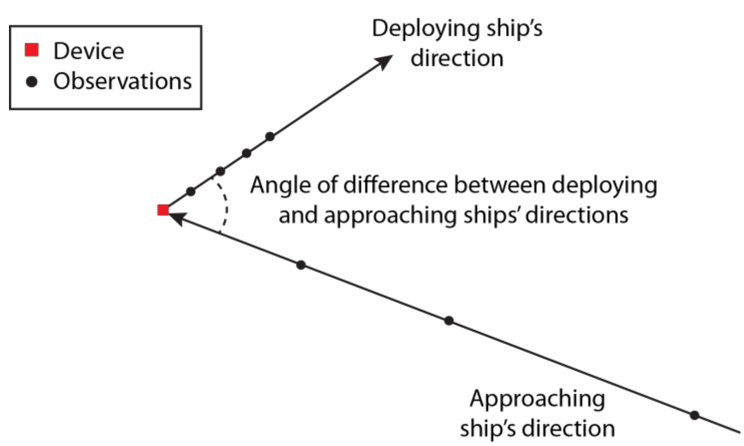


*Figure B2. An example of a geometry of observations collected by a ship that deployed the device on the sea floor and, at some later time, by a ship that is approaching the device. The angle between these two directions was varied between simulations to examine how geometry influences the position accuracy of different localization methods.*

There are an infinite number of scenarios that could be simulated, but we focused on the worst-case scenario: shortly after a fisher deploys a trawl from their ship, a second fisher approaches the deployed trawl with the intention of deploying their own trawl very close by. This is the worst-case scenario because no other localization observations will have been collected other than those by the deploying ship and those by the approaching ship. The goal is to ensure that the approaching fisher has sufficiently accurate position information for the deployed trawl to be able to avoid gear conflict. This means that by the time the second ship is near the deployed trawl, the location accuracy for the devices at the terminal ends of that trawl should be 8 m or less (Requirement 2).

*Both deploying and approaching ship have USBL arrays*

Simulations were run to assess location accuracy as the approaching ship nears a deployed device when both the deploying and approaching ships have USBL arrays and can therefore measure bearings from the ship to the device. In these simulations, a fisher deploys a device and collects 3 observations with a USBL array at a 3-second interval as the deployment ship moves away from the device at 8 knots. Shortly thereafter, a second approaching ship collects additional observations with a USBL array along a track that is 175° offset from the deployment ship's direction of travel. This 175° offset produces a poor geometry, with all of the observations aligned in a nearly straight line. Results are shown for the second ship collecting (1) one observation at 0.5 nautical miles distance from the device (Figure B3), (2) two observations at 0.5 and 0.25 nautical miles (Figure B4), and (3) three observations at 0.125, 0.25 and 0.5 nautical miles (Figure B5). Another simulation was conducted with the approaching ship collecting 3 observations with a USBL array along a track that is 90° offset from the deployment ship's direction of travel (Figure B6). Finally, a comparison of the travel time only localization method and the travel time/bearing localization method as a function of geometry (i.e., as a function of the difference in deploying and approaching ships' directions; see Figure B2) is shown in Figure B7.

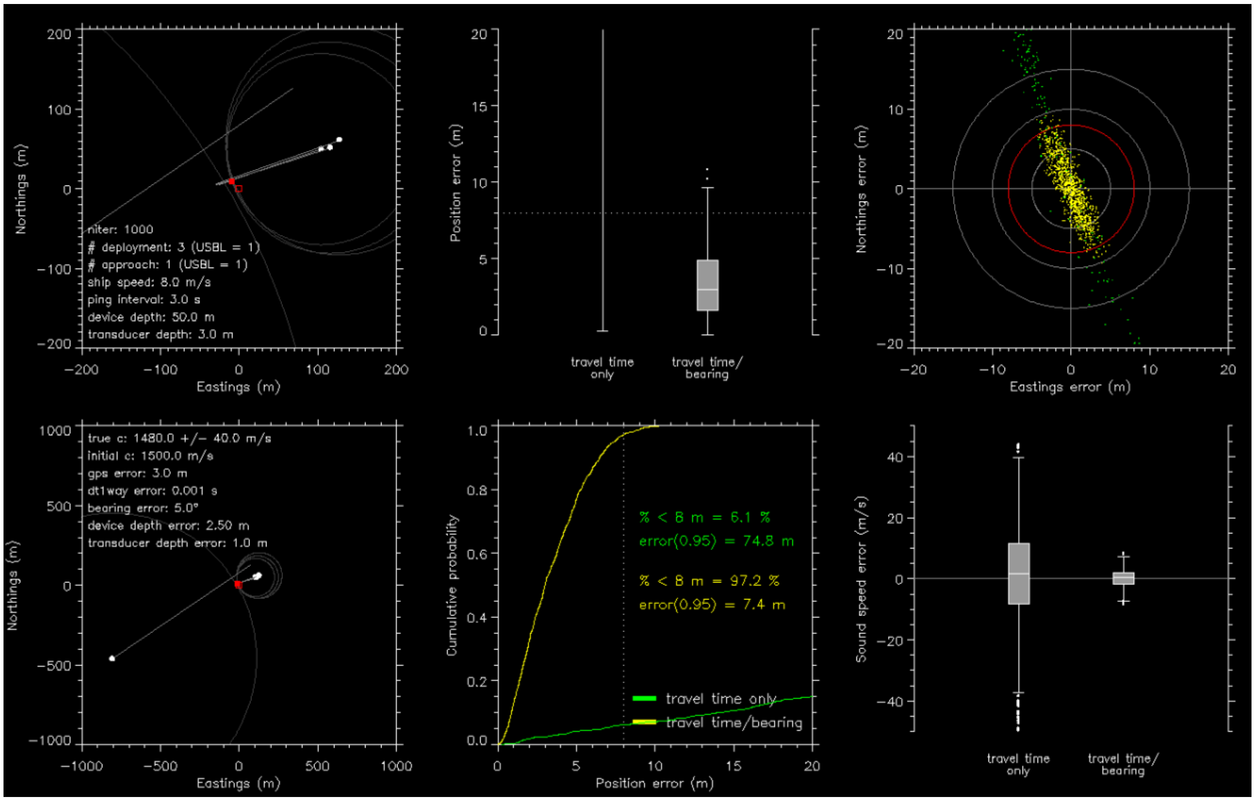


*Figure B3. Simulation of a fisher deploying a device and collecting 3 observations with a USBL array with $\pm 5°$ bearing error at a 3 second interval as the deployment ship moves away from the device at 8 knots. Shortly thereafter, a second approaching ship on a bearing 175° offset from the deployment ship's bearing (see Figure B2) collects 1 observation with a similar USBL array at a distance of 0.5 nautical miles. The two left-most panels display a single iteration of the simulation, including an open red square representing the ship's position when the device was deployed, a filled red square where the device landed on the sea floor, approximate range circles in gray (assuming sound speed is 1500 m $s^{-1}$), and bearing measurements in gray; all other panels are based on 1000 iterations of the simulation. Dotted lines indicate the target accuracy of 8 m. The text in the cumulative probability plot reports the percentage of 1000 iterations that resulted in a position accuracy less than 8 m, as well as the distance below which which 95% of the errors occur. The red concentric circle in the upper right panel indicates the target 8 m location accuracy. Boxplots indicate the median (middle line), lower quartile (Q1; bottom of box), upper quartile (Q3, top of box), values between Q1 – 1.5 × (Q3 – Q1) and Q3 + 1.5 × (Q3 – Q1) (extents of whiskers), and values less than Q1 – 1.5 × (Q3 – Q1) or greater than Q3 + 1.5 × (Q3 – Q1) (small filled circles).*

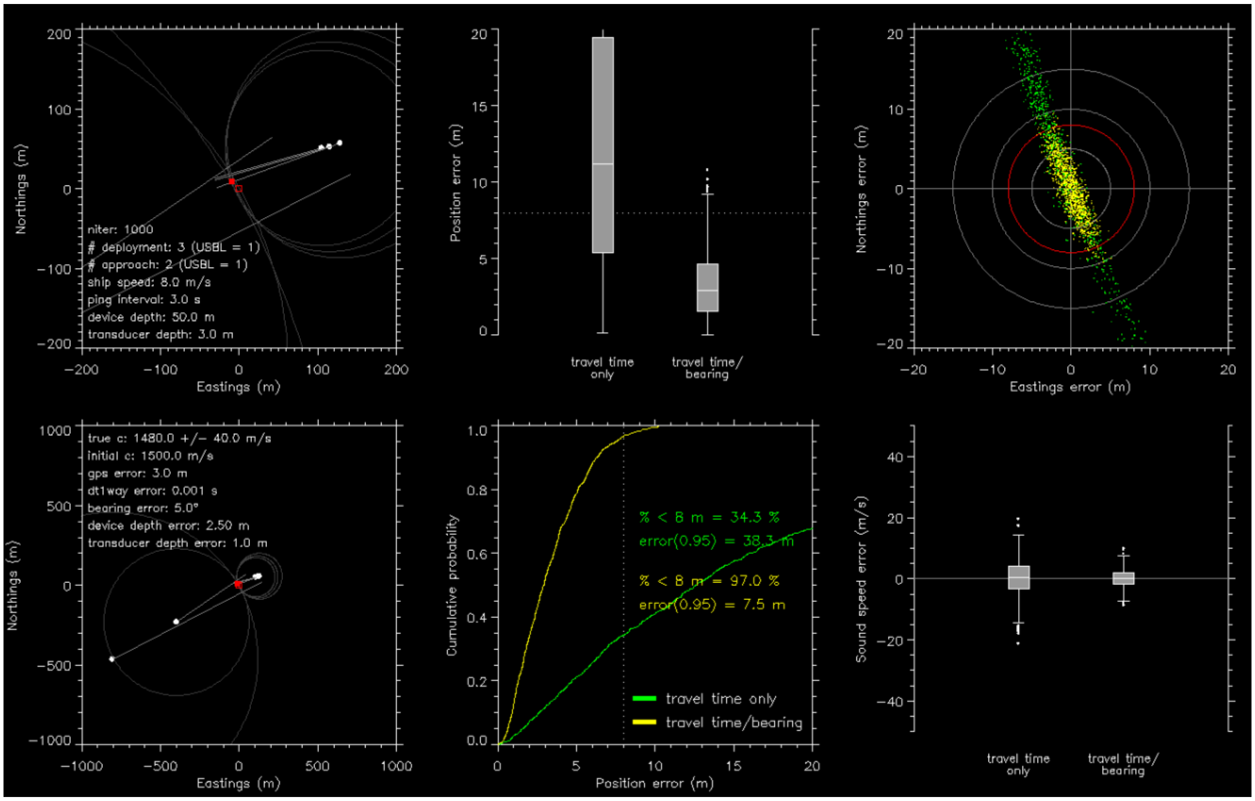


*Figure B4. Simulation of a fisher deploying a device and collecting 3 observations with a USBL array with ±5° bearing error at a 3 second interval as the deployment ship moves away from the device at 8 knots. Shortly thereafter, a second approaching ship on a bearing 175° offset from the deployment ship's bearing (see Figure B2) collects 2 observations with a similar USBL array at distances of 0.25 and 0.5 nautical miles.*

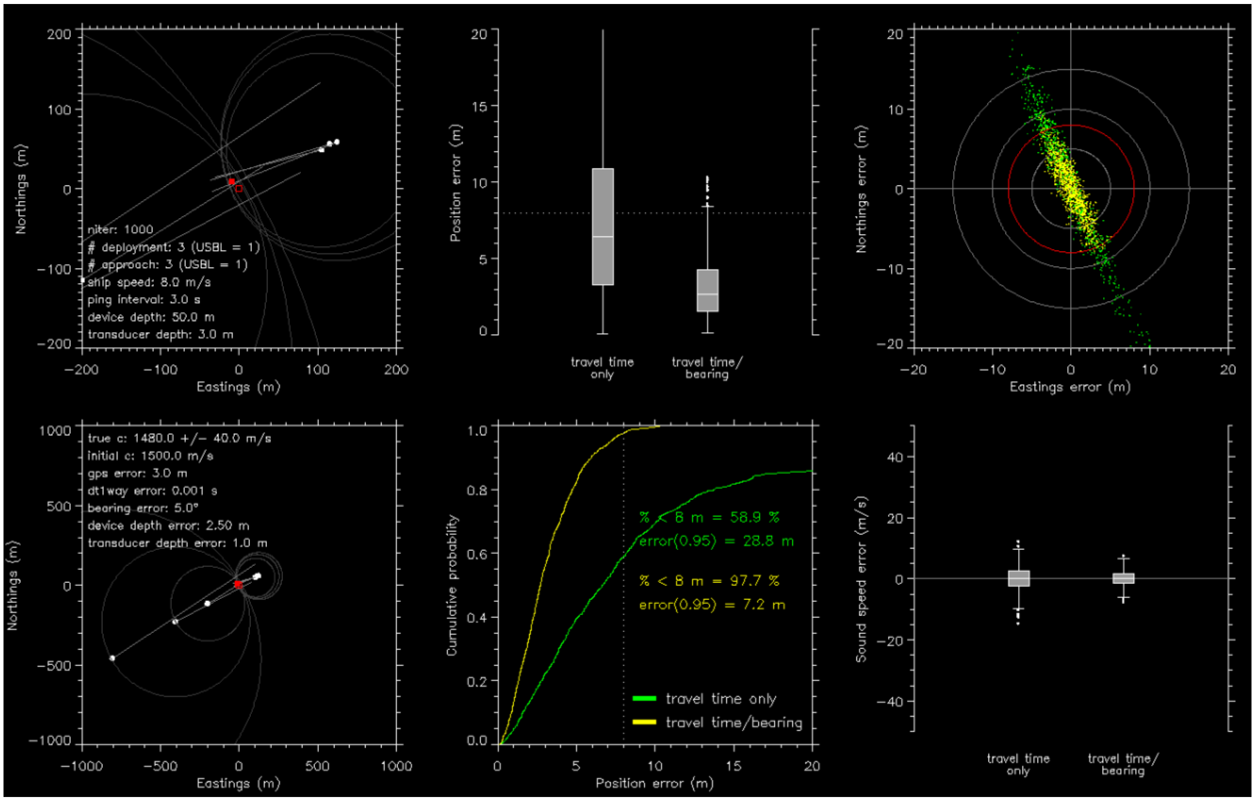


*Figure B5. Simulation of a fisher deploying a device and collecting 3 observations with a USBL array with $\pm 5°$ bearing error at a 3 second interval as the deployment ship moves away from the device at 8 knots. Shortly thereafter, a second approaching ship on a bearing 175° offset from the deployment ship's bearing (see Figure B2) collects 3 observations with a similar USBL array at distances of 0.125, 0.25 and 0.5 nautical miles.*

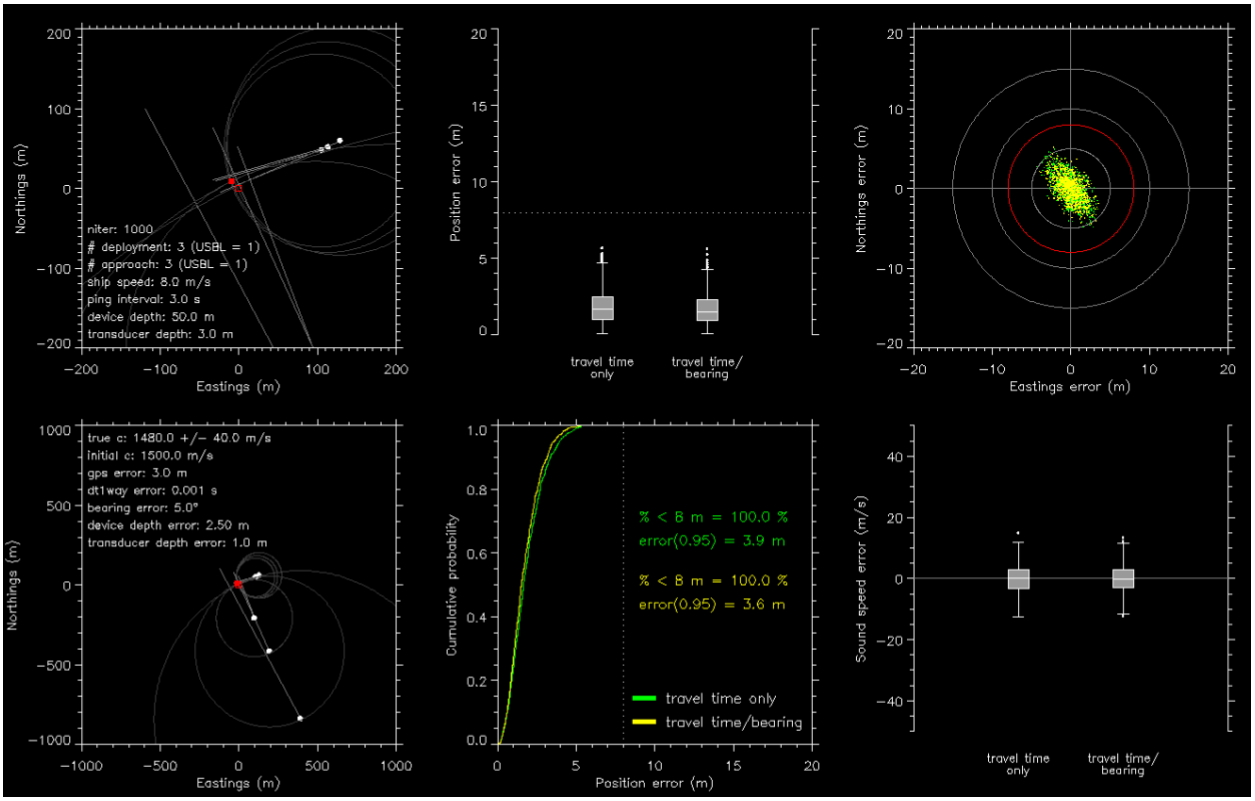


*Figure B6. Simulation identical to Figure B5, except the second ship approaches on a bearing 90° offset from the deployment ship's bearing (see Figure B2).*

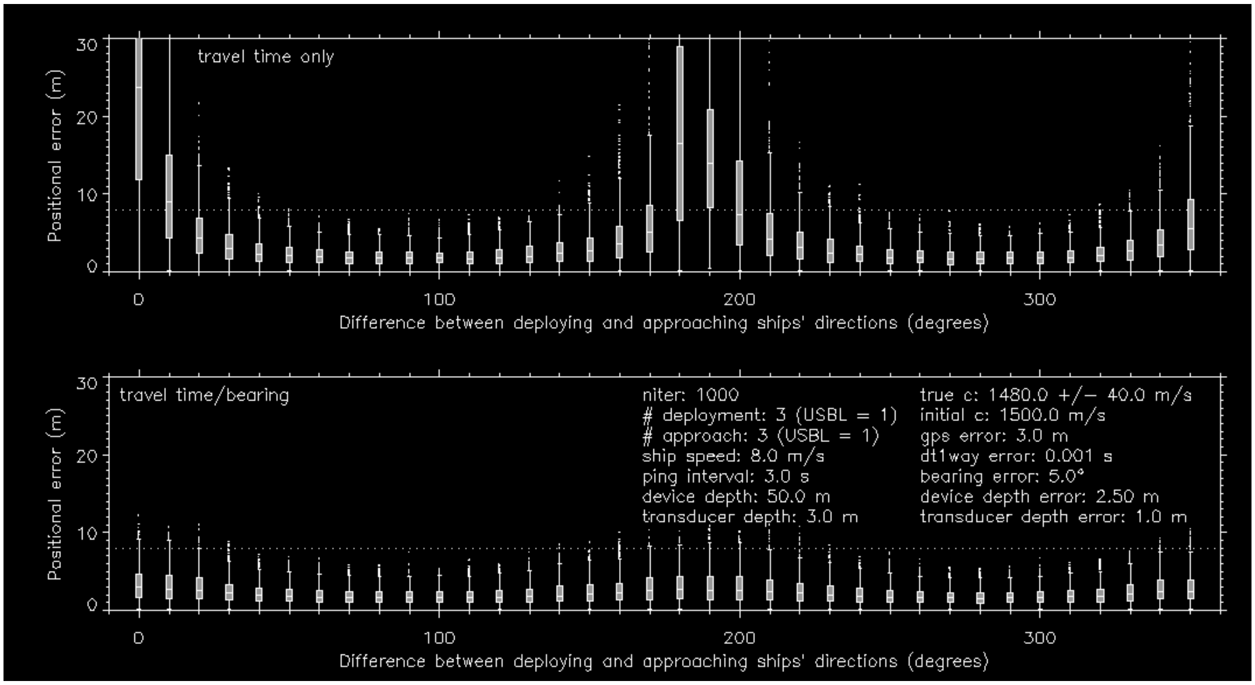


*Figure B7. Simulations comparing position error between localizations using the travel time only method (upper panel) and the travel time/bearing method (lower panel) as a function of observation geometry. Each boxplot shows the distribution of position errors for 1000 iterations. The angle of difference between deploying and approaching ships' directions on the x-axis is depicted in Figure B2.*

These simulations demonstrate the effect of geometry on the localization procedure. With the second ship approaching at a bearing 175° offset from the deployment ship's bearing (a poor geometry resulting in all observations distributed nearly on a straight line), the position error from the travel time only method is high; even with 6 observations (3 collected upon deployment, and 3 additional observations collected by the approaching ship), the percentage of position errors less than 8 m was only 59% (Figure B5). In contrast, localization with bearing information derived from USBL arrays on both the deploying and approaching ships produced very accurate positions, even with just 4 observations (3 collected upon deployment and 1 additional observation collected by the approaching ship; Figure B3). The percentage of position errors less than 8 m was 97.2%, and the distance below which 95% of the position errors occurred was 7.4 m after just the first observation is collected by the approaching ship (Figure B3), and these statistics did not change appreciably with the addition of new observations from the approaching ship (Figures B4 and B5).

The geometry improves markedly when the second ship approaches at a bearing of 90° offset from the deployment ship's bearing, and the location accuracies of the travel time only and the travel time/bearing methods in this scenario are nearly identical (Figure B6). For both methods, the percentage of position errors below 8 m is 100%, and the distances below which 95% of position errors occur are 3.9 and 3.6 m for the travel time only and travel time/bearing methods, respectively. By varying the geometry systematically (Figure B7), it is clear that the two localization methods are both sufficiently accurate when the second ship approaches at most directions relative to the deploying ship's direction of travel except near 0° and 180°. At these two extremes, the position errors of the travel time only method become large (too large to satisfy Requirement 2), whereas the position errors of the travel time/bearing method remain adequately low. A careful reader might note that the position errors of the travel time/bearing method increase near 0° and 180° in a manner similar to the travel time only method (albeit much smaller in magnitude). This is because most of the useful localization information contributed by the approaching ship is in the 1-way travel time measurement, not the bearing measurement (when the bearing measurement has ±5° error); the approaching ship is too far away for the bearing information to contribute very much to the localization procedure (i.e., the range-dependent weights in Eqs. 38 and 39 are quite low).

*Deploying ship has USBL array, but the approaching ship does not*

An identical set of simulations as the ones described above were conducted with the approaching ship lacking a USBL array. In these simulations, the approaching ship only contributes 1-way travel time measurements to the localization procedure and no bearing measurements. As above, the approaching ship collects observations along a track that is 175° offset from the deployment ship's direction of travel (recall that this 175° offset produces a poor geometry). Results are shown for the second ship collecting (1) one observation at 0.5 nautical miles distance from the device (Figure B8), (2) two observations at 0.5 and 0.25 nautical miles (Figure B9), and (3) three observations at 0.125, 0.25 and 0.5 nautical miles (Figure B10). A comparison of the travel time only localization method and the travel time/bearing localization method as a function of geometry is shown in Figure B11. Finally, additional simulations were run with the approaching ship collecting observations without a

USBL array along a track that is 90° offset from the deployment ship's direction of travel, which produces an excellent geometry. Results are shown for the second ship collecting (1) one observation at 0.5 nautical miles distance from the device (Figure B12), (2) two observations at 0.5 and 0.25 nautical miles (Figure B13), and (3) three observations at 0.125, 0.25 and 0.5 nautical miles (Figure B14).

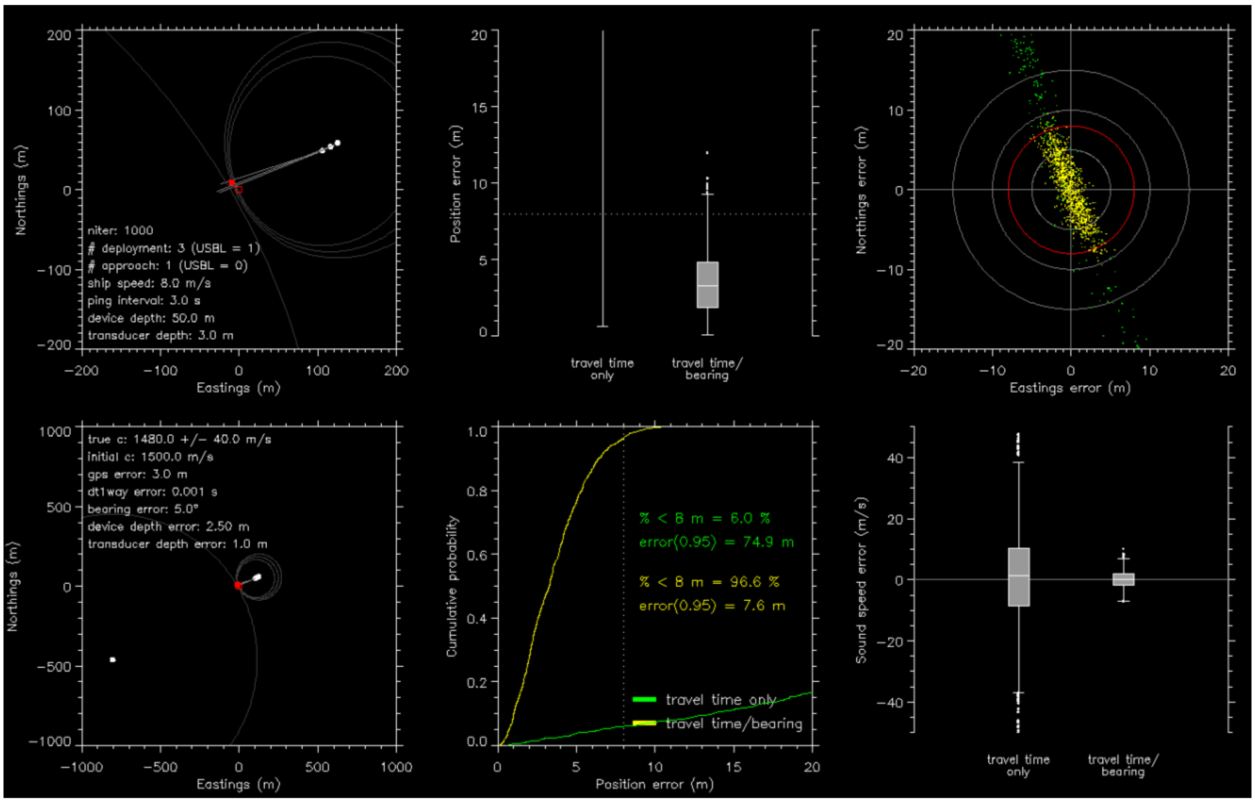


*Figure B8. Simulation of a fisher deploying a device and collecting 3 observations with a USBL array with $\pm 5°$ bearing error at a 3 second interval as the deployment ship moves away from the device at 8 knots. Shortly thereafter, a second approaching ship on a bearing 175° offset from the deployment ship's bearing (see Figure B2) collects 1 observation without a USBL array at a distance of 0.5 nautical miles. Since the approaching ship has no USBL array, no bearing measurements are shown for it (only approximate range circles; see caption for Figure B3).*

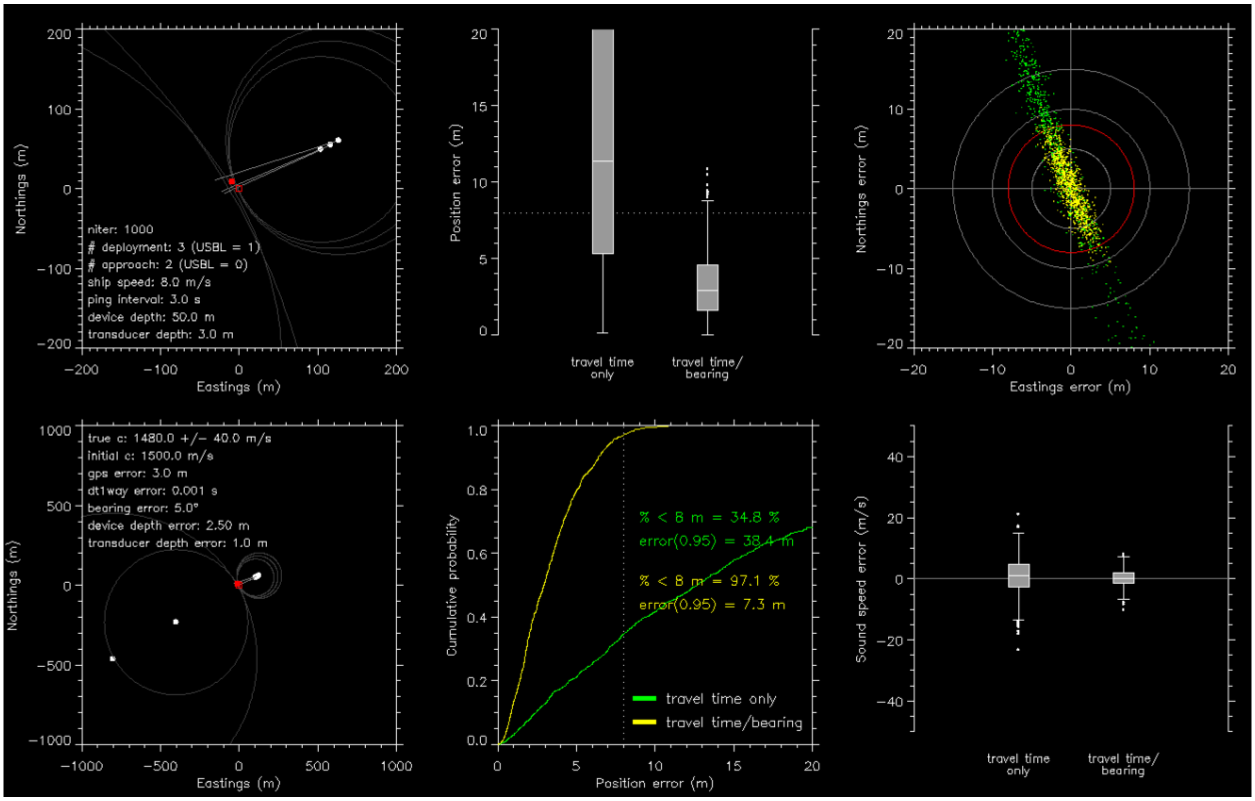


*Figure B9. Simulation of a fisher deploying a device and collecting 3 observations with a USBL array with ±5° bearing error at a 3 second interval as the deployment ship moves away from the device at 8 knots. Shortly thereafter, a second approaching ship on a bearing 175° offset from the deployment ship's bearing (see Figure B2) collects 2 observations without a USBL array at a distance of 0.25 and 0.5 nautical miles. Since the approaching ship has no USBL array, no bearing measurements are shown for it (only approximate range circles; see caption for Figure B3).*

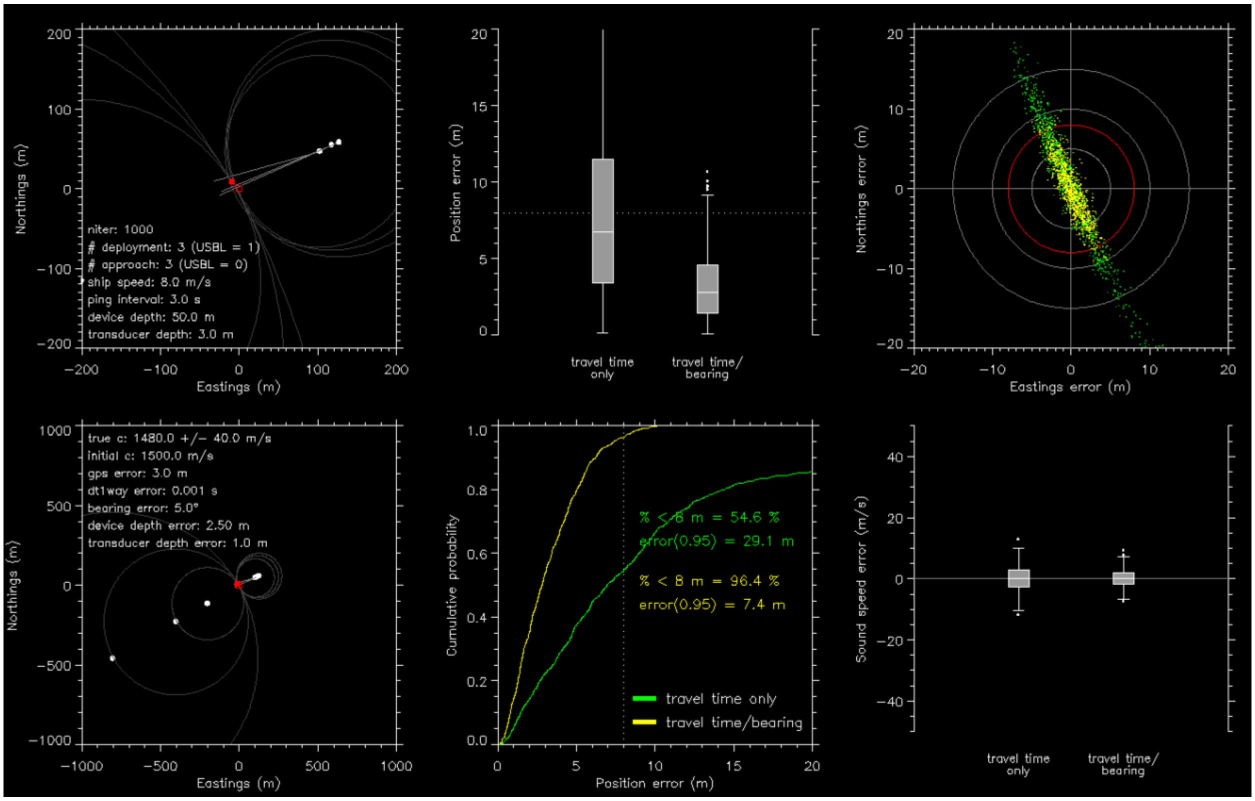


*Figure B10. Simulation of a fisher deploying a device and collecting 3 observations with a USBL array with ±5° bearing error at a 3 second interval as the deployment ship moves away from the device at 8 knots. Shortly thereafter, a second approaching ship on a bearing 175° offset from the deployment ship's bearing (see Figure B2) collects 3 observations without a USBL array at a distance of 0.125, 0.25 and 0.5 nautical miles. Since the approaching ship has no USBL array, no bearing measurements are shown for it (only approximate range circles; see caption for Figure B3).*

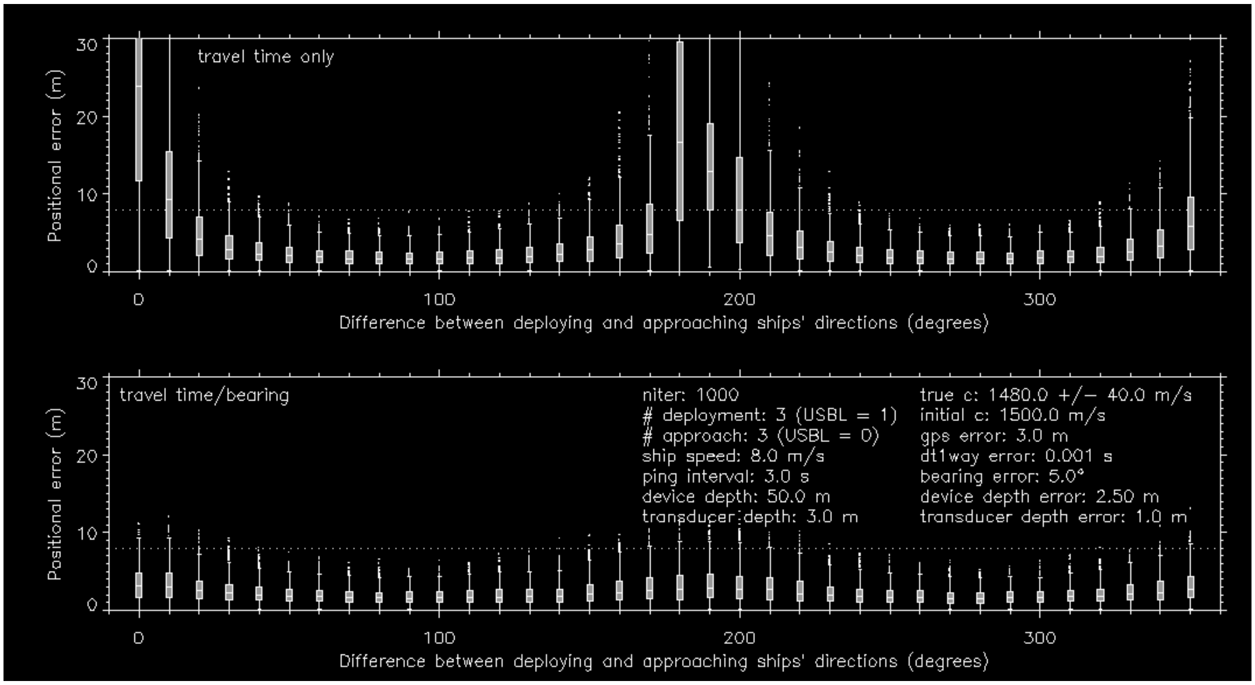


*Figure B11. Simulations comparing position error between localizations using the travel time only method (upper panel) and the travel time/bearing method (lower panel) as a function of observation geometry. Each boxplot shows the distribution of position errors for 1000 iterations. The angle of difference between deploying and approaching ships' directions on the x-axis is depicted in Figure B2. This plot is identical to Figure B7, except the approaching ship in the simulations depicted in this figure has no USBL array.*

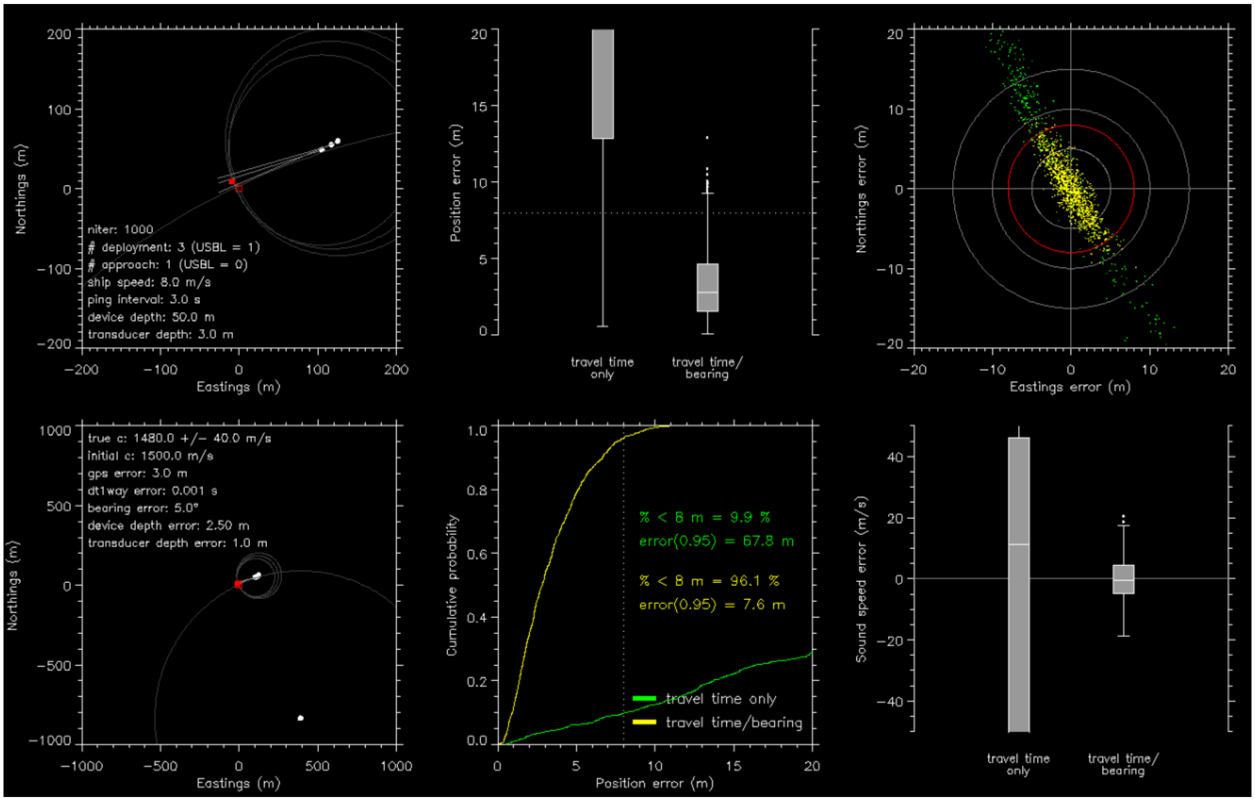


*Figure B12. Simulation of a fisher deploying a device and collecting 3 observations with a USBL array with ±5° bearing error at a 3 second interval as the deployment ship moves away from the device at 8 knots. Shortly thereafter, a second approaching ship on a bearing 90° offset from the deployment ship's bearing (see Figure B2) collects 1 observation without a USBL array at a distance of 0.5 nautical miles. Since the approaching ship has no USBL array, no bearing measurements are shown for it (only approximate range circles; see caption for Figure B3).*

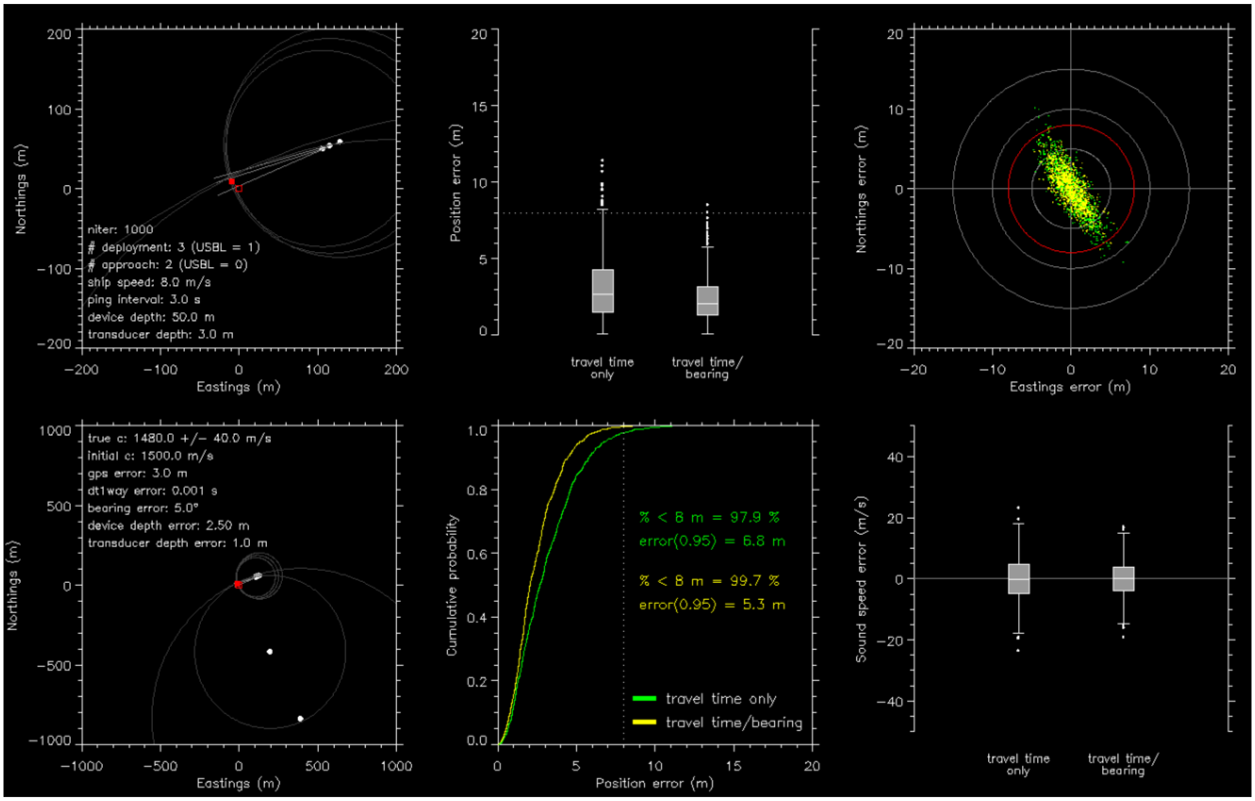


*Figure B13. Simulation of a fisher deploying a device and collecting 3 observations with a USBL array with ±5° bearing error at a 3 second interval as the deployment ship moves away from the device at 8 knots. Shortly thereafter, a second approaching ship on a bearing 90° offset from the deployment ship's bearing (see Figure B2) collects 2 observations without a USBL array at a distance of 0.25 and 0.5 nautical miles. Since the approaching ship has no USBL array, no bearing measurements are shown for it (only approximate range circles; see caption for Figure B3).*

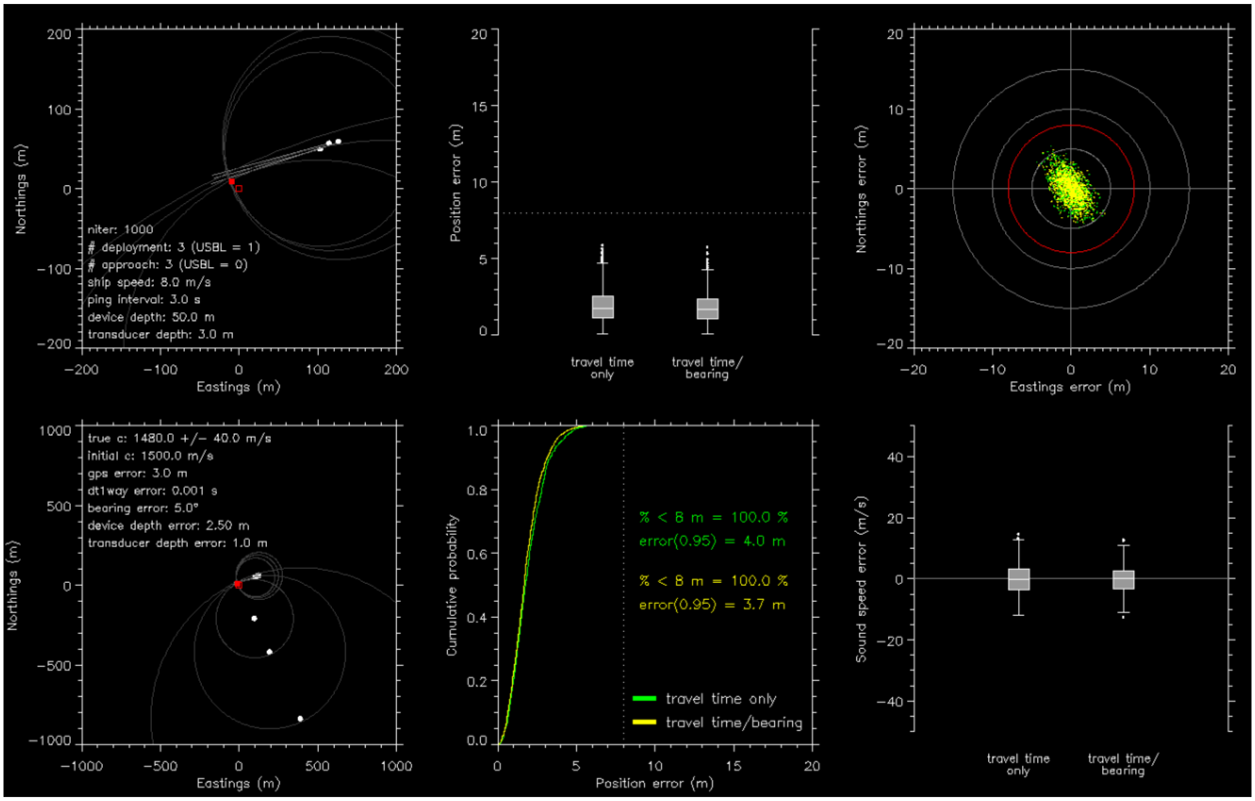


*Figure B14. Simulation of a fisher deploying a device and collecting 3 observations with a USBL array with ±5° bearing error at a 3 second interval as the deployment ship moves away from the device at 8 knots. Shortly thereafter, a second approaching ship on a bearing 90° offset from the deployment ship's bearing (see Figure B2) collects 3 observations without a USBL array at a distance of 0.125, 0.25 and 0.5 nautical miles. Since the approaching ship has no USBL array, no bearing measurements are shown for it (only approximate range circles; see caption for Figure B3).*

The purpose of this set of simulations is to compare localization accuracy between scenarios where the approaching ship has a USBL array (Figures B3-6) and where the approaching ship lacks a USBL array (Figures B8-11). These results indicate that there is no difference in position accuracy with or without a USBL when the approaching ship collects 1 observation (Figures B3 and B8), 2 observations (Figures B4 and B9), or 3 observations (Figures B5 and B10); in all these cases, the percentage of position errors less than 8 m was approximately 97%, and the distance below which 95% of the position errors occurred was approximately 7 m. These results are independent of geometry; Figures B6 and B11 were created with identical simulations except the presence (Figure B6) or absence (Figure B11) of a USBL array on the approaching ship, and they show identical results.

These results suggest that the best results are obtained when the deploying ship is equipped with a USBL array. The utility of the bearing measurements obtained immediately after deployment can be estimated as the difference between the travel time only and travel time/bearing methods shown in Figures B8-10 (for a poor geometry) and B12-14 (for a good geometry), since the only bearing information in these simulations is provided by the deploying ship. In these simulations, the bearing information collected immediately after deployment is critical to achieving sufficient position accuracy (i.e., < 8 m position error) when the geometry is poor (Figures B8-10) or when there is only a single observation from the approaching vessel (Figure B12). For a good geometry, the bearing information from the deploying vessel is less important when the approaching vessel is able to collect 2 or more observations (Figures B13,14). This is the reason why the localization procedure seeks to have an approaching or passing vessel collect localization information (1) at 0.125, 0.25 and 0.50 nautical mile distances and (2) in different quadrants; this increases the chances that there will be a good geometry and that enough observations will be collected to achieve sufficient accuracy if the deploying and approaching/passing ships are not equipped with USBL arrays. This is a methodological approach to reducing the need for a USBL array owing to its cost and complexity.

*What happens if there is no approaching vessel to collect more observations?*

If there is no approaching vessel, there is no risk of gear conflict with another fixed fisher, as there is no one to set gear next to or on top of the gear on the sea floor; thus, the accuracy of the position estimate is irrelevant. If another fisher does approach the gear, then the cloud will direct her or his ship to collect observations to improve the position accuracy. The cloud will ask this ship 3 times to collect observations: once when it is within 0.5 nautical miles, again when it is within 0.25 nautical miles, and again when it is within 0.125 nautical miles of the device. With these 3 additional observations, the gear location should be sufficiently accurate for the approaching fisher to avoid setting over the extant gear.

One question that remains to be answered is whether the initial position estimate is sufficiently accurate for mobile fishers to avoid gear conflict with fixed gear. The initial position estimate will be the ship's position when the gear was deployed. The mobile fleet will not have acoustic modems or USBL arrays to allow the collection of observations (they will receive regular position updates from the cloud via satellite communications), so if they closely approach any gear that has not been accurately localized using the methods and procedures described here, there is a potential risk of gear conflict. If mobile fishers typically tend to stay more than a few tens of meters from fixed gear, then this initial position inaccuracy should not be a problem.

*Conclusions*

If approaching/passing ships only ever collected observations perpendicular (at 90° or 270°) to the direction of travel of the deploying ship, then USBL arrays would not be needed to localize devices on the sea floor; 1-way travel time measurements alone would be sufficient (e.g., Figures B13,14). Of course, this is not at all the case, since fishers approach deployed gear from all directions. USBL arrays are the only means to provide sufficient position accuracy when the geometry of observations is poor (e.g., Figures B8-11), and this is particularly true when the deployment vessel uses a USBL array. Thus, if gear owners wish to improve the position accuracy of their own gear and by doing so, hopefully reduce the chance of gear conflict with others because of position inaccuracy (i.e., others set on top of them because the gear is not where the system says it should be because of localization inaccuracies), they may elect to purchase a USBL array for their ships. In other words, purchasing and using a USBL array may very well be in the fisher's own interests to prevent others from laying over their gear. However, there are many fishing situations where the density of fixed fishing gear is low and 8 m position accuracy is not needed. For example, if there were an area where fishers typically set their gear at least 100 m apart (i.e., the length of a football field or about 5.5 lengths of a 60 ft fishing vessel between trawls), then the position accuracies achieved with 1-way travel time measurements only (shown in the top panels of Figures B7 and B11) would be acceptable, even in the worst-case scenario presented here and when the geometry of observations is poor. Hence, the advantages of using a USBL array may be limited to areas of high fixed fishing gear density where high position accuracy is required, and USBL arrays can be omitted elsewhere. The localization procedure described above allows localization to occur with or without bearing measurements from USBL arrays, so the same procedure can be used for all fishing situations, including low-density and high-density fishing areas, as well as the borders in between where some fishers have USBL arrays and some fishers do not.

**Appendix C: Details of acoustic communication standard**

This appendix provides a detailed design specification for the underwater acoustic communications (acomms) algorithms which form part of the acomms standard known as FONTUS. The FONTUS design is informed by NATO's JANUS Standard, and is similar in structure and function, but is not a repeat of JANUS. We provide a complete specification for the physical structure of the transmitted waveform, and a description and implementation for a suggested receiver. The latter incorporates several heuristic enhancements beyond the JANUS standard which address the requirement for high platform speed.

# FONTUS: Frequency Hopping Acoustic Communication Standard for On-Demand Fishing

**Table of Contents**

# 1 INTRODUCTION

This document describes the simple, robust, low data rate signalling scheme chosen as the first signalling method to be developed for the FONTUS modem. The method is known as frequency hopped (FH), binary frequency-shift keyed (BFSK), non-coherent modulation. It conveys information at a nominal 40 bits per second (bps) and is highly tolerant of noise, multipath, and interference from other modems. The method provides a basic header packet of 7 bytes (56 bits) which may be an independent packet or which may precede a cargo packet containing additional information which eventually can be carried by a variety of modulation schemes. We emphasize that any cargo packet follows immediately behind the header packet, and is not a separate transmission.

We begin with an introduction to basic communications theory as it relates to underwater acoustic communications (acomms). We attempt to keep the discussion as non-mathematical as possible, but a thorough appreciation of the details will require some academic background in both digital signal processing and communications theory.

The method described in this document is similar to the scheme initiated by the author for NATO, a method eventually named JANUS. JANUS is an open-source signalling scheme designed to facilitate interoperability among Navies and merchant shipping. However, we have purposely designed the FONTUS modem to be distinctly different from the JANUS version of an FH-BFSK in both physical structure and in the organization of the information carried in the header packet. We can, in future, provide FONTUS with a JANUS-compatible version if desired.

All FONTUS design details are discussed later in this paper, but we begin in Table 1.1 with a glossary of terms and a listing of the core parameters of the waveform which define the Standard.

Table 1.1. Acronym and Parameter Dictionary

| Parameter or Acronym | Definition, value, or use |
|---|---|
| W | Signal Bandwidth, approximately 7520 kHz (not including sidelobes) |
| Fc | Center Frequency, 25,000 Hz |
| Fsb | Baseband sample rate (complex samples/sec) = 20480 samples/sec |
| Fsp | Passband ample rate (real samples/sec) |
| chip | An elemental waveform, in our case a short sinusoid |
| Tc | Duration of a chip = 12.5 ms |
| Nchip | Total number of chips in a basic header packet = 176 |
| Nsynch | Number of chips in the acquisition portion of the header packet = 32 |
| Nblock | Number of possible “hops” across W = 46 |
| Q | The interleaver prime number, fixed for an FONTUS header packet = 13 |

| | |
|---|---|
| Qsize | Prime number informing Galois algebra calculations = Nblock+1 =47 |
| SNRi | Input signal to noise ratio, in decibels |
| SNRo | Output signal to noise ratio, in decibels |
| AWGN | Additive Gaussian white noise (bandlimited to approximately >/= W Hz) |
| FEC | Forward Error Correction, accomplished with rate ½, constraint length 9 convolution encoding |
| CRC | Circular Redundancy Check. Error check vector of 8 bits (1 byte) |
| HFM | Hyperbolic Frequency Modulated signal: Wh = 8000 Hz, Th = 50 ms. |

We note that the combination of chip duration and baseband sample rate is designed to provide a power of 2 integer number of samples across the chip. This is a necessary design consideration and must be considered when choosing a passband sample rate to ensure that a third-party modem will properly obtain the correct number of chip samples upon reception of the packet.

In the accompanying repository we provide four primary Matlab routines which: a) build the symbol stream to be transmitted; b) build the baseband waveform; c) build a vector of AWGN; and d) perform a very simple simulation with a basic receiver. Supporting routines are also provided. We include tutorials at the end of this appendix on several topics pertinent to FONTUS.

# 2 BASIC COMMUNICATIONS THEORY

The primary function of modems is to transmit and receive signals that represent digital data—binary ones and zeros—over what usually is a hard-wired link such as a telephone line or through the use of electromagnetic waves such as a microwave link. In fact, the word modem is derived from the terms modulation and demodulation, which refer to the coding and transmission, and the receiving and decoding of digital data, respectively. Two key factors measure a modem's performance: speed and reliability. Speed, is measured by determining the number of <u>information</u> bits transmitted per second, which is referred to as the data rate, or bit rate. Reliability is sometimes measured by determining the symbol error rate, which is the ratio of the number of transmitted symbols received in error to the total number of symbols transmitted. We prefer a different definition of performance, which is <u>packet</u> failure or success, which simply addresses the question: did the packet get through the channel successfully?

Except when noise interference is high, modems that transmit and receive data over phone lines or microwave links typically function nearly error free, and at data rates of 128,000 bits per second (bps) or more. In addition, repeater systems allow virtually unlimited transmission ranges. Those same performance factors are also used to measure the capabilities of undersea modems. However, when the transmission medium is water and the transmitted signals are acoustic, a number of physical barriers exist that constrain those performance factors which are not present in either wire or microwave links.

The major factors that constrain the performance of any communications system that uses water as a communications medium are the relatively slow speed of sound in water, the signal fading characteristics due to sound absorption, the multipath interference due to sea surface and sea floor reflections, and reflections from nearby objects.

The speed of sound in seawater, on average, is about 1500 m/s. This is compared to electromagnetic signals that travel at nearly the speed of light. However, the relatively slow speed of sound in seawater has no direct effect on the data rate of the modems; it affects only the latency between the transmission of a signal and its reception.

Signal fading is primarily caused by spreading loss and the absorption of sound in water, but it is also caused by destructive interference due to multipath, a situation where signals at similar frequencies nearly cancel each other. This frequency-dependent fading occurs when a multipath-induced reflection of the transmitted signal arrives at the receiving transducer at the same time as a transmitted signal of the same frequency. The result is a reduction in the amplitude of both signals. Signal fading due to spreading loss is a result of the dispersion of energy as it radiates outwardly from the transmitting transducer. Signal fading due to the absorption of sound in water increases with increasing frequency. To a lesser extent, environmental factors such as temperature, pressure, and salinity also affect absorption, and absorption also occurs at the sea floor.

Multipath is the factor that most restricts both the data rate and the reliability of an acoustic modem. Multipath, which is particularly severe when attempting to communicate over the horizontal channel in shallow water (or in a test tank), is the result of sea-surface and sea-floor reflections, reflections from objects that are near the receiving modem, and refractions from thermal gradients and water turbulence. Using directional remote transducers reduces the effects of multipath when the transducers are aimed at each other, yet reflections from objects such as piers or boats that are near the receiving transducer cause overlapping of the received signals, resulting in decreased reliability. In addition, multipath is usually not stationary; hence even techniques used to track and reduce the effects of multipath do not significantly improve modem performance in increasingly dynamic multipath situations. As a result, multipath forces continual trade-offs in the speed, the reliability, and the cost of acoustic modems.

The primary advantages of FH-BFSK over other schemes developed for underwater acoustic communications are the following:

- Simplicity of design. This is probably among the least complicated forms of acoustic communications yet devised.
- Robust to noise. This signal should be useable when the signal to noise ratio (SNR) in a given band is at better than -4 dB (for our selection of frequency and bandwidth).
- Robust without tracking for "reasonable" amounts of relative speed (range rate), although the degree of robustness is frequency specific.
- FH-BFSK is the optimal approach to use for asynchronous, multi-access (multi-user) applications.
- It may be optimal for robustness in the presence of all types of interference, including intentional jamming.
- Depending on SNR, FH-BFSK may be quite difficult for third parties to detect by conventional means – for example, by energy detectors of all forms.
- Because FH-BFSK is a "constant envelope" waveform, a transmitter is not concerned with amplitude crest factors, and thus may allocate maximum power to the transmission.

### 2.1.1 FONTUS System Components

The diagram below illustrates the elements of a FONTUS communication system. A FONTUS source, or transmitter, transmits data via an immersed transducer, through a signal path that is subject to noise, arriving at another immersed transducer before passing to a FONTUS receiver. Note that noise may also be added at other stages in the process, particularly at the output of the source and before transmission along the sea path.

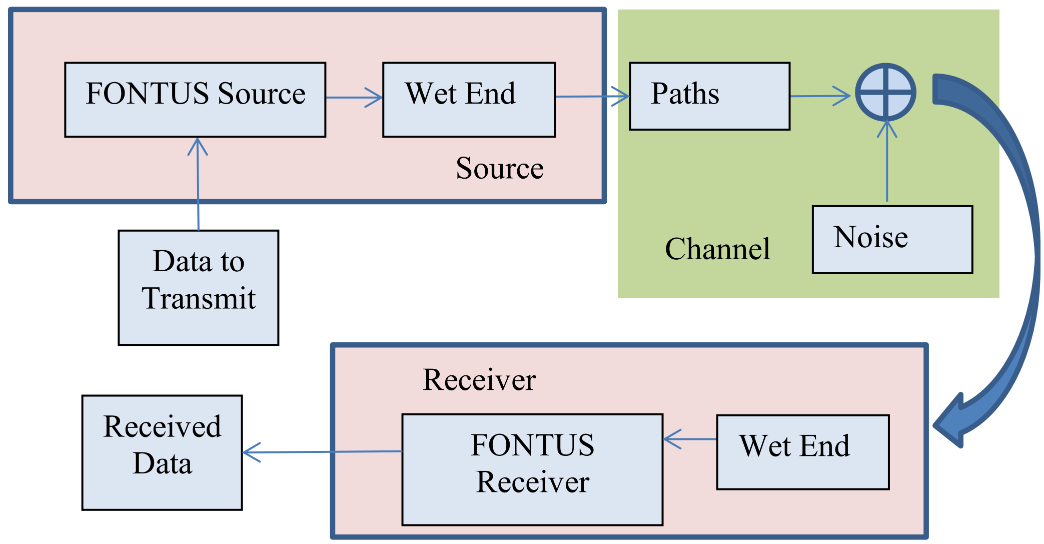


*Figure C2-1 - A FONTUS modem system.*

### 2.1.2 The FONTUS Modem transmitter (overview)

As the purpose of a modem is to transmit information across a channel, we first discuss the methods we choose to use to prepare information for transmission. We assume here that the data to be transmitted are provided to the modem in the form of binary "bits" (that is, symbols drawn from the set of zeros and ones, which we describe as {0,1}). Thus, we begin with a data stream of N binary symbols. While we could directly convert this stream to on-off pulses, this would provide an extremely inefficient modem. Instead, we add complexity to this data stream by adding "redundancy" and reshaping the stream to add protection against "burst" errors, to be described later. We note here the use of some specific terminology:

1. Binary information data are called <u>bits</u>
2. Bits subjected to redundancy are called <u>coded symbols</u>
3. Coded symbols are transformed into <u>channel symbols</u> through the modulation process
4. "Chip" is the term used to identify the actual physical waveform which conveys a channel symbol through the channel.

Redundancy can be achieved simply by repeating each data symbol multiple times. At the receiver, the expectation is that, even if the channel causes failure to receive one of the repeats, the others will compensate for the loss. This is valid and may be used in the second stage of this project. Note, however, that most forms of redundancy increase the duration of the transmitted waveform, thus decreasing the effective data rate.

For all signalling schemes we will use a separate form of redundancy known as forward error correction coding (FECC). This is a mathematical procedure which generates a symbol stream with many coded symbols sharing the information carried in one data bit.

We typically add one additional feature to a modem signalling scheme which specifically is called a cyclic redundancy check (CRC). This is an addition of either 8 or 16 special bits appended to the end of the information bit stream which serve to identify the success or failure of the packet at the output of the receiver. A complete transmit process is shown in Figure C2-2.

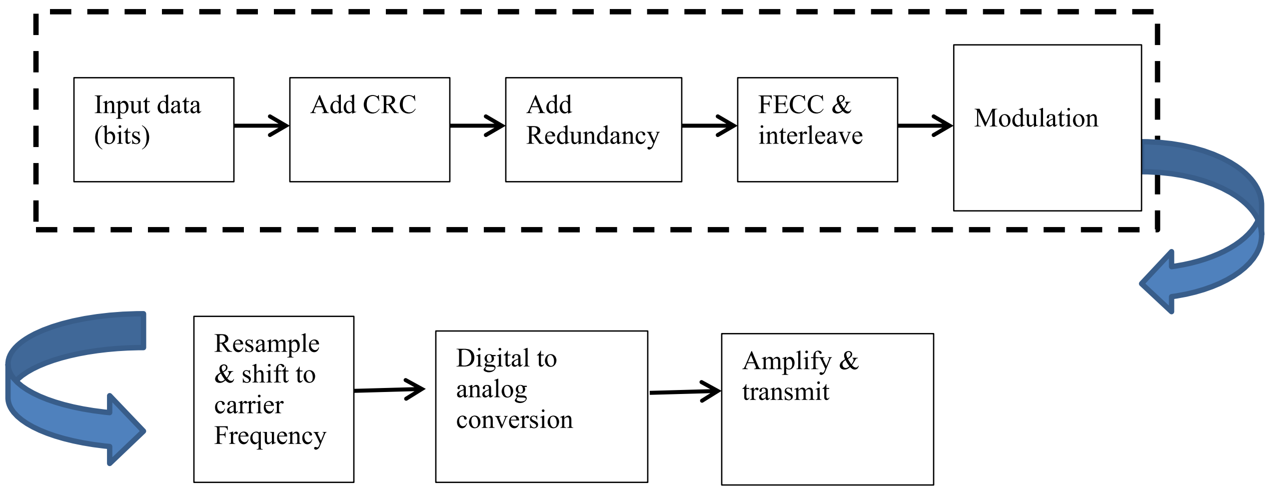


*Figure C2-2. Preparation of data for transmission.*

### 2.1.3 Convolutional (forward) error correction

The easiest way to describe convolutional forward error correction (CFECC) is by use of a picture, such as Figure C2-3. Here we show the incoming data stream (bits) entering a 2-path structure in which every bit is progressively multiplied by a fixed number (2K) of binary symbols, with all multiplications summed at each step. Each step is identified with the delay symbol $z^{-1}$. At each step two coded symbols are extracted, and they are interleaved, one after the other. This is not as simple as described, as both the multiplication and summation are conducted, not with real numbers, but within a "finite field" structure, which always returns symbols of the same nature as the input data stream. That is, if the input stream is {0,1}, then all output coded symbols are also {0,1}. Careful review will show that each input bit affects 2K output coded symbols. We call the structure a rate ½ (2 paths), constraint length K convolutional encoder. A CFECC is typically used in acomms rather than other types of FEC because it is independent of the length of the input data. A general rule for CFECC is that the length of the input information must be greater than about 5K.

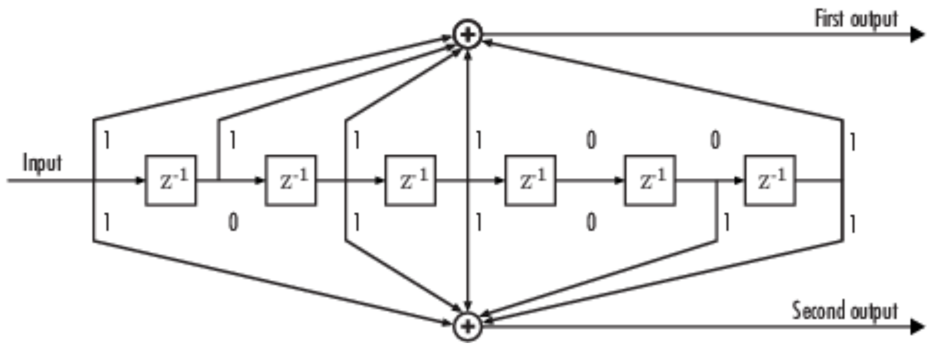


*Figure C2-3. A typical rate ½ CFECC.*

### 2.1.4 Interleaving

A peculiar feature of convolutional forward error correction coding is that the decoder (discussed below) is very sensitive to "burst" errors, which means groups of coded symbols which together are contaminated with noise or faded by multipath. To reduce this problem, we typically interleave the output of the encoder prior to modulation and transmission. Some of the received (now interleaved) channel symbols may have burst errors, but, upon deinterleaving (that is, reversing the interleaving), these bursts are separated and made rather more random. We use a "prime number" interleaver as it leaves the length of the encoded symbol stream unchanged.

### 2.1.5 Modulation

The next task for the transmitter is to convert the coded channel symbols into a representation which can be transformed as acoustic energy projected into the water. This is called modulation, and is completely dependent on the nature of the signalling scheme we are using. In order to describe the specific implementation, we use for FH signalling, it is necessary first to describe several signal processing concepts. The first of these is the Fourier Transform. The Fourier Transform is more general than the so-called Fast Fourier Transform (FFT), but for our purposes they are the same, so we will simply refer to the forward FFT (FFFT) and the inverse FFT (IFFT) (see Tutorial A). We only consider signals (chips, in this case) of finite duration. The FFT is a transformation from the time domain to the frequency domain.

A (complex, analytic) time series waveform s(n) might be a tonal, or single frequency ($f_0$), chip, as defined by eqn (2.1).

$$s(n)=\exp(i2\pi f_0 n\delta t),\ 0\leq n \leq(N-1) \qquad (2.1)$$

This tonal exists only at a frequency $f_0$ for a duration $0\leq n\delta t \leq T$, with $i = \sqrt{-1}$, and $\delta t = 1/Fsb$. When we apply an FFFT to this tonal, we essentially do a pattern recognition with a finite set of possible tonal signals. The one pattern which best matches the chip produces the largest value in the output of the FFFT. All other patterns will show a reduced, or zero response to the chip. Figure C2-4 shows, in the upper plot, a time series representation of a (baseband) tonal at Fc = 28000 Hz with a duration of Tc = 12.5 ms second. The power spectrum for this signal, shown in the lower plot, is the magnitude squared of the FFT of this waveform.

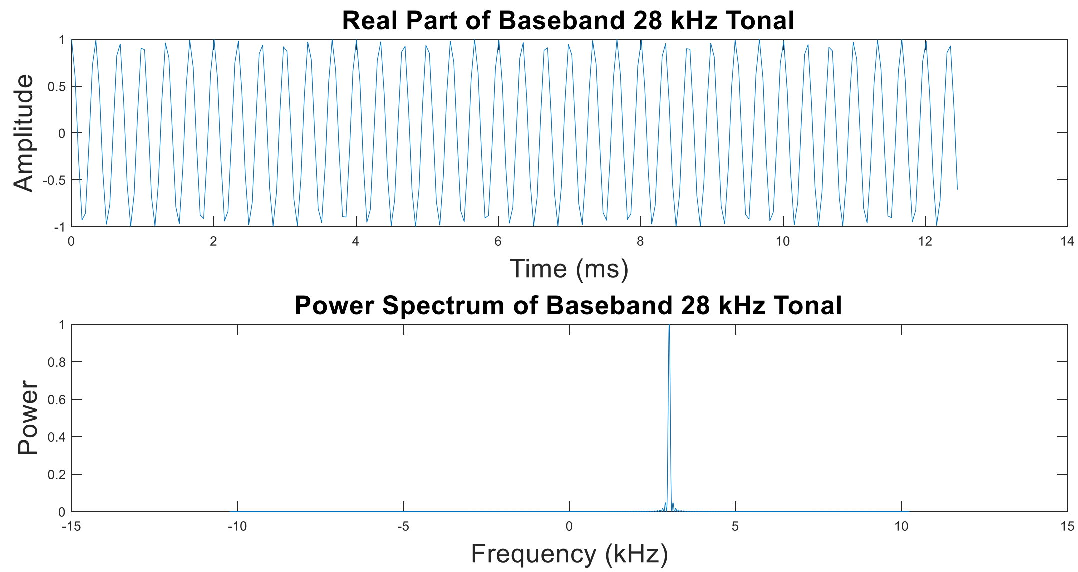


*Figure C2-4. Time series and power spectrum for a tonal signal of 12.5 ms at 28 Hz.*

A broadband signal has a very different character, as shown by the baseband version of our 8,000 Hz HFM chirp in Figure C2-5. The (real part of the) time series for this 50 ms chirp is shown in the top plot, and the power spectrum is shown in the lower plot.

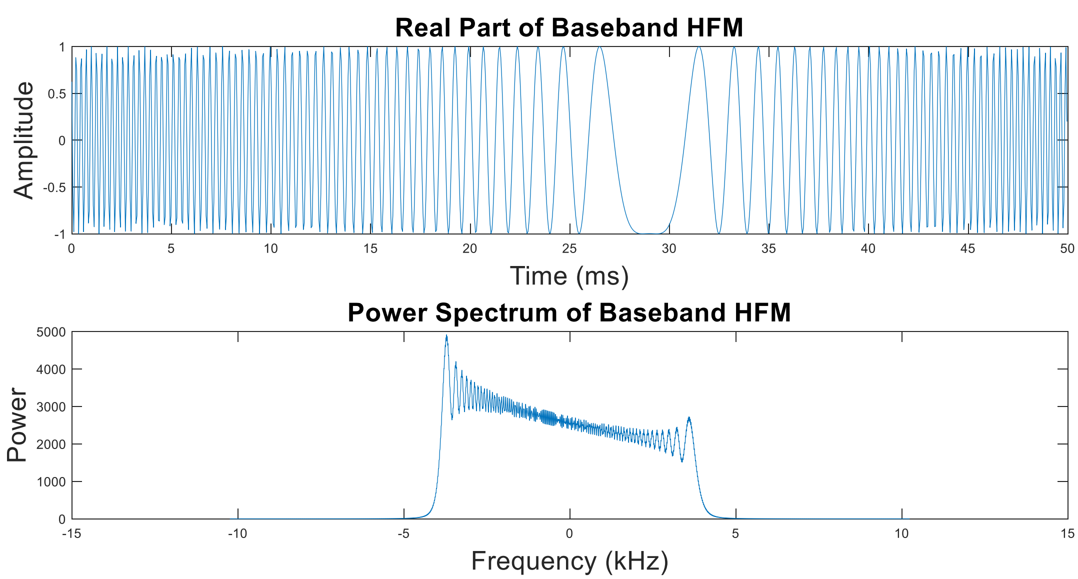


*Figure C2-5. Time series and power spectrum for a baseband 50 ms x 8 kHz HFM signal.*

The FONTUS modem deliberately chooses a simple but robust digital coding technology that is well-known and that can easily be adopted by a wide range of existing systems. The physical coding scheme is known as Frequency-Hopped (FH) Binary Frequency Shift Keying (BFSK), as shown in **Error! Reference source not found.**re C2-6. FH-BFSK has been selected for its known robustness in the harsh underwater acoustic propagation environment and simplicity of implementation. FH-BFSK is a common phase-insensitive (noncoherent) physical encoding technique, already used in commercially-produced modems, and is known to be robust to a variety of environmental conditions. It is also robust to packet collision, supporting a number of modems with simultaneous access that is valuable in a simple protocol with a limited medium access control complexity.

With FH-BFSK modulation, we select one coded symbol from the interleaver and assign it to one of two adjacent tonal frequencies. If the symbol is a 0 (zero), we place it in the higher frequency location (a "slot"). If it is a 1 (one), we place it in the lower frequency slot. The two slots together form a "block" of frequencies. We generate a time series for this tonal. If we compute the power spectrum of this slot, it will appear similar to that of Figure C2-4.

FH-BFSK uses a sequence of short duration tones (chips) to transmit binary values. The transmitter produces only a single tone at any time but this tone may be one of two adjacent frequencies in a block to represent a binary value (symbol). The important idea behind FH is that the location of the block in the wider available operating band is determined by using an algorithm that pseudo-randomly finds locations that are distinct from all others- as much as is possible.

Figure C2-6 shows the time-frequency plane for an FH BFSK signal. Note that one block is generated each chip duration (i.e., a baud period), and that the location in frequency of the blocks appears to be random.

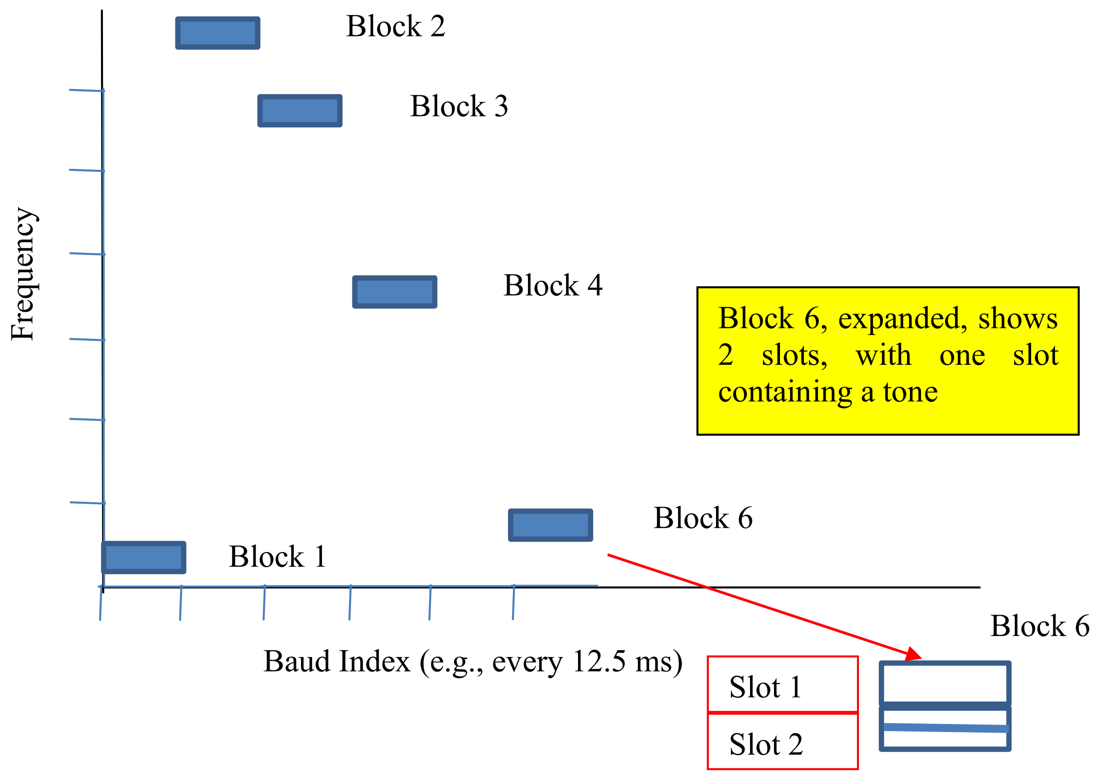


*Figure C2-6. A time-frequency representation of an FH BFSK waveform.*

The hopping algorithm employed for FONTUS modulation has a unique property that dramatically minimizes collisions among mutually interfering waveforms. We can frame the algorithm to reflect the specific implementation for FONTUS signalling as follows. For any continuous sequence of 46 hops, there will be no more than 3 collisions, no matter the portions of the waveforms which overlap. In Figure C2-7 we show three different hopping conditions. The blue + shows our desired waveform, the red O shows a 1 baud delay of the same waveform, and the green X shows a 10 baud delay. There are no collisions among any of these over the 50 baud periods shown.

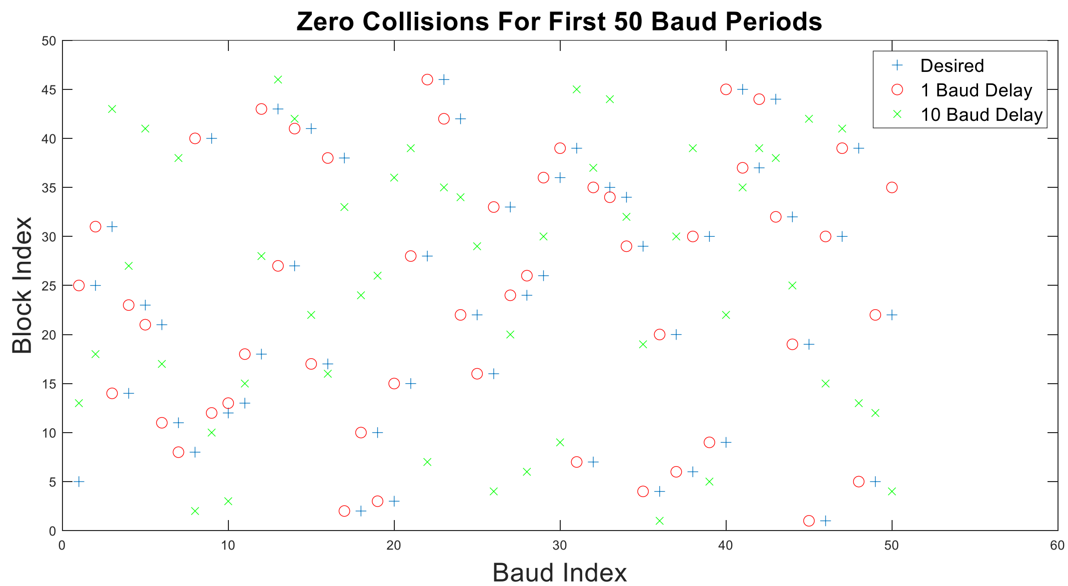


*Figure C2-7. Demonstration of minimal to no collisions among three time-shifted versions of the same waveform.*

# 3 MATHEMATICAL AND CODING DETAILS

One of the key features of our FH-BFSK design is the pseudo-random nature of the tonals (chips) placed in the time-frequency plane. Until now we have qualitatively discussed this, but in this section we provide the design details. While we try to be as tutorial as possible, it will be useful if the reader has some background in finite field mathematics (specifically Galois mathematics). The nature of the waveform is determined by several key relationships among sample rate, chip duration, and bandwidth. For our purposes we assume the following:

1. Waveform bandwidth = W = 7520 Hz
2. Chip duration = Tc = 12.5 ms
3. Sample Rate = Fsb = 20480 samples per second when the waveform is baseband and analytic (described in the Tutorial B)
4. N = number of samples per chip (=Tc*Fsb)

Each chip (tonal) has a bandwidth of exactly b = 1/Tc Hz. From Figure C2-6, each block therefore uses 160 Hz of bandwidth. The number of available blocks then is WTc/2 = 46.

Please refer to the Matlab program FONTUS_MESSAGE.M

For discussion purposes, our test message (information packet) will be

message = 50,49,16,85,119,51,238

which translates to a 56-bit binary message of

Binary message =
[0 0 1 1 0 0 1 0 0 0 1 1 0 0 0 1 0 0 0 1 0 0 0 0 0 1 0 1 0 1 0
1 0 1 1 1 0 1 1 1 0 0 1 1 0 0 1 1 1 1 1 0 1 1 1 0]

### 3.1.1 The Cyclic Redundancy Check specification

Packet integrity is ensured using an 8-bit Cyclic Redundancy Check (CRC). The version used here was designed for JANUS and is included in the repository as CRC.M. The 8 bits of the CRC are appended to the 56 bits of the FH-BFSK. The 8-bit CRC for this packet is

CRC = [1 1 1 1 0 1 0 0]

In the provided Matlab code the final 64 bits of the message are referred to as ISymbols.

### 3.1.2 The convolutional encoding specification

A rate ½ convolutional encoder with constraint length 9 is applied to the 64 bits of information and CRC, resulting in 144 symbols of output. The generator sequences used for the encoder are:

$$g1(x) = 1 + x1 + x2 + x3 + x5 + x7 + x8 \tag{3.1}$$

$$g2(x) = 1 + x2 + x3 + x4 + x8$$

Prior to encoding, 8 zeros are appended to the data to flush the encoder, discarded at the receiver. The total number of symbols output by the encoder then becomes 2*(64+8) = 144. The convolution encoder follows the IS-95 CDMA standard.

For our test message, with CRC, the 144 coded symbols are

[0 0 0 0 1 1 0 1 0 1 0 0 0 1 0 1 0 1 0 1 1 1 0 0
0 1 1 0 0 1 0 0 0 0 0 1 1 0 0 1 0 0 1 1 0 1 1 0
1 0 1 1 0 0 1 1 0 1 0 1 1 1 0 1 0 1 1 0 1 0 0 0
1 0 0 1 1 1 1 0 1 0 0 0 1 0 0 1 0 1 0 1 0 0 0 1
0 0 1 1 0 1 1 0 0 0 1 1 0 0 0 1 1 1 0 0 1 0 0 1
1 0 0 1 0 1 1 0 0 0 0 0 1 1 1 1 1 0 1 1 0 0 0 0]

### 3.1.3 The Interleaving specification

A process called interleaving is applied to the 144-symbol message after the convolutional coding. The interleaving process separates each consecutive symbols by a constant spreading value, chosen to be a prime number selected according to the size of the message. For our FH-BFSK encoded message length of 144 symbols, a spreading value of Q = 13 is chosen. The output of the interleaver are referred to as channel symbols. For the test case, the channel symbols are

[0 1 1 1 0 1 1 1 0 0 0 0 0 1 0 1 0 1 0 0 1 0 0 0

0 0 1 1 1 1 1 0 0 0 0 0 1 0 0 1 0 1 0 0 0 1 0 1

1 1 0 1 0 1 1 1 0 1 0 0 1 0 0 1 1 1 1 1 1 0 1 1

1 0 1 1 0 0 0 1 0 1 0 0 1 0 0 1 1 1 0 0 0 1 0

0 0 0 1 1 1 0 1 0 0 0 1 0 0 1 0 0 1 1 1 1 0 0 1

1 1 0 1 0 0 1 0 1 0 1 1 1 0 0 0 0 0 1 0 0 0 0 0]

See Matlab routine ILEAVER.M, provided in the repository, for details.

### 3.1.4 The Frequency Hopping sequence specification

The order in which the 46 pairs of slots are used to encode the binary data is chosen to provide optimal Inter-Symbol Interference (ISI) rejection that could otherwise be caused by multipath or collision with FH-BFSK packets from other users. This pseudo-orthogonal Frequency Hopping (FH) sequence is fixed and therefore known to all potential receivers.

The FH indices are derived from Galois Field arithmetic using a primitive prime number to generate 46 frequency blocks to provide good orthogonality properties. The FH sequence is defined by an algorithm that, given a prime number Qsize (Qsize=47 for the FONTUS FH-BFSK, the number of tone pairs plus 1) and a number K (K is set to 3 for the FONTUS FH-BFSK standard) generates a pseudo-random sequence in the range {1,Qsize-1} following the procedure developed by T.S. Seay (1982)[1]. Note that Qsize is explicitly a function of the ratio of available bandwidth W divided by tonal bandwidth b. If W is reduced in isolation, then Qsize is reduced, with accompanying loss of protection against interference. See Matlab routine PRIMITIVE.M in the repository.

The heart of the sequence generation algorithm is essentially a matrix multiplication. A generator matrix is multiplied by a user parameterised row vector to create (Qsize-1) new sequence elements. The first column of the generator matrix is defined as [α0,α1,α2,…, αK-1]T where α is a number selected in conjunction with Qsize such that α modulo Qsize generates every number between 1 and Qsize-1. Remaining columns are generated by multiplying the first column of the generator by the previous column. The multiplication is carried out modulo Qsize and yields the Qsize-1 columns of the generator matrix.

Note, for acquisition purposes described below, we add 32 hops (tones) to the front of the message, creating a total of 176 hops.

For our FH-BFSK, α=5,Qsize=47, and K =3. Using <u>either</u> routine HOPINDEX.M or routine GIO_HOP_PATTERN.M, whichever is easier for you to follow, we obtain the following (first 25 of 176) hops:

slots = 5 25 31 14 23 21 11 8 40 12 13 18 43 27 41 17 38 2 10 3 15 28 46

Each number, when multiplied by 2b, specifies the exact lower frequency edge of a “block” of 2 tonal “slots,” one of which will contain a tone depending on the binary value of its channel symbol. Note for reference that a sequence number of zero (0) corresponds the lowest frequency block for a baseband waveform, while a sequence number of 46 identifies the highest frequency block.

The preceding only applies to the message portion, as the 32 acquisition tones have no information. For those, the tone selected is determined by the FH sequence number and whether the digital channel symbol is a ‘0’ or ‘1’.

[1]Mersereau & Seay, "Multiple Access Frequency Hopping Patterns with Low Ambiguity", IEEE Trans Aerospace & Elec. Sys, Vol AES-17, No.4, July 1981

### 3.1.5 The Initial 32-chip Detection and Synchronisation preamble specification

The FONTUS FH-BFSK packet starts with a fixed sequence of 32 chips, with no temporal gap either between the chips or between the preamble and the main (modulated) part of the FH-BFSK packet. The tones are simply the first 32 FH sequence with channel symbol value set to the following pseudo-random 31-bit m-sequence (with a final ‘0’ appended):

{0,1,1,0,1,0,1,1,1,1,0,0,0,1,0,0,1,1,0,1,0,1,1,1,1,0,0,0,1,0,0,0}

Once the fixed preamble phase of the waveform is complete, the sequence generator continues smoothly into the message section and the data symbols are then taken from the encoded message to be transmitted.

The reader should note that in the code for FONTUS_MESSAGE.M both the hop locations (vector “slots” above) and the specific slot to be filled with a sinusoid are identified in the Nchip x 2 matrix called “Slots” (note the capital letter). This is used in the next routine to build the baseband waveform.

All of the preceding part of section 3 is covered in MATLAB program FONTUS_MESSAGE.M and its sub functions.

### 3.1.6 The optional Data Cargo payload

The Baseline FH-BFSK Packet may be followed, without a break, by additional data, encoded according to the user-specified application into a continuation of the FH sequence. Such ‘cargo’ is to be encoded using a contiguous continuation of the frequency-hopped sequence following directly after the final chip of the Baseline FH-BFSK Packet. The same convolutional encoder and interleaver are to be used as for the main Baseline FH-BFSK Packet. The ‘cargo’ will include a 2 byte CRC. The header packet will specify the length of the cargo packet.

### 3.1.7 Modulation

This section is covered in MATLAB program FONTUS_SIGNAL_GEN.M and its supporting sub-functions. Following Figure C2-6, we begin converting the (176) blocks and slots to the time frequency plane. For example, the first frequency block is 5, so the lower edge of this block is located at 10b. The next block index is 25, so the lower frequency edge is located at 50b. Because the FH-BFSK waveform is binary, we select each channel symbol individually. The first channel symbol is 0, so we create a complex chip (a sinusoid) at 10b. That is

$$S1 = \exp(j2\pi 10bn/Fsb) \qquad 0<n<(N-1) \tag{3.2}$$

As the next block is a 25 and the channel symbol is a 1, we create the second chip as

$$S2 = \exp(j2\pi 51bn/Fsb).$$

The third block is a 31, and the channel symbol is 1, thus the chip is

$$S3 = \exp(j2\pi 63bn).$$

And so on.

An alternate, and perhaps more user-friendly method is via the frequency domain (this method is employed in the Matlab code). We have chosen our combination of chip duration and baseband sample rate to give us a power of 2 integer number of samples that span the temporal duration of the chip. In this case N = 256, which we therefore also use as our FFT size. Every FFT bin will represent a frequency span of b = 1/Tc = 80 Hz. Therefore, we have a one-to-one relationship between the block and slot counts (of matrix Slots) with the FFT bin count.

We first identify the mid-frequency of the signal band as (using the Matlab code):

mid=(Nblock/2)*Mary*Chipfrq = 3680 Hz (3.4)

We form, for later use, a complex shifting exponential which also spans a chip duration

e=exp(-i2π*mid*(0:N 1))/Fsb); (3.5)

Following the example set by eqn (3.2) the first block kb = 5, and slot = 0 in that block is to be occupied by a tonal. Define a vector X of all zeros and size N, and recall that we are dealing with a binary alphabet, which we identify in the code as Mary = 2. The FFT bin to be populated is

f0 = kb*Mary + slot +1= 11 (3.6)

We next compute an inverse FFT of X and point-by-point multiply by e (eqn (3.5))

A1 = ifft(X,N).*e (3.7)

and A1 is identical to S1 of eqn (3.2). We note that in the code we employ a very modest window (variable “win”) which reduces the sharp temporal corners of the chip and permits better visualization of the waveform. This is not to be considered part of the standard, but including it will not impact performance.

An example of a complete FH-BFSK waveform is shown in Figure C3-1. Here we show time on the x-axis, and frequency on the y-axis.

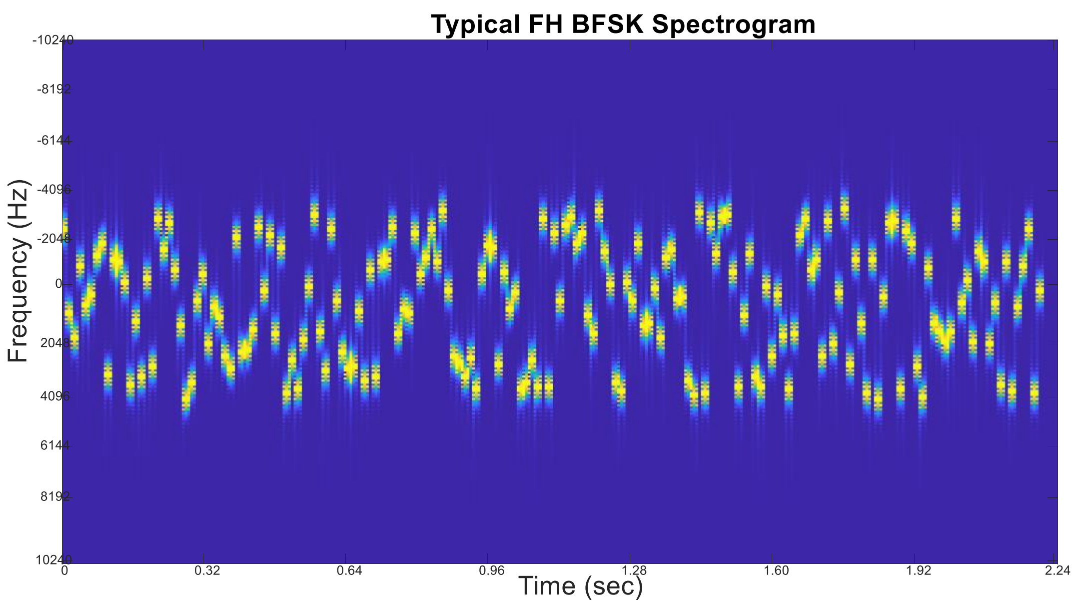


*Figure C3-1. Time-frequency representation of a baseband FH-BFSK waveform.*

Note, Figure C3-1 shows the frequency axis spanning both negative and positive frequencies. This is characteristic of a baseband signal. At this stage the waveform is sampled at a minimal rate, specifically 20480 samples/sec. During the transmission stage we resample the waveform to a much higher rate, for example 163K samples/sec, or 102.4 K samples/sec and effectively heterodyne the baseband waveform from 0 Hz to Fc (25000 Hz, in our case).

The final stages are to stream the digital samples to a digital-to-analog converter (DAC), amplify the resulting analog signal, and pass it through the transducer and into the water.

#### 3.1.8 Auxiliary Acquisition Signal

The ropeless fishing application requires that the acomms be effective between ± 10 kts. Unfortunately, at the carrier frequency of 25 kHz the standard non-coherent acquisition process (see the next section) will likely fail at the upper and lower end of these relative speeds. Indeed, simulation shows that the non-coherent acquisition loses effectiveness beyond about 6-7 kts. However, it is a much more robust method (in non-AWGN, especially with multipath, impulsive noise, and interference) than the alternative, so we recommend that the standard non-coherent method be implemented (see routine BASIC_ACQUISITION.M, which is "commented out" in the simulation in favor of the alternative). The alternative developed here, in contrast, is to employ a simple hyperbolic frequency modulated (HFM) waveform, which is processed with a matched filter (or replica correlator).

The HFM waveform is extremely insensitive to Range Rate (RR), but does incur an RR-induced time-shift in the apparent arrival estimate. By being insensitive to RR, the HFM does not provide us with the requisite information needed to correct the packet for RR. We show in the next section how to make this correction.

An HFM waveform is defined by the following equation:

$$A(t) = \exp(i\theta) \tag{3.6}$$

where

$$\theta = 2\pi \int f(t)dt \tag{3.7}$$

$$f(t)=1/(at+b)$$

$$A(t) = \exp(i2\pi \ln((at + 1/f_{min})/a - Ft) \tag{3.8}$$

where $f_{maxn}$ = F+W/2 and

$$a = (W/(T^*f_{min}^*f_{max}) \tag{3.9}$$

Note that the baseband waveform MUST be built at passband, then shift back to baseband! See Matlab routine "hfm.m" provided in the repository

We employ a 50 ms x 8 kHz HFM as a precursor to our FH waveform, with a 50 ms delay between them. Figure C3-2 shows the magnitude of the resulting baseband waveform.

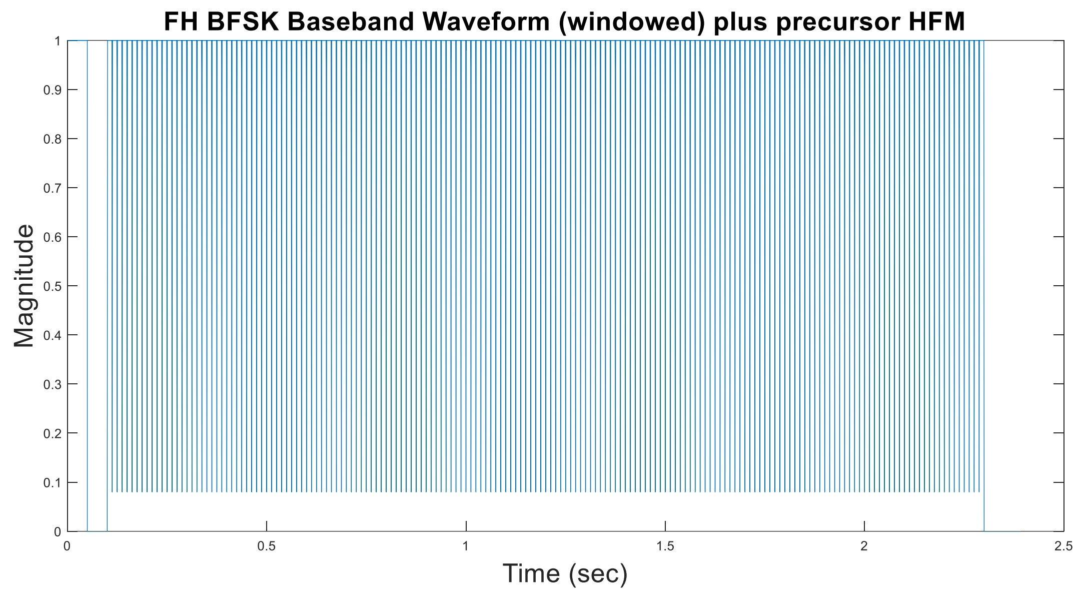


*Figure C3-2. Baseband representation of the magnitude of the TX signal.*

Note that this routine also produces a copy of the baseband time series of the 32 chip FH acquisition sequence, which is labelled "fh_replica.mat" in the code. The HFM is also provided to the receiver, as the vector "pre_sig.mat". The former will be used in the receiver to refine estimates of arrival time and RR.

# 4 THE FONTUS MODEM RECEIVER

The receiver described in this section is provided as a basic capability, with the vendor free to add or subtract enhancements. This receiver is embedded in a simple AWGN simulator which the user may run to extract performance statistics and to provide performance comparisons with other receiver implementations.

There are several component functions necessary in the receiver. These include the following

1. Conversion from analog to digital representation.
2. Basebanding from a "real" signal residing at passband (Fc = 25000 Hz), to an analytic representation with Fc translated to 0 Hz.
3. Acquisition, or detection of the presence and start of the waveform (program "SIGNAL_FIND.M" and its supporting sub functions)[2]
4. Demodulation, or conversion of the digital waveform to channel symbol form (program "FONTUS_DEMODULATE.M" and its supporting sub functions)
5. De-interleaving, decoding, CRC check, followed by delivery of the information (programs within "FONTUS_DEMODULATE.M")

Each of these is discussed in detail in the following sections.

[2] We also provide the Matlab code for non-coherent acquisition in routine "BASIC_ACQUISITION.M" We recommend that readers familiarize themselves with this routine and consider implementing it in their modems.

In order to use the simulator, please run “PREPARE_NOISE.M” in advance.

#### 4.1.1 Analog to Digital Conversion (ADC)

The transducer converts electrical energy into acoustic energy, and the reverse as well. In this section we consider the electrical signal generated by the transducer and its supporting electronics. This electrical signal (the analog signal) is balanced within an acceptable voltage range by a device known as automatic gain control (AGC) circuit, which is not discussed in this paper, but which may be important for proper functionality if the analog to digital converter (ADC) has a limited dynamic range (e.g., J=12-bit or 16-bit). The voltage out of the AGC is fed directly to a J-bit (ADC) which produces integer numbers. If a voltage is at the allowed maximum, then the output of the ADC will be close to $2^J$-1. A minimal voltage signal will cause an ADC output close to zero (0). Each sampling of the analog signal produces one 16-bit number. This digital stream of 16 bits is created at a rate of, for example, Fsp = 163K (real) samples/sec, which is fed to the DSP microcomputer for processing. When using an ADC with a small J, it is important that the average noise level be kept at or near the mid-level of the ADC.

#### 4.1.2 Basebanding

It is possible to do all of the receiver functions at the passband “sample rate” of Fsp. However, the computation load at Fsp is prohibitive for our small DSP. The so-called “Nyquist rule” tells us that the information contained in a waveform is preserved if the sample rate is a small multiple of the bandwidth. For example, our signal has a bandwidth of 7520 Hz, so a sample rate of, for example, 20K (20480 samples per second) is sufficient if we can reduce the center frequency appropriately. We therefore heterodyne (bandshift) the waveform from Fc to 0 Hz and reduce the sample rate from Fsp to Fsb = 20480 samples/sec. Program “BASBND3.M” can be studied to see an efficient implementation of a base-banding algorithm

#### 4.1.3 Initial Acquisition, RR estimation and precision arrival estimation

We assume that the waveform will arrive at the receiver at an arbitrary time, and the issue in this section is the methods we use to identify both that the signal has arrived and its precise location in time. This is by far the most difficult portion of the receiver, and we describe it in some detail. (see routine “SIGNAL_FIND.M” and “ARRIVE_REFINE.M”).

We are searching for the HFM, which was transmitted just before the FH signal. The best method for finding the chirp is to use a matched filter (replica correlator). We employ a 50% overlap-and-save technique (see Tutorial A), with a few enhancements in routine SIGNAL_FIND.M. The goal of this routine is to find the desired signal while rejecting spurious noise and interference. The routine detects in real time, then stops the process to allow vernier refinement to occur. The inputs to the routine include a detection threshold – we are using 16 dB (converted to power), which reflects the number of standard deviations of the noise above the mean noise. We note that “noise” here explicitly means the magnitude squared output of the replica correlator in the absence of signal. Of special note in the routine, it is highly likely that noise and interference can create multiple peaks that may meet the detection criteria, especially as the statistics are stabilizing. We therefore evaluate any threshold crossing to verify that the peak exists in reasonable isolation. If so, we set a variable “burst” to 1, 0 otherwise. We cannot declare an acquisition until burst = 0. See Figure C4-1 for an example.

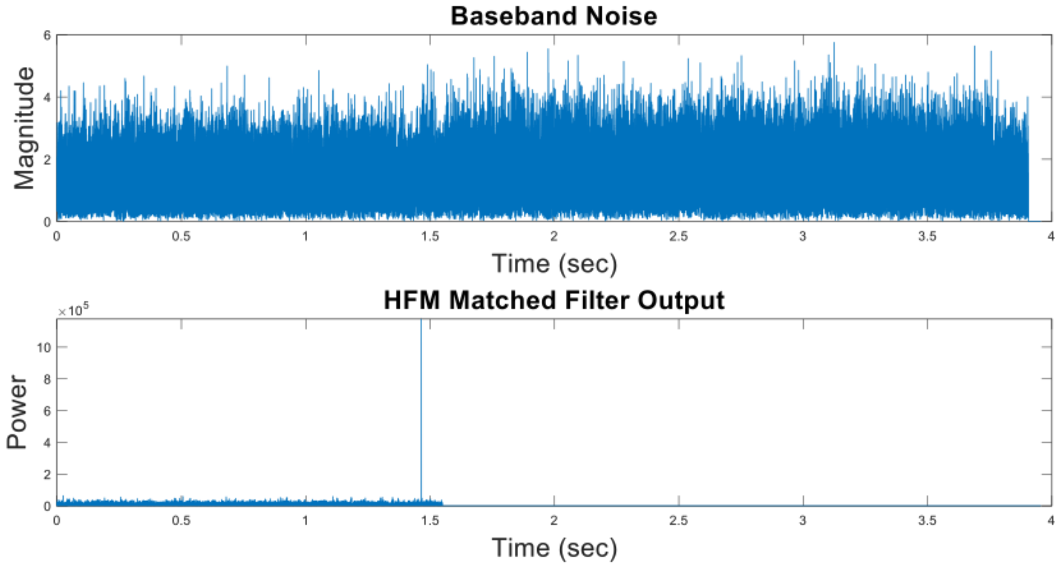


*Figure C4-1. Baseband received signal and noise (upper plot) and matched filter (replica correlator) output (lower plot).*

The HFM waveform is, by design, insensitive to RR, and further introduces a temporal error in localization if RR is present. We need to estimate the RR in order to correct the waveform prior to demodulation. For this we turn to routine "ARRIVE_REFINE.M" which essentially applies a multi-hypothesis test to the 32-chip FH acquisition. The user must inform the routine of the maximum (absolute) anticipated RR (in knots) and the increment to use among the hypotheses. For this center frequency and signal duration, the increment should be on the order of 0.5 kts.

As discussed above, we check every peak at each hypothesis to ensure the peak exists in isolation. For this waveform, an incorrect RR match may cause the output of the matched filter to exhibit multiple "multipath" structures, as shown in Figure C4-2.

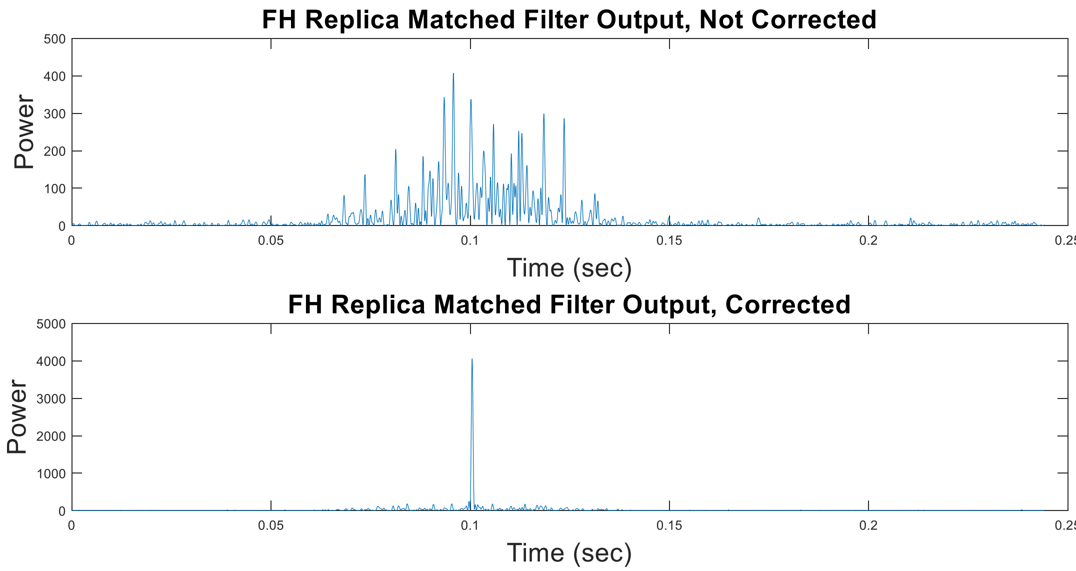


*Figure C4-2. Comparison of FH replica correlator output. Upper plot, 6 kt replica for a 3 kt RR, while lower plot shows 3 kt replica for the same data.*

Once we have determined the best estimate for RR, we correct the remainder of the waveform for this estimate. We use routine "DILATION.M", but the vendor may choose to modify the passband sample rate instead.

Although we have yet to discuss demodulation, the output of the simulator is instructive in the way RR affects performance, as can be demonstrated with an example: we consider in Figure C4-3 the effects of range rate on acquisition performance and demodulation performance. Performance generally will be a function of input signal to noise ratio (SNRi) so for this example we consider an SNRi[3] of -4 dB.. In the figure we show, in the upper plot, solid curve, the number of chip (symbol) errors (prior to decoding and de-interleaving), for RR = -4 kts, <u>without</u> compensating for the RR. The numbers in the top of the upper plot show the number of successful packets (out of 10). The lower left-hand plot shows the <u>estimate</u> of SNRi for each specified SNRi. It is useful to note that the SNRi estimates, based on the HFM chirp, are nearly unaffected by the RR of -4 kts. In the lower middle plot we show estimates of RR, although in this case the estimates were forced to be zero (thus avoiding compensation).

In Figure C4-4 we show performance with full estimation for a compensation for the RR. Note the significant improvement in packet success, the elimination of channel symbol errors, and the excellent estimate of RR.

[3] SNRi is the receiver input signal to noise ratio defined as the signal power divided by the power of the background noise in the same bandwidth as the signal.

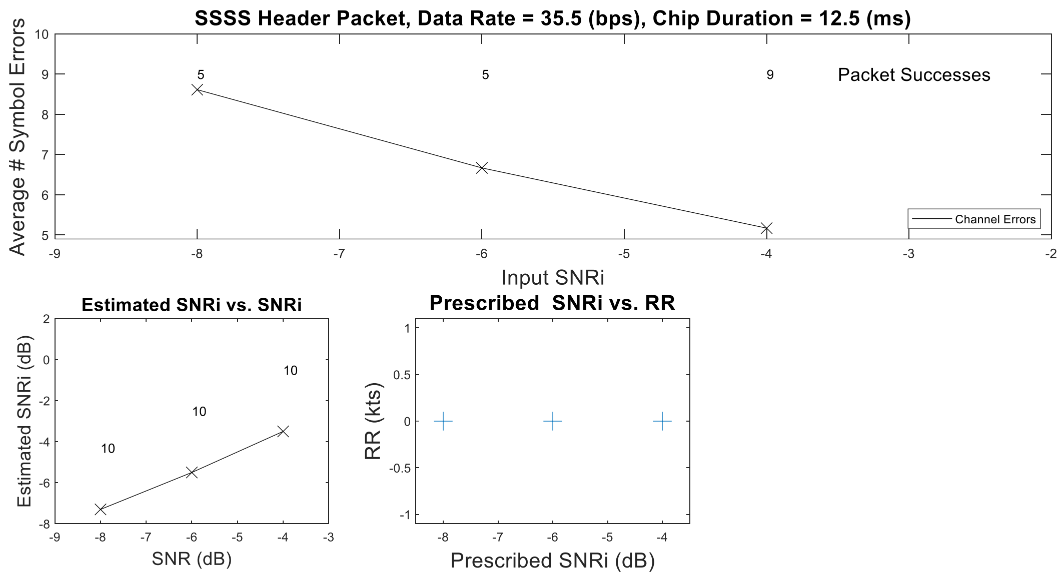


*Figure C4-3. FH receiver performance under AWGN simulation. The imposed RR is -4 kts, but no compensation for the estimated RR is permitted.*

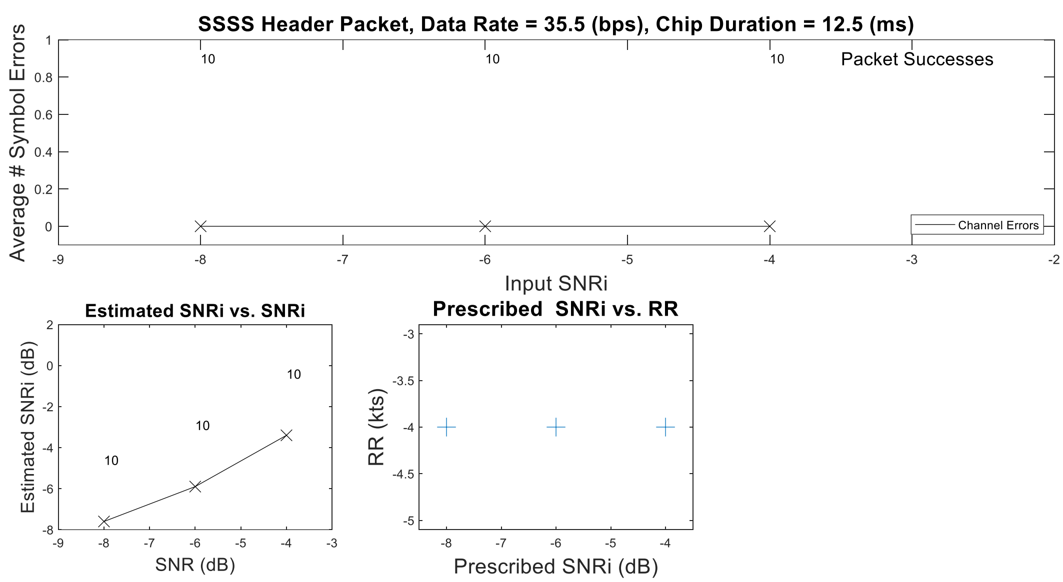


*Figure C4-4. FH receiver performance under AWGN simulation. The imposed RR is -4 kts, now with compensation for the estimated RR.*

### 4.1.4 Demodulation, Decoding, and CRC

The three processes described here are essentially a reversal of the operations employed to build up the baseband TX waveform. That is, we demodulate the signal and prepare the results in a form suitable for de-interleaving. The de-interleaved, coded symbols are passed through a maximum likelihood decoder, with the results checked by a CRC. The following sections describe each of these and refer the reader to applicable Matlab code.

### 4.1.5 DEMODULATION

Demodulation is the method used to extract probabilistic representations of the information carried by the physical layer (chips). Different signalling schemes employ different methods, but for our purposes we reverse the order described for modulation, and utilize the frequency domain to isolate individual chips. We refer to routine FONTUS_DEMODULATE.M which is called following SIGNAL_FIND.M and ARRIVE_REFINE.M. by the simulation routine FONTUS_SIM_RUN.M.

In the signal generation (routine FONTUS_SIGNAL_GEN.M) we used an FFT size which is an exact match to the number of samples spanning one chip (N = 256). We can use this same size FFT for demodulation, but the provided Matlab code utilizes a larger FFT which provides interpolation in the frequency domain. This complicates the algorithm somewhat, but supports the possibility and future need to track and correct for residual RR throughout the packet (especially longer FH cargo packets).

To begin demodulation, we assume that the leading temporal edge of the first modulated chip has been correctly identified. Let RSignal be the baseband time series which begins with the leading edge of the first chip. We extract 256 samples, then compute an FFT (magnitude squared). The FFT size is $N \geq 256$. For convenience, we compute an FFTSHIFT of the spectrum, putting the middle of the signal band at the center of the spectrum:

```
chip=abs(fftshift((fft(RSignal(grab1:grab2),N)))).^2;
```

where, for the first chip, grab1 = 1 and grab2 = 256, etc,

Recall that we previously identified the middle of the signal band, which is simply called “mid”. We also retained a copy of the entire frequency location of each block (vector “fkeep”) – or you can reconstitute it block by block from the HOPINDEX.M routine. We compute an offset for each block:

```
off=freqs(posit)-mid/ff+N/2;
```

where ff = Fsb/N is the FFT bin width (Hertz). There will be J FFT bins spanning the spectrum of the chip. If N = 256 (minimum), then J = 1. The power spectrum should reveal samples of a sinc function across the J bins. We test both of the slots available to this block, and record the maximum power in each. In the Matlab code the peak powers are stored in a 2 x (Nchip-Nsynch) matrix called Stats. These processes are repeated for each chip.

This concludes demodulation.

### 4.1.6 DECODING AND CRC

The next step is de-interleaving and decoding. We begin with hard decision decoding, in which we identify the slot which has the highest power, which we call “hard” in routine FONTUS_decoding. For simulation purposes we compare this with the coded channel symbols (vector “Coded)” to inform us of the number of hard decision errors. We next de-interleave “hard” to obtain “hard_dl”, using the same prime number Q that was employed to construct the channel symbols. We will employ a Viterbi decoder, which prefers to use soft decisions, so we construct a 2 x (Nchip-Nsynch) matrix R with a value of 0.75 for a hard decision, and a value of 0.25

otherwise. We then compute a final vector Rm with a function "FSK2PROB.M"[4] which provides us with "soft" probabilities of a 0 channel symbol. We insert Rm into the Viterbi decoder, and it returns the decoded bits, including a CRC vector at the end.

We extract all of the decoded bits, except for the last 8, which presumably contain the CRC vector. We recompute a CRC precisely as done in Section 3.1, now using the decoded bits. This provides us with a new 8-bit vector, which we compare with the remaining 8 bits from the decoded vector. If they are precisely the same, we conclude that the message was correctly received and processed.

The user may refer to the Matlab code to understand soft decision decoding. It is similar to hard decisions except that we independently de-interleave the two rows of the matrix Stats, then combine the result to form our R matrix. From there the processes are identical.

We have found from practical experience that the user is well advised to compute both hard and soft decision decoding. We have found that a small percentage of receptions are successfully decoded by the former, but not the latter.

# 5 DISCUSSION

We have provided both a tutorial and a design document for the FONTUS_FH signalling scheme. The MATLAB code is available in a repository upon request. There are brief tutorials below on several topics that a potential implementor should fully understand. Those who desire to implement the algorithms in their hardware are welcome to communicate with the lead author of this appendix:

Dale Green

daleg141@gmail.com

[4] Routine developed by Sandipa Singh at WHOI

# 6 TUTORIAL A: THE FOURIER TRANSFORM

The Fourier Transform, implemented as a Fast Fourier Transform (FFT) is a key signal processing tool, especially for implementing an efficient receiver. This tutorial provides a simplified overview of the transform – for our purposes it is not necessary to understand the computational details of the FFT.

Consider a finite duration tonal, such as described by eqn(2-1), and repeated below:

$$s(n)=\exp(i2\pi f_0 n\delta t),\ 0\leq n \leq(N-1). \quad \text{(A1)}$$

This tonal exists only at a frequency $f_0$ for a duration $0\leq n\delta t \leq T$, with $i = \sqrt{-1}$, and $\delta t = 1/Fsb$; We consider all possible filters to apply to s(n) which will extract it from additive noise, and chose a filter for efficiency, accuracy, etc. according to our needs. The optimal set of M filters for a finite duration tonal signal of unknown frequency (but perfect temporal alignment) has the exact expression given by eqn(A2).

$$y(n)=\exp(-i2\pi f_m n\delta t),\ 0\leq n \leq(N-1). \quad \text{(A2)}$$

where $f_m$ is a potential frequency at which we may discover the true signal. If we assume that $f_0$ is unknown, then we must test all of the M possibilities against the received data. The test that provides the greatest output is selected as the filter and frequency best representing our received signal.

We test our set of possibilities (in statistics, called hypotheses) by sample by sample multiplying and summing the signal with each possibility. That is:

$$S(m) =\sum_{n=0}^{N-1} |(exp(-i2\pi f_m\ n\delta t)\ x\ exp(i2\pi f_0\ n\delta t))|^2 \quad \text{(A3)}$$

Note that, if m ≡ 0, then $S(m=0) = \sum_0^{N-1}(1) = N$, which is the maximum value of eqn(3), hence all other choices of m will produce a smaller output.

The FFT implements eqn(A3) in a very computationally efficient way assuming that we are only interested in a discrete set of M filters which are uniformly spaced. If we plot all values for the M filters, we obtain a picture similar to our Figure C2-4. Thus, in this case, we use the FFT to identify the spectral content (frequency) of a tonal signal.

For a broadband signal, the mathematics are more complicated, but if we can assume that the waveform is constructed of a set of tonals of different frequencies, then the FFT will provide us with a good estimate of the spectral content of that signal.

For the FH-BFSK waveform, we extract a single baud period of data (assuming perfect temporal alignment) and apply eqn(A3) to it using the FFT. We anticipate a single large peak to be revealed among the M possibilities, which tells us both the block location and which of the 2 slots are filled – this defines demodulation for this type of signal.

### 6.1.1 Convolution and Correlation

We will demonstrate here the use of the FFT in providing an efficient method for performing convolution and correlation, which are key concepts in detecting the arrival and temporal location of a waveform. First we describe convolution and its use in filtering.

The use of all linear (discrete) filters of length K samples can be described by the convolution process of eqn(A4). This equation may be interpreted as follows: we have a long duration sampled input d(n) which contains somewhere in time a short signal of interest. This signal may be buried in noise so it is difficult to identify, and we propose to use a (matched) filter to pull the signal out of the noise. Our convolution process multiples those signals which "line up" with the filter ,sums the results, and stores the sum in a register we call z(n), n being a measure of temporal position into the received data stream. We then advance the filter by a single sample, and repeat the multiplication and summing process.

$$z(n) = \sum_{k=0}^{K-1} F(k)d(n-k) \tag{A4}$$

Figure C6-1 shows two plots. The upper plot shows the magnitude of the received time series d(n). The lower plot shows the magnitude of the filtered output (eqn (A4)). Note that the length of the filtered data is longer than the input time series – by exactly 1 less than the length of the filter. This is a consequence of the convolution implementation, which inserts zeros at the beginning and end of the time series to facilitate the full convolution. In practice the output from these zeros are discarded.

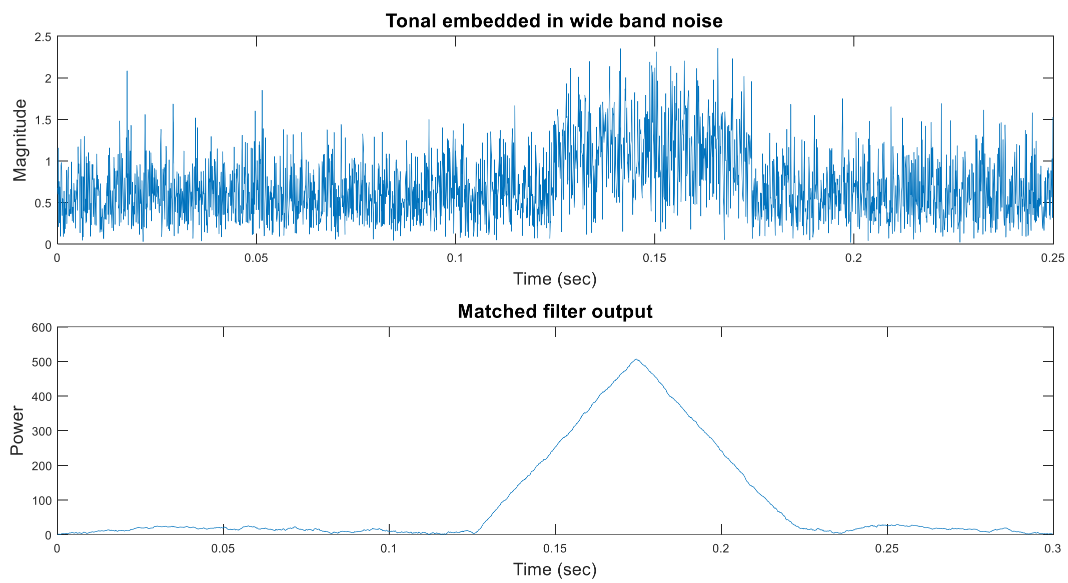


*Figure C6-1. Filtering example for a tonal in wide band noise.*

For most purposes in developing our modem we will employ correlation rather than convolution. The process is very similar in appearance to Eqn (A4), but has a wholly different result for wideband signals. Eqn (A5) defines correlation

$$c(n) = \sum_{k=0}^{K-1} F^*(k)d(n+k) \tag{A5}$$

Where the subscript * identifies conjugation. Typically we compute the squared magnitude of eqn (A5), as shown for an LFM example in Figure C6-2.

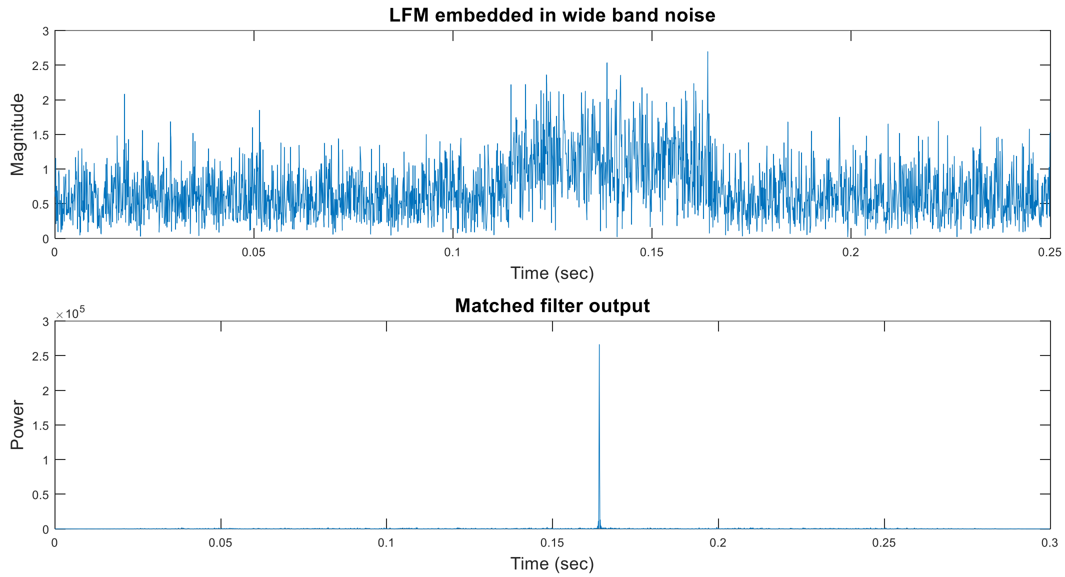


*Figure C6-2. Example of a wideband LFM chirp signal embedded in noise. Upper plot shows the received time series, and the lower plot shows the magnitude squared matched filter output.*

### 6.1.2 Fast Convolution and Correlation

The convolution and correlation processes of eqns (A4) and (A5) are computationally intensive. It is common practice to replace these formulas with "fast" processes, which invoke a property of the Fourier Transform that convolution (correlation) in the time domain is equivalent to multiplication (conjugate multiplication) in the frequency domain. This means that time domain processes can be more efficiently accomplished via frequency-domain operations involving the FFT and IFFT. An appropriate computational method is the so-called "overlap-and-save" method of fast processing [2]. We recommend the user review routines "CCONVOLV.M" and "SIGNAL_FIND.M for examples.

# 7 TUTORIAL B: BASEBANDING

It is possible to do all of the receiver functions at the passband "rate" of Fsb. However, the computation load at Fsb is prohibitive for our small DSP. The so-called "Nyquist rule" tells us that the information contained in a waveform is preserved if the sample rate is a small multiple of the bandwidth. For example, our signal has a bandwidth of 7520 Hz, so a sample rate of, for example, 20K is sufficient if we can reduce the center frequency appropriately. This section provides an overview of the process, which we call basebanding.

For this section we will use an LFM waveform as our example. Our LFM will be W = 5000 Hz, with T = 0.05 seconds, and Fsp = 163K. Figure C7-1 shows two versions of this digital signal as output directly from the ADC. The upper plot shows the time series, while the lower plot shows the magnitude squared (power) of the Fourier Transform of this waveform (power spectrum). Note in the latter that the center of the band is located at Fc = 25520 Hz, and the majority of the power spectrum exists within about W/2 about Fc. Note also that a mirror image exists at –Fc, which is a feature of a Fourier Transform. This mirror image is always equally positioned about 0 Hz.

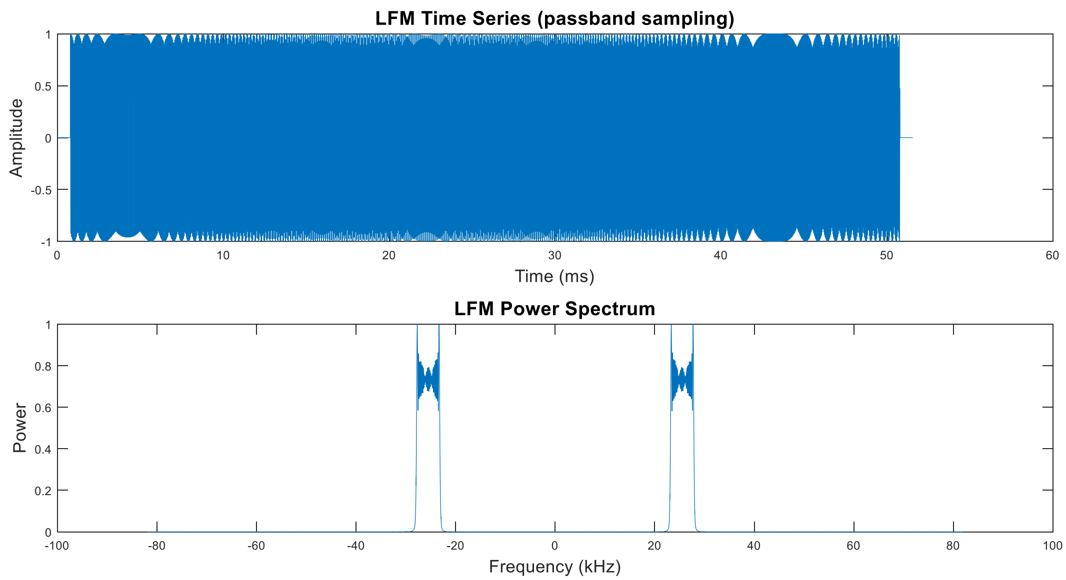


*Figure C7-1. Example LFM signal. Upper plot shows the time series, and the lower plot shows the power spectrum.*

We can see from Figure C7-1 that the sample rate is already greater than necessary. The rule tells us that we must sample at more than twice the band of the signal, which in this case is approximately Fc + W/2. Because the signal is actually bandlimited about Fc, we can easily shift the frequency, as follows. Let s(n) be the sampled signal at passband, with n the time index. We will generate a complex sinusoid e(n) and multiply it times the waveform, or

$$x(n) = s(n)*e(n),$$

where

$$e(n) = \exp(-j2\pi Fct(n))$$

and t(n) is the sampled time, with t(1)=1/Fsp. Figure C7-2 shows the results of this process. This power spectrum is not properly mirrored about 0 Hz, and thus is not a valid representation of our LFM. Note that one of the clusters of energy is found at 0 Hz, which is where we want it, but there is another at – 25520 Hz. Fortunately, we can remove this simply by passing the waveform through a low pass filter which will remove this cluster. With this gone, we have a single cluster of energy, centered at 0 Hz, and we can reduce the sample rate to a rate corresponding to W. The result is shown in Figure C7-3, which shows our final stage, which is an analytic (complex) baseband waveform, now sampled at 10240 samples/sec.

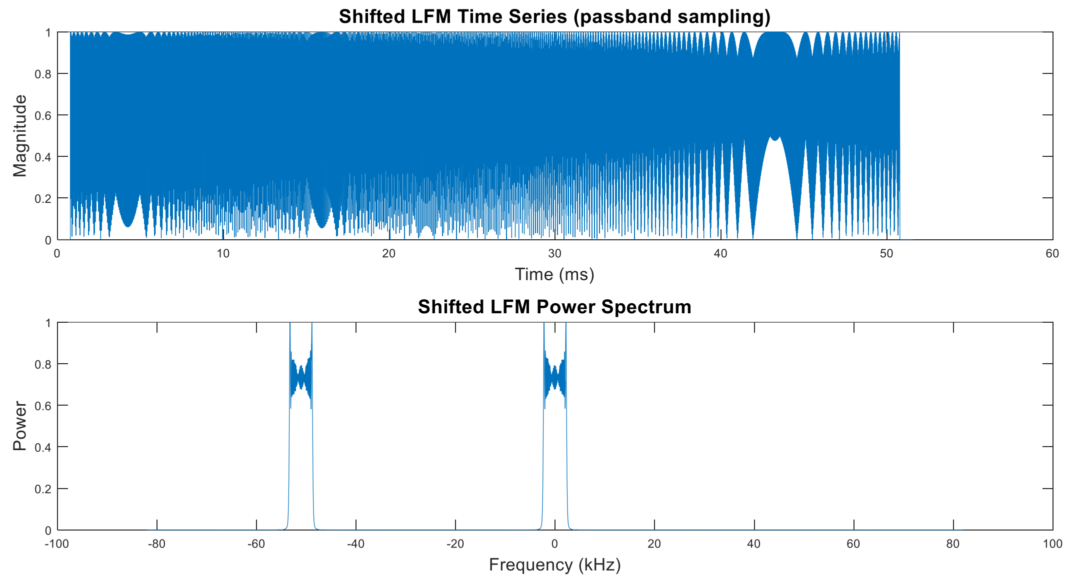


*Figure C7-2. Shifted waveform, time series and power spectrum.*

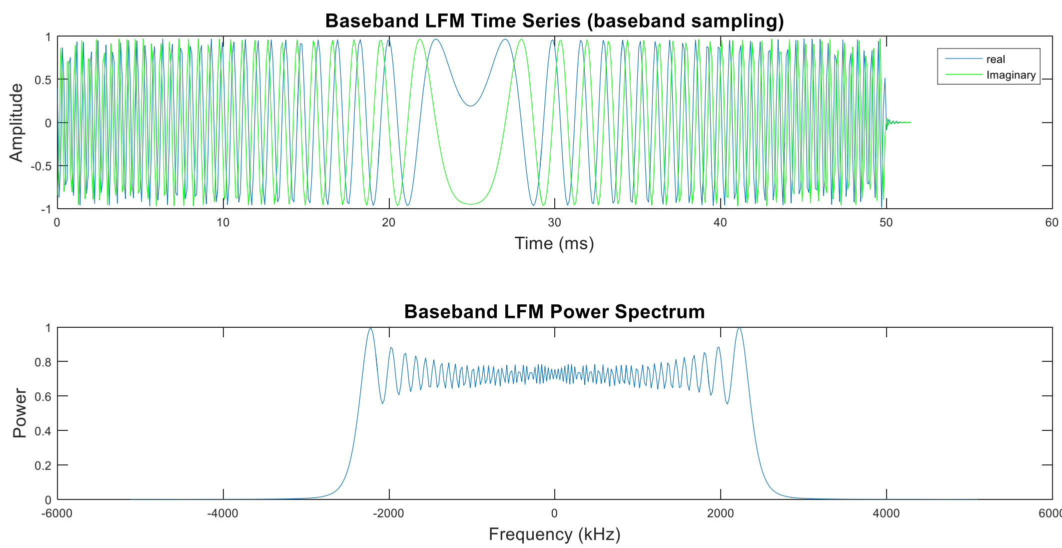


*Figure C7-3. Final result, baseband time series and power spectrum.*

This processing of "basebanding" is what is used in all cases to transform the incoming digital stream of data to the lowest possible sample rate, without loss of information.

The reverse process is used to generate waveforms for transmission. That is, we begin with a baseband waveform (Figure C7-3), and (conceptually) resample it to a rate appropriate for our passband center frequency, shift the middle of the band (currently at 0 Hz) to the desired center, or carrier, frequency Fc. That is, if "data" is our baseband waveform, then we interpolate data to change the sample rate from Fsb = 20K (complex) samples/sec, to (for example) 96 kHz. In Matlab we do this in two steps:

X=resample(data,Fsb,24000),

which gives us a 24000 samples/sec (complex) representation of data – which is still a baseband waveform. We then interpolate X:

X=interp(X,4)

Which changes the sample rate to fs = 96 kHz, with N samples. We follow this by generating a complex exponential E

E= exp(i2πFc(0:(N-1))/fs)

And sample-by-sample multiplying this against X. If we now retain only the real part of the complex waveform, we will obtain Figure C7-2. This real, discrete (digital) waveform is sent to the digital-to-analog converter (DAC), then to the amplifier for transmission.

The user may refer to the routine BASBND3.M from the CD which shows an efficient, poly-phase method of basebanding.

## Appendix D:  Ultra-short baseline (USBL) positioning for on-demand devices

# 1. INTRODUCTION AND FUNCTIONAL DESCRIPTION

This document provides both a tutorial and a detailed design for the algorithms and procedures underlying Ultra-Short Baseline (USBL) positioning. The document should be considered a follow-on to Appendix C describing the FONTUS acoustic communication standard. The USBL described here is designed as an enhancement to an underwater acoustic modem using the FONTUS frequency hopping (FH) modulation. While this document covers all functional and algorithmic aspects of USBL design and implementation, we intentionally exclude hardware, electronic design, and software/firmware implementation. However, Matlab code for all aspects of USBL functionality is provided in an accompanying repository.

We assume that the USBL will be physically attached to a modem and will strictly utilize modem communications waveforms for purposes of estimating the directions of arrival (DOA) of signals received from a remote, cooperating modem. We further assume that bearing estimation accuracy of 5 degrees is acceptable and readily achieved, which eliminates any need for costly system calibration.

The USBL hardware package must include the following:

1. An array of 4 very small hydrophones arranged in a tetrahedral shape, as indicated in Figure D1. This array will be "potted" within an acoustically-transparent, protective enclosure.
2. A motion reference unit (MRU) physically placed between the modem and the array (see Figure D2). For reasons of cost and calibration we do not include an integrated compass but assume the USBL will be mounted to reference boat heading.
3. Four channels of analog-to-digital conversion (ADC) functionally combined with a 4-channel FIFO.
4. A DSP or other processing device which processes and interprets the digital samples received from the ADC.

In the following we discuss functional requirements for each of these four items.

Please note that ALL USBL/MRU processing is accomplished within the modem DSP, and thus it may be necessary to increase on-line memory or add additional hardware capabilities. The user may choose to provide tracking software and displays external to the modem.

## 1.2 ARRAY HYDROPHONES AND GEOMETRY

Our USBL will be based on the tetrahedral geometry shown in Figure D1. Please note the axis definitions in the figure caption. The hydrophones should be as small as possible, no larger than approximately $\lambda/8$, where $\lambda$ is the design wavelength (defined later). However, it is likely that the sensitivity of the hydrophone will decrease with decreased diameter, so a tradeoff analysis is important. Most potting compounds used in sonar systems are chosen such that the product of water density and the speed of sound is close to unity. In our case it is more important to minimize refraction such that the speed of sound within the USBL approximate the speed of sound in the water environment. This may be a difficult tradeoff, especially if the unit will be used in fresh, brackish and salt water.

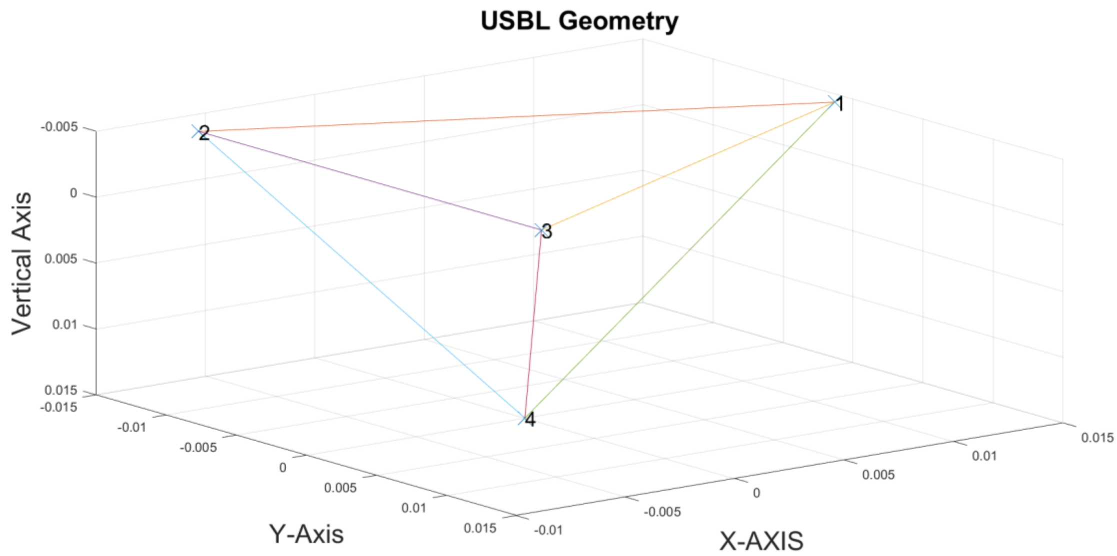


*Figure D1. Tetrahedral Geometry. This is a "right-hand" system, with positive Z down. Zero degrees azimuth is along the X-axis, and through the element labeled 1. Vertical angles are positive down from the X-Y plane*

## 1.3 MRU/COMPASS

The full-body system is described by Figure D2. The functional requirements for the MRU are simply stated: MRU error should be less than about 25% of the acceptable Direction of Arrival (DOA) estimation requirement. Thus, for example, if the DOA requirement is 5 degrees (RMS), then the acceptable error of the MRU should be less than 1.25 degrees, with other errors together less than about 3.75 deg. The MRU contribution refers to random errors, and not to implementation errors such as element location within the array.

A compass often is included as a package with the MRU. We exclude discussion of incorporation of a compass with the MRU in favor of boat heading and boat-maintained compass. However, a vendor should feel free to include this if desired. Be aware, however, that less expensive compasses may not respond (or stabilize) quickly enough to fast rotations, and, in particular, may saturate during shock loading, such as with rapid wave-induced motion.

## 1.4 ANALOG TO DIGITAL CONVERSION & FIFO

The USBL ADCs should each be the same device used in the primary modem. They should sample at the same rate as the primary ADC, and there must be no delays across the four channels (simultaneous sampling). The FIFO attached to each channel must be able to store at least two (2) times the duration of the acquisition portion of the waveform (for the FH acquisition signals, there are 32 tones, each 12.5 ms in duration).

## 1.5 PROCESSING DEVICE

There are two options for the processing device: a) real-time programming of the modem DSP in which you either process the 4 channels while the modem is performing its other tasks (e.g., demodulation) or you take control of the DSP after the demodulation has concluded. We cannot advise on this, but we believe the first approach is possible. The other approach is to utilize a separate DSP which operates semi-independently of the modem DSP. This allows you to build an almost independent electronic board specifically for USBL purposes.

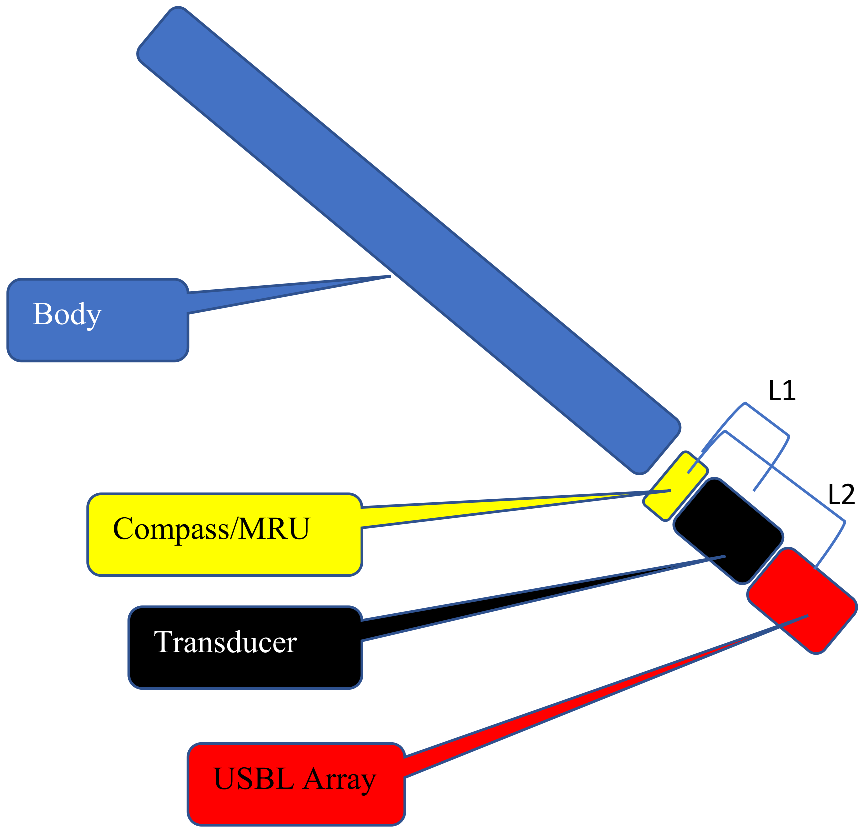


*Figure D2. Modem, MRU and USBL configuration*

## 1.5 A FINAL FUNCTIONAL REQUIREMENT

The USBL algorithm, described later in more detail, utilizes the full FH acquisition waveform in a coherent (matched filter) method. Unlike the non-coherent acquisition using the same waveform, this coherent method is extremely sensitive to range rate (RR). In principle, the USBL function is not strongly influenced by RR, but the algorithm requires a well-defined matched filter output signal to function properly. This requires that the modem DSP perform a detailed analysis of the acquisition waveform to precisely estimate and correct for RR, then pass on details of the correction to the USBL processor. We have provided previous Matlab algorithms showing how to accomplish this analysis. We emphasize that implementing this precision estimation and correction process within the modem DSP is fundamental to good USBL performance.

In addition to the above, it must be remembered that the fundamental concept underlying USBL is that the same signal, other than time/phase difference caused by geometry, is present on all array elements. This is especially pertinent if one decides to build a calibration facility, as there are stringent requirements on "suitable" separation between all portions of the calibration system and the acoustically reflective boundaries of the facility.

## 2. USBL THEORY

As shown in Figure D1, the array consists of four equi-spaced hydrophones (elements) which are spaced D units apart. D will be identified later, but it will always be on the order of one half of a wavelength – again, to be defined later. A signal arrives at the array with a DOA of $\{\theta,\Omega\}$ where $\theta$ is the horizontal angle, and $\Omega$ is the vertical angle. The signal reaches each of the N elements with a time delay relative to the "first" element that is unique for each DOA. If we are dealing with a sinusoidal waveform s(t), there is a direct relationship between time delay and phase, as described by eqn (2.1).

$$S_n(t+T_n) = \mathrm{real}(\exp(i2\pi Fc(t+T_n))) \tag{2.1}$$

and the phase is simply

$$\beta = 2\pi FcT_n \tag{2.2}$$

Now $T_n$ is a function of the DOA and the geometry of the array, so we can measure either time delay or phase to obtain the other. However, measuring time of arrival sufficiently accurately enough requires high SNRi. For a sinusoid, the best filter is a matched filter, which is the transmitted sinusoid itself. Let us consider the baseband version of eqn (2.1), which is simply

$$\hat{S}_n(t+T_n) = \exp(i2\pi Fc(T_n)) \tag{2.3}$$

so the relationship between time of arrival and phase is simply a constant multiplier. The matched filter output is shown in Figure D3. The lower plot has AWGN added to the signal, with a resulting SNRo of 15 dB. It is clear that the location of the peak is "fuzzy", even at this rather high SNRo. The width of the peak is approximately 40 ms, which implies a potential ranging error of at least 60 m.

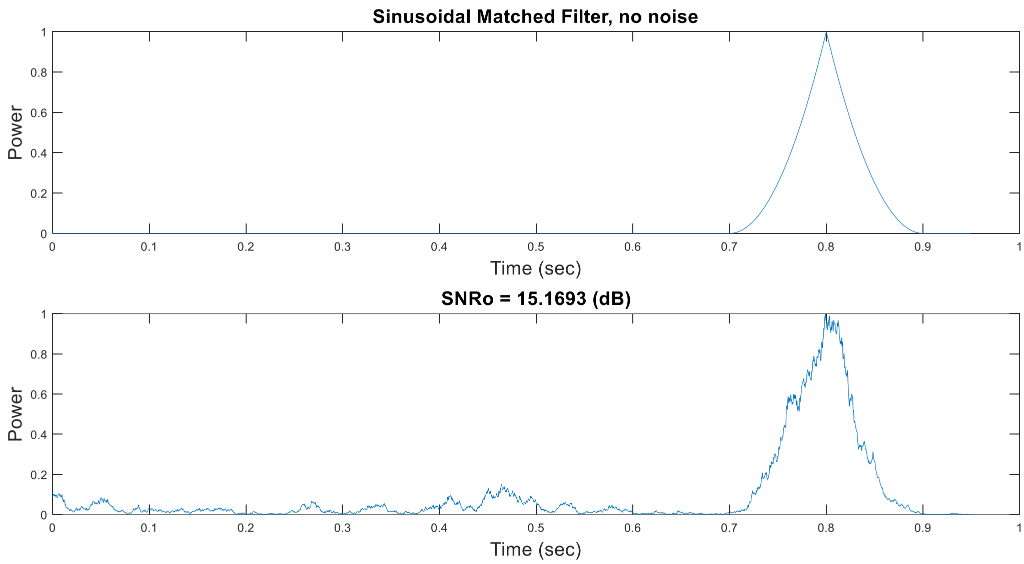


*Figure D3. Example of identifying signal arrival using a tonal waveform.*

For USBL purposes, we need to measure either time-difference of arrival (TDOA) among the hydrophones, or we need to measure phase and infer arrival time. With a sinusoidal approach, we need a very long duration waveform in order to accumulate the SNRo required for good phase estimation, but this reduces the range estimation capability. Simply due to the potentially poor ranging capability of a sinusoidal waveform, we elect to approach this in a different way.[1]

Using wideband waveforms, with matched filter processing, provides us with good accuracy in estimating TDOA for acquisition and alignment purposes. However, with a temporal resolution of approximately 1/W (at low to modest SNRi), this still is not accurate enough for precision DOA estimation. We will use the underlying phase angle for DOA purposes.

Let us consider a tetrahedral USBL device operating at Fc = 25000 Hz center frequency, with a bandwidth of approximately W ~ 7520 Hz. Although somewhat arbitrary, we choose to base our USBL design using the following parameters:

1. Target wavelength ($\lambda$) = c/(Fc+W/2) (2.4)
2. Spacing between hydrophones ($X_d$) = 0.45* $\lambda$ (2.5)

While we are focused on a specific FH acquisition waveform, we can more easily describe the performance of broadband USBL using a mathematically tractable LFM waveform. Consider an LFM waveform as described by eqn (6), with any phase uncertainties that might occur due to RR, pressure-release surface, wave motion, etc. accounted for through the addition of $\theta$:

[1] *The method to be described here was presented by Tom Austin of the Woods Hole Oceanographic Institution (WHOI) at Ocean 9 Teledyne Benthos independently developed this method at a later date without being aware of Austin's contribution, and filed patent* ***WO2007084164A3*** *in 2006. Teledyne has provided written permission to disseminate this USBL method for JANUS-like applications*

$$A(t) = \exp(i2\pi((W/T)t^2/2+f_{min}t)+ \theta) \quad (2.6)$$

The replica correlation of A(t) at a fixed lag L is (with a = W/T)

$$R(L) = \int_{-T/2}^{T/2} \exp\,(i2\pi[at^2 + f1t] + i\theta)\exp(-i2\pi[a((t+L)^2 + f1(t+L)])dt \quad (2.7)$$

which, after some manipulation, becomes

$$R(0) = \exp(i\theta) \quad (2.8)$$

$$R(L) = K\sin(\pi aTL)\exp(i\theta) \quad (2.9)$$

The factor K is a complex number dependent on L, but $|K|\sim 1$ when $L \ll 1/W$. We consider eqn(8) to reflect the replica correlation $R_1(0)$ of the primary hydrophone, and eqn (9) the replica correlation $R_2(L)$ of a secondary hydrophone whose signal arrival is delayed by traveling over a distance L from the reference hydrophone. At the same sample time that we measure the complex correlation of the reference hydrophone we also measure the correlation on the secondary hydrophone, then compute their complex product

$$U = R_1^*(0)\, R_2(L) \sim \sin(\pi aTL) \quad (2.10)$$

And finally, the angle of U = √U is the argument of the sinusoid, so

$$L = \surd U/(\pi W) \quad (2.11)$$

Fortunately, the divisor in eqn(2.11) is common to all hydrophones, so we only need to use the angles to represent time delay among hydrophones. Note especially that all of the extraneous phase angle errors are canceled by this process. In particular this means that range rate is unimportant for USBL purposes since all hydrophones receive approximately the same waveform, and we are only searching for differences in phase.[2] Figure D4 shows an example of phase for two hydrophones of the tetrahedral array using an FH waveform, with the blue line showing the power of the correlation function. The red curve shows the phase (angle) relative to the peak of the first hydrophone correlation. The green line shows the phase angle of another of the 4 hydrophones. Note that these curves were obtained using a high sample rate, relative to the bandwidth.

[2] However, the algorithm does require a well-defined matched filter output, which will not be available unless precision estimation of and correction for RR is accomplished in the modem DSP.

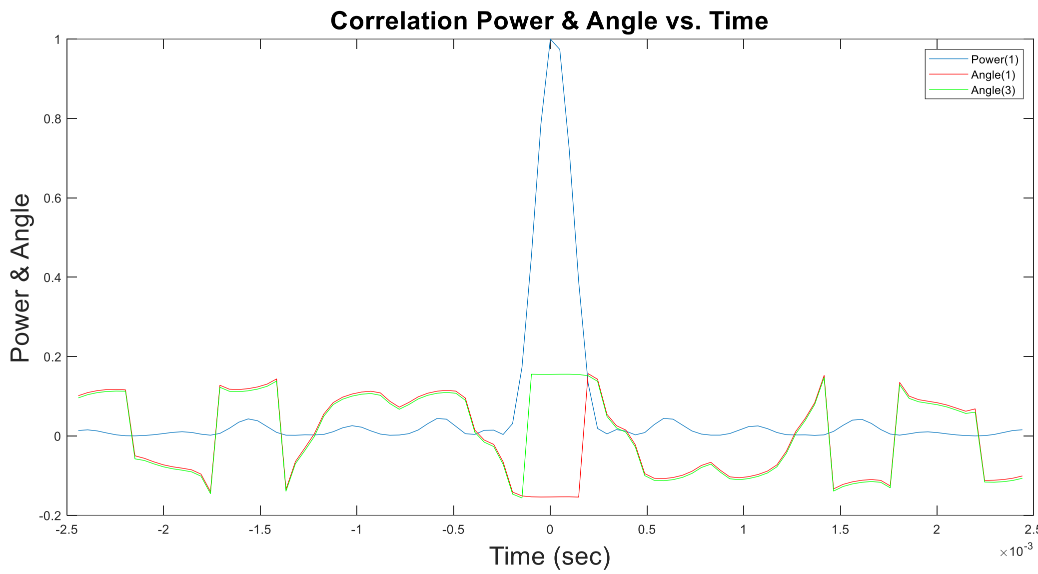


*Figure D4. Overlay of correlation power and phase angle for the reference hydrophone (black and red) and phase angle for the third hydrophone (green) showing that the phase below the peak is nearly constant, but changes with travel distance. It is reasonably constant for other wideband waveforms.*

Our USBL will be based on the geometry shown in Figure D1. Please note the axis definitions in the figure caption.

For the USBL application, we (arbitrarily) choose one of the hydrophones to be the reference hydrophone. We note the arrival sample for the peak of the correlation on the reference. We then measure the phase at **this** sample index for all four of the hydrophones. Note that this will not necessarily be the sample for the peak arrivals at the other three hydrophones. The time delay among the hydrophones will manifest itself as phase differences, which we will use shortly to estimate DOA.

The quality of the DOA estimation will depend on SNRi and sample rate. SNRi is not too great an issue, as we rely on the processing gain (TW) of the waveform to provide high SNRo. Sample rate, however, will affect the quality of the estimate. As a rule of thumb, the sample rate at baseband should be at least 4W.

A tetrahedral array, with orientation as shown in Figure D1, has a geometry defined by the following matrix $\underline{X}$:

H=sqrt(6)/3;
B=H/4;
C=1/2;
D=0.5*tan(pi/6);
E=0.5/cos(pi/6);

$$\underline{X} = X_d \begin{bmatrix} -E & 0 & -B \\ -D & C & -B \\ -D & -C & -B \\ 0 & 0 & 3B \end{bmatrix} \tag{2.12}$$

We have found from experience that

$$X_d \approx 0.45\lambda \tag{2.13}$$

$$\lambda = c/(Fc+W/2) \tag{2.14}$$

where c is the sonic speed (~1500 m/s). From eqn (12) we form direction cosines ($D_c$) by dividing each row of $\underline{X}$ by its own norm.

## 2.1 THE USBL ALGORITHM

Using the primary modem transducer, we identify the arrival time (and traveled range) of the waveform. Assuming that the signal has been captured in parallel FIFOs for the four hydrophones, we compute the complex matched filter for each hydrophone. We observe the location of the peak for the reference hydrophone, and note that it occurs at sample s1. We extract the phase $P_n(s1)$ for each of the N hydrophones. The time offset to each hydrophone is

$$T_n = -2\pi/Fc(\mathrm{angle}(P_1^*(s1)\, P_n(s1))) \tag{2.15}$$

Then compute the vector U by projecting the time vector onto the direction cosines:

$$U = T^T * Dc \tag{2.16}$$

where superscript T indicates transpose to a row vector, or, alternately

$$U = T_3 * Dc(3,:) + T_2 * Dc(2,:) + T_4 * Dc(4,:) \tag{2.17}$$

And, finally

$$\Theta = \tan^{-1}(U_1/U_2) \tag{2.18}$$

$$\Omega = -\sin^{-1}(U_3/|U_{12}|) \tag{2.19}$$

Figure D5 shows DOA estimation performance for our FH waveform. The simulation operates by placing a radiating source each 10 degrees, then computing the estimated DOA according to the above algorithms eqns (15-19). The input SNRi is 10 dB. The figure shows, in the upper plot, the bearing error over 0-360 degrees. The standard deviation of bearing error is 0.15 degrees, with individual realizations approaching 0.3 degrees. The lower plot shows the estimated vertical angle, with a very small deviation about the prescribed target elevation angle of 10 deg.

In the repository we provide a stand-alone MATLAB-based simulation for the FH USBL.

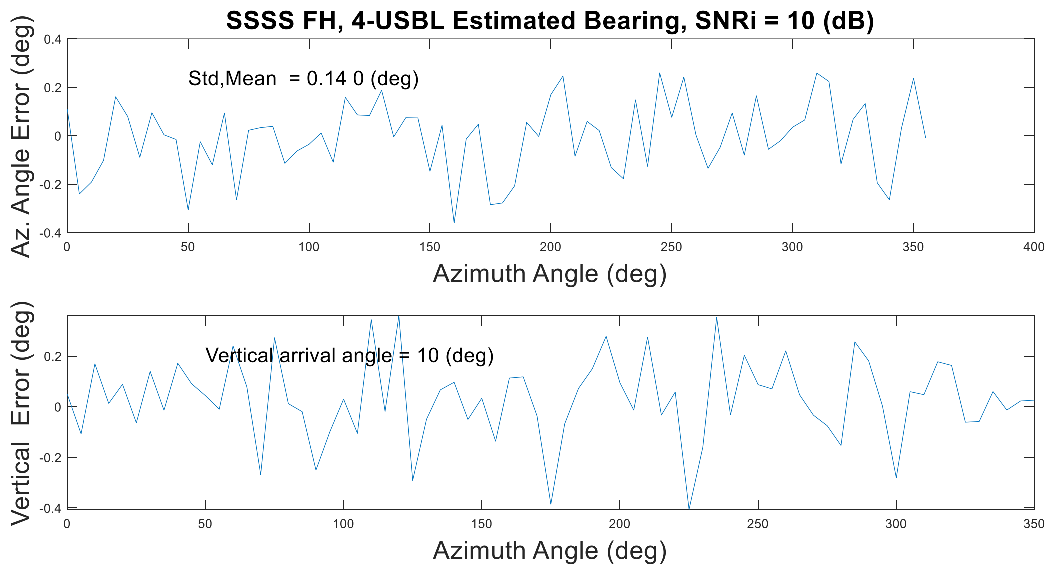


*Figure D5. An example of simulated performance for a 4-element array specific to the FH waveform. The vertical arrival angle is 10 degrees, and the input SNRi =10 dB*

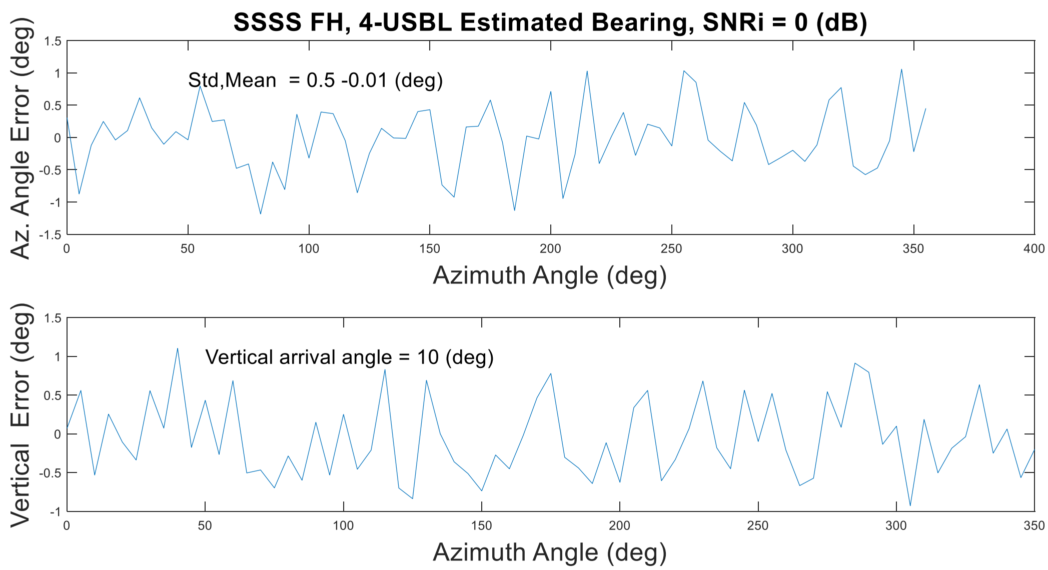


*Figure D6. Same as Figure D5, but now with SNRi = 0 dB.*

# 3. ERRORS IN GEOMETRY

It is extremely important to observe that eqn (2.12) and the direction cosines derived from it reflect our best estimation of the final geometry of the USBL array. However, let us assume that the directions cosines are based on a perfect geometry, while there may be unknown errors in the locations of the array hydrophones. For example, the design element separation is 23.4 mm, but we assume (unknown to the algorithm) that the first element is displaced further away by 1 mm from its nominal location. Figure D7 shows the results, which should be compared with Figures

D5 and D6. This comparison demonstrates the need for calibration and/or more careful hydrophone placement, as an effort to reduce the effects of geometric, potting, and orientation errors.

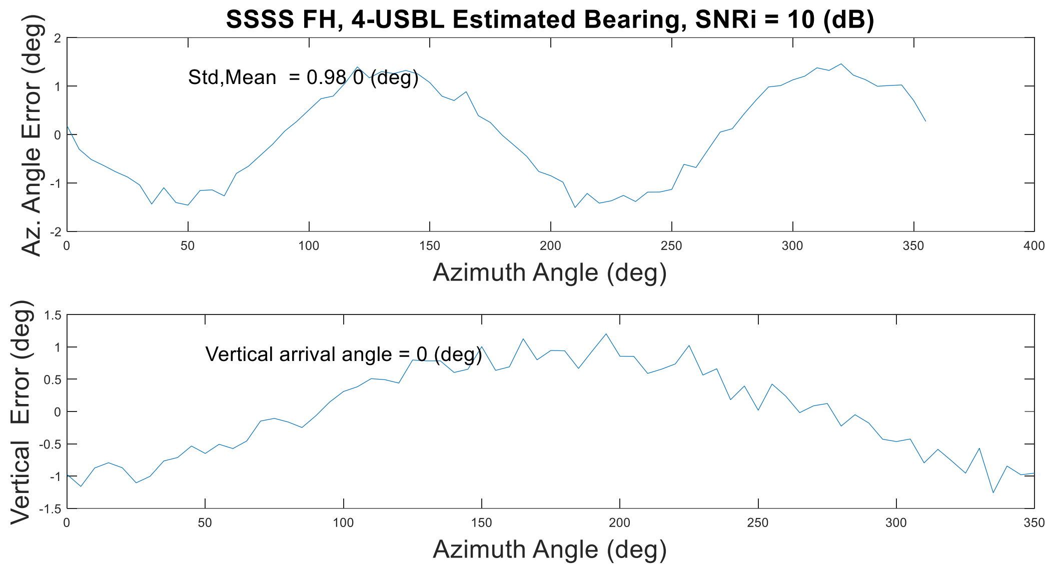


*Figure D7. Performance for the same conditions used for Figure D5, but with the third hydrophone moved away from its nominal position by 1 mm along the x-axis.*

# 4. SUGGESTIONS FOR IMPLEMENTATION

## 4.1 ADCs, FIFOs, and RR Compensation

The USBL will require an additional four ADC devices. It should be possible to repeat the design of the FONTUS modem single-channel device. It is important that there be NO delays among the four ADCs – they must sample their respective data streams at the same time. The FONTUS modem design uses a baseband sample rate of 20480 (complex) samples/second.

In the FONTUS modem, RR compensation is accomplished in the following steps:

1) you get an initial acquisition using the non-coherent FH processing. Meanwhile, a one-channel FIFO has filled with the received 32-chip acquisition waveform.
2) you extract the data in the FIFO, do some matched filter (correlation), and determine a more precise time of arrival, and obtain an estimate of the range rate. All this is done before you start processing the modulated data.
3) You modify the 102,400 sample rate to compensate for the RR estimate - but only for the modulated data, and presumably any cargo packet as well.

Please note that this process does not change the sample rate for the FIFO data. For the USBL application, the 4 channels MUST be compensated for the RR determined from the single FIFO. This can be done at baseband using the “dilation.m” routine, or you can change the sample rate at passband for the four FIFO vectors.

The basebanding, RR compensation, and USBL processing needs to be completed by the time the header packet is fully processed, or, if there is a delay, it needs to be a universal delay that all modems know about and thus can use that in their estimation of range between modems.

It might be useful to study the possibility that, when designing the 4-channel ADC board, a separate DSP chip be included solely for USBL purposes. This would effectively eliminate the USBL computation load from the main modem DSP.

### 4.2.1 Potting Compound

The potting compound which will surround the four hydrophones needs to have approximately the same speed of sound as does water. You can verify this by constructing a rectangular brick of potting material with a transducer imbedded at one end, and a hydrophone imbedded at the other. You can transmit a very short tonal burst through the brick and measure the time delay between Tx and Rx. We suggest you surround the brick with sound absorbing material (e.g., bubble wrap).

When potting the array, it is extremely important that there be no bubbles in the hardened material. You may need to pour the material inside a vacuum chamber.

We suggest you pot the primary transducer and the USBL array as a single unit.