Modeling Acoustic Telemetry Detection Ranges in a Shallow Coastal Environment

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ABSTRACT

Acoustic telemetry is a popular way of monitoring underwater environments and habitats, but an understanding of the detection range and efficiency of the receivers in variable conditions can provide a significant advantage over the detections alone. Receivers can be attached or integrated into autonomous underwater vehicles (AUVs) allowing wide spatial coverage for telemetry networks while collecting environmental data. The integration of calculated sound speeds and received pings gives an estimation of variation in detection efficiency due to changes in environmental conditions, allowing underwater network users to better quantify the range of reliable detection.

Data from a Slocum glider deployed over an array of 16 moored telemetry instruments on the inner shelf off Georgia in 2019 and 2020 indicate that detection efficiency and range vary seasonally. Beam density analysis using ray tracing is proposed as a novel approach that quantifies probability of detection as a function of range, modeling sound speed variability and propagation using co-located temperature and salinity measurements. This approach is validated through comparison of modeled to observed distributions, which suggests that beam density analysis is a promising method to remotely estimate detection efficiency in real time. This real time capability can be leveraged through adaptive sampling in the design and implementation of robotic acoustic telemetry networks.

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KEYWORDS

Acoustic Telemetry, AUVs, Thermoclines, Oceanography, BELLHOP Modeling, Beam Density Analysis

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1 BACKGROUND

Acoustic telemetry has been used by both the scientific and fisheries communities to better understand marine populations [1,2]. Telemetry is reliant on effective and efficient underwater signal transmission, which is affected by increasingly stratified warmer oceans [3]. Detection range of these systems is typically given as a constant on the order of 200-1000m depending on the environment, but sound speed (and therefore sound propagation) is a function of temperature, depth, and salinity, all of which are spatially and temporally dynamic in the coastal ocean [1,2,4,5], even on tidal time scales [6]. In a given time series of detections, it is impossible to discern if a tagged animal has moved away or if the sound channel no longer permits its detection by the receiver, since telemetry only reports presence and not absence. The range at which receivers reliably detect active acoustic transmissions can be key to assessing fish movement patterns and other telemetry applications, such as in underwater networks, but receivers do not record the distance and bearing of detected transmissions.

Autonomous underwater vehicles (AUVs) such as Slocum gliders are now being used as mobile receiver platforms to track the physical water properties and detect transmissions [7]. Integration of the sensors into the vehicle allows reporting of detections in near-real time (each time the vehicle surfaces) rather than having to retrieve moored instruments or use ship time after an extended deployment. Environmental modeling of the soundscape using co-located estimates of sound speed from the vehicle's sampling instrumentation (measuring conductivity, temperature and depth, CTD) can allow incorporation of varying detection efficiency into telemetry assessments, making gliders even more attractive platforms for gathering acoustic data.

This study proposes a novel method of modeling acoustic transmission using real time data streams from in-situ environmental measurements. Water column and telemetry data from experiments conducted at Gray's Reef National Marine Sanctuary (GRNMS) in 2019-2020 are then used to validate the model. These data are used in a predictive capacity to understand the probability of detection as a function of range in near-real time to be leveraged by underwater telemetry networks for adaptive sampling by mobile platforms. Previous studies with similar instrumentation under comparable conditions [7,8] have shown higher detection rates and larger detection ranges during mixed cooler winter months, and fewer detections during stratified summer months. Those efficiency estimates will be compared to the findings of the model for a series of three glider deployments spanning fall 2019 and spring 2020.

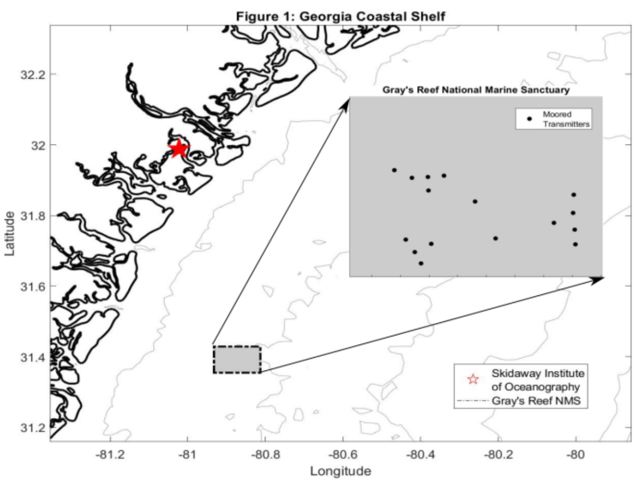

Figure 1: Locations of the 16 acoustic telemetry receivers installed on the inner shelf at Gray's Reef NMS. The 10, 20, 30, 40, and 50m isobaths are indicated in light gray.

2 *METHODS*

2.1 Acoustic Telemetry Array

Gray's Reef National Marine Sanctuary (GRNMS) is a 22 square mile near-shore marine protected area (MPA). As a hard-bottom reef that is a habitat for hundreds of large invertebrates and demersal fish species, Gray's Reef is an ecologically important feature of the continental shelf of the United States where much of the bottom consists of flat sand [8]. As part of recent soundscape and acoustic telemetry monitoring efforts, 16 VEMCO V16 acoustic telemetry receivers were installed within Gray's Reef (Fig. 1). While deployed each receiver emits a reference acoustic signal once every 10 minutes containing identifiers unique to the transmitter (staggered to avoid collision), with a frequency of 69 kHz and a reported effective range of 1km. This regular interval provides a reference for known acoustic transmissions, eliminating a significant unknown present in other acoustic telemetry experiments, the fact that silence could mean absence of anything transmitting or a missed detection.

2.2 AUV Strategies & Data Collection

A 150m Slocum glider was deployed for three 4-5-week missions to collect physical data and acoustic transmissions. Using a buoyancy pump to inflect up and down in the water column, gliders move at 25-30 cm/s horizontally. The glider communicates and fixes GPS positioning when it surfaces (every 4 hours); the glider's submerged position is later interpolated between the two known surfacing positions. This lack of precise location information while underwater adds uncertainty to distance measurements but use of the glider allows for detections to be transmitted back to shore near-real time.

Water column data is sampled with a continuously pumped CTD sensor (conductivity, temperature, and depth) measured and stored at 0.5Hz. To minimize time at the surface only a subset of the data (30s resolution of every 3rd or 4th profile) is sent back to shore each surfacing. For the purposes of this experiment the full datasets were used, though future studies will include testing of these same techniques using different configurations of real-time data subsets.

The glider was outfitted with upward-and downward-facing VEMCO VR2c acoustic receivers that identify and decode active unique transmissions in the form of a series of 8-10 pings over 3-5 seconds (Pulse Position Modulation, PPM). The successful detections and known transmission rate (transmission every ~10 minutes) allow for the calculation of detection efficiency, e.g., the ratio of how many pings were heard to how many pings occurred while the glider was estimated to be within a certain distance of the mooring. In the calculations below, the range bin size is chosen such that time in range is sufficiently large to evaluate efficiency as a smooth, real-valued function over the 2019 and 2020 field experiments.

$$Efficiency = \frac{Detections}{\left(\frac{Time\ in\ Range}{600\ Seconds}\right)} = \frac{Detections}{Estimated\ Possible\ Detections}$$

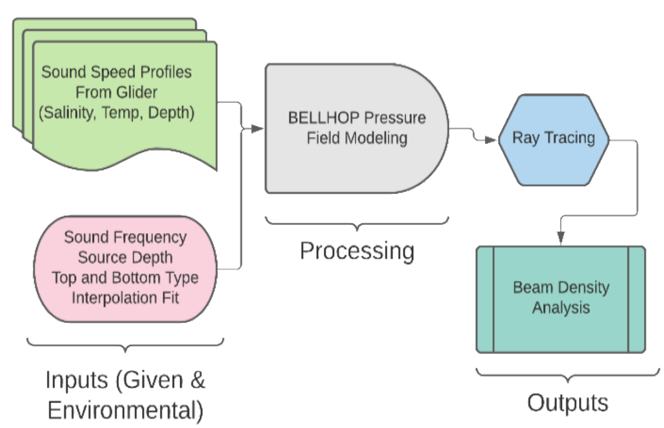

Figure 2: Model framework and information flow. AUV CTD data is used to calculate sound speed profiles as input for BELLHOP ray tracing.

2.3 Environmental Parameters
Sound speed depends heavily on temperature, increases with pressure and has a weak positive dependence on salinity [6]. GRNMS, much like other coastal ocean shelf habitats, is characterized by warmer, less dense water layered over the cooler saltier water at the bottom. This layering is revealed by the presence of a thermocline (region of rapidly change in temperature over depth). As sound travels the thermocline acts as a barrier, refracting the soundwaves back towards the depth of relative minimum sound speed [10]. Depending on the thermocline's strength and position in the water column, this refraction can have substantial effects on sound propagation, especially in shallow water. Knowing the depth of the glider relative to this stratification reveals a relationship between the two instruments; the transmitter and receiver can either be on the same side of the barrier or separated by it, an important distinction for detection [1, 3, 4, 7, 8]. For the purposes of this study, when the largest temperature difference is below a threshold of 0.005 °C/m, the water column is considered well-mixed and the thermocline is set at the surface. This threshold (0.005 °C) is a small enough change in temperature that sound is not refracted back. This distinction prevents large swings of the perceived thermocline depth when in well-mixed environments (e.g., in November data) and allows the inclusion of a value for the minimum gradient studied.

2.4 Acoustic Channel Modeling & Analysis
Acoustic transmission is modeled using AUV-collected profiles of temperature, salinity, and depth, allowing estimates of how sound propagates through the environment using BELLHOP. BELLHOP is a tool to trace acoustic ray paths given a sound speed profile (SSP) [11, 12, 13]. SSPs are calculated along the glider's dives, linearly interpolating between points to give a continuous profile. The robots inflect ~2.5m from the bottom, and the last measured sound speed is extrapolated to the bottom. The bottom boundary is considered an acoustoelastic half-space, over which a relationship between the stress applied and the resulting strain is used [13]. The acoustic source depth in the model is set at 1 meter above the measured bottom, similar to that of the GRNMS moored transmitters and some reef dwelling species, and is given a -20° to 20° angle fan of 1000 rays propagating at 69 kHz. The output is a full ray tracing of possible transmissions paths through the specified water column to a maximum 2km range.

Three distinct profiles have been selected from three missions for modeling analysis to demonstrate variation among deployments: March, early spring with a thermally stratified water column; April, during the spring transition with a cooler, fresher surface layer; and November, when waters were well-mixed. These cases can be considered representative of expected seasonal changes. Only the November 2019 and April-May 2020 missions are included in detection & detection efficiency data. The March deployment was interrupted with storms that moved the glider out of the primary array, resulting in very few detections; the CTD data is used to estimate SSPs as input for BELLHOP modeling.

The full ray tracing allows for a novel approach: beam density analysis, which tracks the percentage of rays reaching a distance downfield. Beam density analysis can be used as a proxy for the probability that an AUV will hear a particular transmission based on its distance from the source and will be highlighted moving forward as a possible solution to the changing detection range in variable conditions.

3 RESULTS
3.1 Total Detections
During the April and November missions, the glider's integrated receivers detected 351 and 463 unique transmissions from moorings. For this study, the focus is on transmissions from known locations, so detections of tagged fish and echoes in the data are disregarded. Three moored transmitters were not detected after deployment and are presumed to have malfunctioned, and thus are not included in the analysis that follows.

Of a total of the 814 unique detections, 733 (90%) were received while the receiver and transmitter were on the same side of a thermal gradient. Table 1 separates detections by range and position relative to the thermocline at the time of detection. Most detections were received within the manufacturer's reported working distance of 1km and below the thermal gradient (484, 59.5%). There is a clear distinction in the detection distances between the two missions: there were 203 (43.8%) detections beyond 1km in November versus only 67 (19%) in April/May.

Acoustic Detections: Moored Transmitter to AUV-Integrated Receiver

November 2019: 11 Days on Reef, n=463

Estimated Distance	<500m	500-1000m	1000-2000m	2000-3000	>3000	Total
Above Thermocline	5 (1.0%)	14 (3.0%)	9 (1.9%)	0	0	28 (6%)
Below Thermocline	106 (23.0%)	135 (29.2%)	136 (29.4%)	56 (12.1%)	2 (0.4%)	435 (94%)
Total Detections	111 (24.0%)	149 (32.2%)	145 (31.3%)	56 (12.1%)	2 (0.4%)	463

April/May 2020: 18 Days on Reef, n=351

Estimated Distance	<500m	500-1000m	1000-2000m	2000-3000	>3000	Total
Above Thermocline	11 (3.1%)	30 (8.5%)	12 (3.4%)	0	0	53 (15%)
Below Thermocline	104 (29.6%)	139 (39.6%)	55 (15.8%)	0	0	298 (85%)
Total Detections	115 (32.7%)	169 (48.2%)	67 19.1%)	0	0	351

2019 & 2020: 29 Days on Reef, n=814

Estimated Distance	<500m	500-1000m	1000-2000m	2000-3000	>3000	Total
Above Thermocline	16 (2.0%)	44 (5.4%)	21 (2.5%)	0	0	81 (10%)
Below Thermocline	210 (25.9%)	274 (33.6%)	191 (23.5%)	56 (6.9%)	2 (0.2%)	733 (90%)
Total	226	318	212	56	2	814

Table 1: Acoustic transmissions detected by glider and position relative to the thermocline. Percent shown of total detections.

3.2 Estimated Detection Efficiency

Average detection efficiency over both seasons is reported in Figure 3 along with a histogram of time spent in each of the 100m range bins. The detection efficiency generally decreases as a function of range; the <100 meter bin does not follow this trend for April, but has a very small sample size due to limited time spent by the glider in close proximity to the moorings. In addition, the detection efficiencies are comparable with other published results from AUVs (20% efficiency at 600m [7]) and from a stationary array at Gray's Reef (36.2% at 167m [8]).

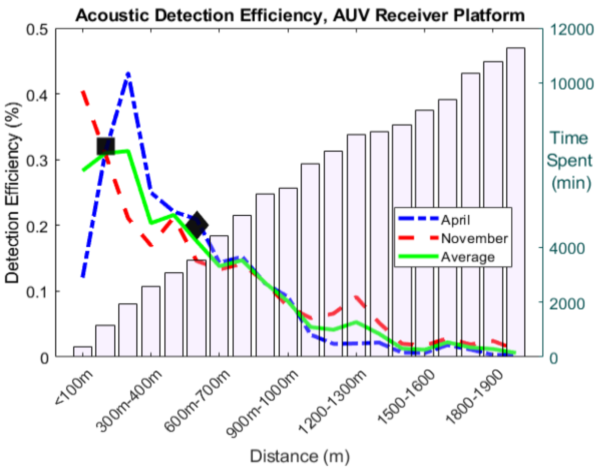

Figure 3: Detection efficiency as a function of cumulative time spent within range. Average reported for the Mid Atlantic Bight inner shelf [7] and prior work in Gray's Reef [8] are indicated as a diamond and square, respectively.

3.3 BELLHOP Modeling & Beam Density Analysis

Resulting ray traces show the formation of shallow sound channels, reflecting off the surface and refracting the sound back towards the bottom. The effects of the thermocline are evident in both the sound speed profile and resulting model where 1 °C difference in temperature corresponds to a 4.0 m/s increase in sound speed, significantly changing how sound travels through the medium. A defined thermocline is present in March and April, when the water column is stratified, but is absent during well-mixed conditions in November (Fig. 4). Sound speed profiles in April (4b) suggest that near-surface salinity stratification from the spring freshwater may lead to the development of two shallow channels. Sound could become trapped on either side depending on the source depth; the transmitters in this experiment are moored to the ocean bottom and therefore more sound propagates in the lower channel.

BELLHOP ray tracing shows a steep drop off and a plateau in the first 100m, representing a water column that is saturated with sound. To clearly show the range of propagation, percentage of rays within 100m is then set at 100%. The waves at this distance reach the thermocline and surface at an angle lower than the critical angle, ensuring penetration through this barrier.

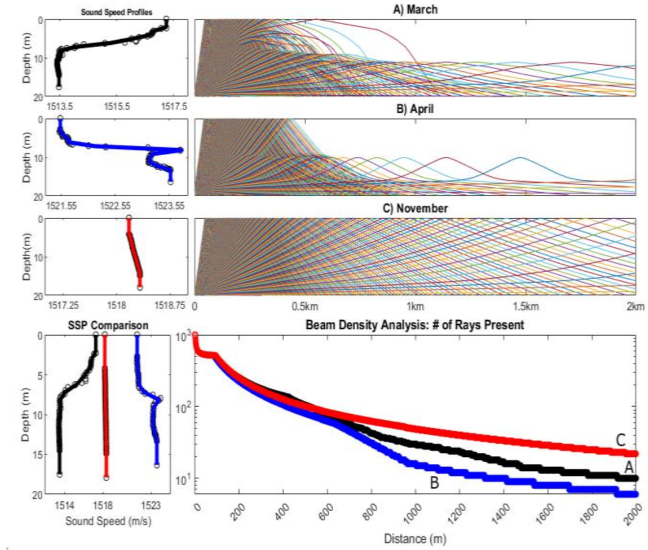

Figure 4: Separate sound speed profiles from March (A), April (B), and November (C), with estimates of propagation and beam density analysis of the resulting ray traces.

As beams approach the reported 1km effective range, the difference in propagation is the most prominent, especially between April's stratified and November's mixed conditions: 1km, 16 to 49 rays; 1.5km, 9 to 31 rays; 2km, 6 to 22 rays. This drop in modeled ray paths corresponds with periods of less detections and a shorter effective range.

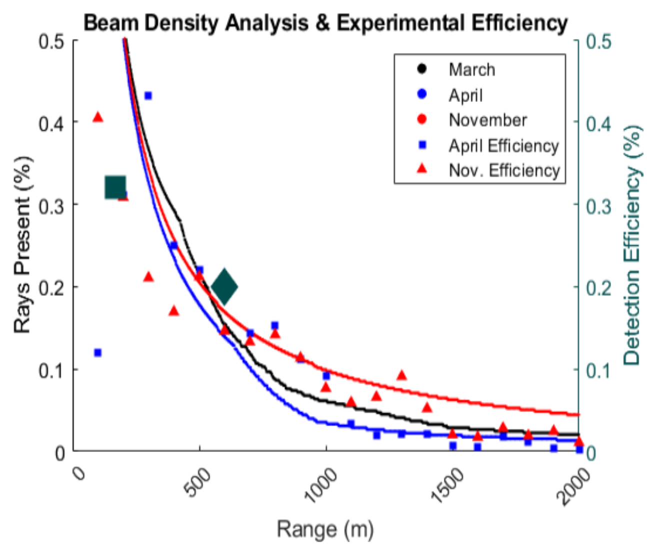

Figure 5: Modeled beam density analysis (lines) and observed detection efficiency (symbols). Average efficiencies reported for the Mid Atlantic Bight inner shelf [7] and prior work in Gray's Reef [8] are indicated as a diamond and square, respectively.

4 DISCUSSION

Detection efficiency is strongly related to distance, in agreement with past research [7,8,9]. This trend is reproduced in the ray tracing models, with fewer rays propagating to distances beyond 1km. During the well-mixed November mission almost 45% of detections occurred past 1km, and the beam density analysis predicts that significantly more rays (~300%) should be propagating to that extended range given the conditions. The modeled percentage of rays present is comparable to the observed detection efficiency as a function of range from the field experiments in 2019 and 2020 as, seen in Figure 5: there is a steep drop off followed by a smooth descent in both the experimental efficiencies and modeled rays. This agreement (R^2=0.78, April, and 0.87, November) gives confidence in beam density analysis as a predictive tool for estimating acoustic detection efficiency in a shallow coastal ocean. Estimates of detection efficiency in 2019 and 2020 differ significantly within the first 100m, where very little time was spent. This lack of detections may be an indication of close proximity detection interference (CPDI, 14), or of the "doughnut effect" attributed to the design of the integrated receiver [7]. April and November's missions have a nearly 35% difference in detection efficiency (with low sample size). There is a possibility that the seasonal stratification changes led to the difference and the presence of CPDI, but there is also insufficient time spent at that range to make adequate assessments of these potential effects, and Kessel's previous work had trouble finding this interference in a noisier, turbid environment that prevents clear echoes.

Future Considerations

Beam density analysis appears to be a viable, quantitative way to estimate probability of detection as a function of range using glider-based acoustic telemetry, providing valuable context for the design of underwater networks and for fisheries managers. Improved localization of the glider when submerged would refine distance estimates, and simulated environments can help narrow the gap between the two case studies presented. Future AUV-based surveys can potentially leverage this information in network design and operations in real time, with less separation between vehicles when the predicted detection range is small, and greater separation when the predicted detection range is large.

Prior work in Gray's Reef suggests that both range and bearing relative to the cross-shore direction are important predictors of detection efficiency due to cross-shore temperature and salinity gradients on the inner shelf [4,6]. BELLHOP 3D may be used to account for these differences. Future work will explore these factors within the moored receiver array data, as well as incorporating along- and cross-shore asymmetries into BELLHOP 3D sound speed profile inputs. Accounting for variable bottom composition may also allow for a better understanding of possible transmission losses.

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