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2026-09-15

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UNIVERSITY OF CALIFORNIA SAN DIEGO

Environmentally Aware Autonomy to Optimize UUV Acoustic Communications

A thesis submitted in partial satisfaction of the
requirements for the degree Master of Science

in

Oceanography

by

Adam Morales

Committee in charge:

Eric Terrill, Chair
Sophia Merrifield, Co-Chair
Mark Anderson
Ryan McCarthy

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University of California San Diego

2026

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ACKNOWLEDGEMENTS

I would like to thank Dr. Eric Terrill and Dr. Sophia Merrifield for their mentorship and for providing me with the incredible opportunity to pursue a Master of Science in Applied Ocean Science. I am deeply grateful for their hard work, guidance, and willingness to expose me to different facets of oceanography and unmanned systems. My time at the Scripps Institution of Oceanography greatly broadened my perspective on the scientific community and deepened my appreciation for the complexity of ocean science.

I would also like to thank Dr. Ryan McCarthy for his advice, patience, and dedication to helping me learn underwater acoustics and data analysis. His contribution to my education cannot be overstated.

Thank you to Dylan Kriegman for helping program the UUVs used throughout the different assessments and for guiding me through the initial challenges of learning unfamiliar software systems. His tireless efforts in software development, running simulations, preparing equipment, and transferring data were essential to the successful completion of field testing and analysis.

Thank you to Dr. Mark Anderson for challenging me to look at problems from different perspectives and for encouraging me to simplify solutions rather than overcomplicate them.

Thank you to Andy Nager for patiently answering my many questions about unmanned systems and their capabilities.

Thank you to Ted Torgesen for being my wingman as we navigated the coursework and the requirements of being graduate students.

To the entire staff at the Coastal Observing Research and Development Center, thank you for contributing to my education and for the professionalism, patience, and support you showed throughout my time at Scripps.

I would also like to thank the Office of Naval Research and the Naval Special Warfare community for funding this research and allowing me to pursue such a challenging and rewarding program.

Thank you to my parents, Vincent and Laura, for their enduring support as I continue to explore my career path and pursue new educational opportunities.

Most importantly, thank you to my amazing wife, Samantha, for her love, patience, and unwavering support throughout the ups and downs of this master's program while we also juggled becoming new parents to our boys, Wesley and Dutch. I could not have done this without you.

OpenAI ChatGPT was used as an editorial tool to assist with revising text, troubleshooting LaTeX, and preparing selected graphical materials. All technical content, data analysis, interpretation, and conclusions are the work of the author.

VITA

2006–2010 Bachelor of Science, California Polytechnic State University, San Luis Obispo
2010–2012 Assistant Zookeeper, Central Coast Zoo, Atascadero, CA
2012– United States Navy, Active Duty
2024–2026 Master of Science, University of California San Diego

ABSTRACT OF THE THESIS

Environmentally Aware Autonomy to Optimize UUV Acoustic Communications

by

Adam Morales

Master of Science in Oceanography

University of California San Diego, 2026

Eric Terrill, Chair

Sophia Merrifield, Co-Chair

Reliable underwater acoustic communication is important for Unmanned Underwater Vehicle (UUV) operations but is affected by environmental conditions and vehicle geometry. The objective of this research was to identify factors affecting acoustic communication performance for a REMUS 100 UUV and to develop autonomous behaviors that could improve communication reliability during mission execution.

Laboratory and field experiments conducted through the Scripps Institution of Oceanography (SIO) Coastal Observing Research and Development Center (CORDC) evaluated the effects of vehicle self-noise, vehicle depth, and vehicle orientation on communication performance

using a WHOI Micromodem-2 operating at 25 kHz. Communication success was evaluated under varying operating conditions, and BELLHOP acoustic propagation modeling was used to support interpretation of depth-dependent communication performance.

Results showed that changes in vehicle propulsion RPM produced minimal changes in acoustic energy near the communication frequency and did not provide a strong basis for adaptive behavior development. In contrast, communication performance varied with vehicle depth and orientation relative to the receiver, identifying both as controllable parameters that could be used by the vehicle to respond to communication degradation. Based on these findings, autonomous depth-seeking and broadside-deviation behaviors were developed and integrated into the REMUS 100 software architecture. Field testing demonstrated that the vehicle could autonomously modify its depth or orientation following communication degradation and subsequently return to the planned mission trackline. Successful communication recovery was observed during both adaptive behavior assessments, demonstrating that communication status can be incorporated into UUV autonomy and used to influence vehicle motion in response to degraded underwater acoustic communication conditions.

Chapter 1

Introduction

1.1 Underwater Acoustic Communication

Unmanned underwater vehicles (UUVs) use acoustic communication to exchange navigation information, mission updates, and vehicle status data with surface and subsurface platforms. Unlike radio frequency signals, which attenuate rapidly in seawater, acoustic signals can propagate over substantially longer distances underwater.

The communication system used in this thesis consisted of a REMUS 100 UUV equipped with a 25 kHz WHOI Micromodem-2 communicating with a towfish deployed from a surface vessel, a gateway buoy (GWB), or a Wave Glider. The experimental assessments evaluated vehicle self-noise, changes in communication performance with vehicle depth and range, and the effect of relative vehicle orientation. Acoustic propagation, the SVP, multipath propagation, ambient noise, and transmitter-receiver orientation can affect received signal strength and whether an acoustic message is successfully decoded. The following sections describe the acoustic principles needed to interpret these experimental assessments.

1.2 Acoustic Wave Propagation in the Ocean

Within the ocean, temperature, salinity, and pressure determine the local sound speed. Variations in these properties can change the direction and distribution of acoustic energy [18, 26, 30, 45]. Changes in sound speed produce refraction and can contribute to multipath

propagation and acoustic shadow zones [18]. Depth-dependent refraction and shadowing can cause received signal strength and communication performance to vary as the UUV moves through the water column.

1.2.1 Sound Velocity Profile

Because the speed of sound in seawater is a function of temperature, salinity, and pressure, empirical equations are commonly used to estimate sound speed. One widely used relationship, shown in Eq. (1.1), estimates the speed of sound in seawater for depths down to approximately 8,000 m [27, 30]. In this equation, c is the sound speed (m/s), T is the temperature ($^{\circ}\text{C}$), S is the salinity (ppt), and D is the depth (m) [27].

$$\begin{aligned} c(T, S, D) = & 1448.96 + 4.591T - 5.304 \times 10^{-2}T^2 + 2.374 \times 10^{-4}T^3 \\ & + 1.340(S - 35) + 1.630 \times 10^{-2}D + 1.675 \times 10^{-7}D^2 \\ & - 1.025 \times 10^{-2}T(S - 35) - 7.139 \times 10^{-13}TD^3 \end{aligned} \quad (1.1)$$

A sound velocity profile (SVP) displays the vertical variation of sound speed in the ocean. Near the surface, wind and wave dynamics can produce a mixed layer with relatively uniform temperature. Below the mixed layer, temperature decreases rapidly with depth through the thermocline, which typically causes sound speed to decrease. Beneath the thermocline, temperature becomes more uniform within the deeper isothermal layer, while increasing pressure causes sound speed to increase with depth [26, 30, 45].

1.2.2 Refraction and Ray Paths

Refraction occurs when sound propagates through regions of varying sound speed. Snell's Law, shown in Eq. (1.2), describes this behavior, where θ is the angle of the acoustic ray relative to the horizontal and c is the local sound speed. Acoustic rays bend toward regions of lower sound speed, producing curved propagation paths through the water column [18, 26].

$$\frac{\sin \theta}{c} = \text{constant} \quad (1.2)$$

When sound speed decreases with depth in a thermocline, acoustic rays are refracted downward. When sound speed increases with depth, acoustic rays bend upward. These refraction patterns can concentrate or spread acoustic energy, producing spatial variations in received signal strength [18, 26].

Refraction can also create acoustic shadow zones when acoustic rays bend away from a region. Reduced acoustic energy within a shadow zone can result in lower received signal strength or complete communication loss [18, 26, 45]. Figure 1.1 shows how changes in the SVP affect acoustic ray paths and can create a shadow zone.

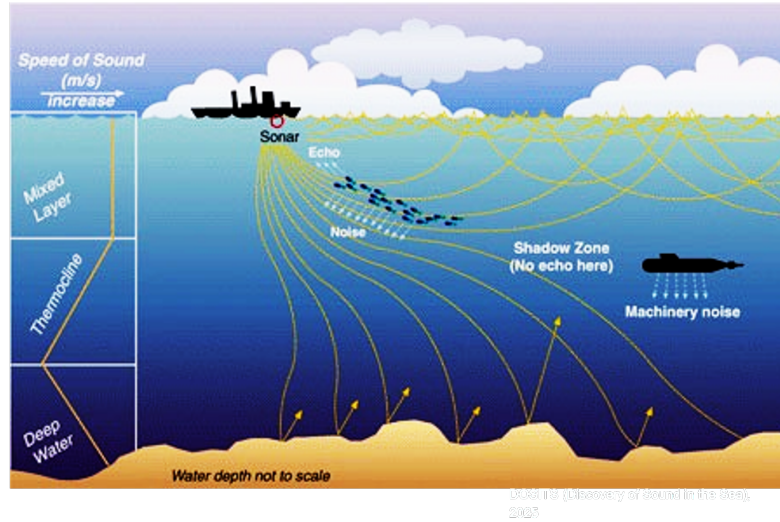


Figure 1.1. Illustration of acoustic ray propagation in a stratified ocean environment. The sound velocity profile is shown on the left, with the resulting ray paths, boundary interactions, and acoustic shadow zone shown on the right. Adapted from [21].

Ray Tracing Methods

Ray tracing is commonly used to model high-frequency acoustic propagation in the ocean. Sound propagation is represented as a collection of rays that follow paths determined by local sound speed gradients. Ray tracing can be used to visualize acoustic propagation paths, estimate travel times, and identify areas of high or low acoustic intensity [7, 18, 29, 34].

BELLHOP Acoustic Model

The BELLHOP acoustic model is a commonly used ray tracing tool for simulating how sound propagates underwater. BELLHOP predicts acoustic ray paths and transmission loss (TL) using environmental inputs such as the SVP, bathymetry, and boundary conditions [7, 18, 34, 33]. In this study, BELLHOP was used to model acoustic propagation between the UUV and receiving platforms using measured SVPs and test-site environmental data. The resulting ray paths and TL fields were compared with received SPL and communication results to evaluate how vehicle depth and range affected acoustic propagation.

1.3 Transmission Loss

TL describes the reduction in acoustic signal strength as sound propagates from a source to a receiver. It directly affects communication range and received signal strength. The primary sources of TL include geometric spreading, absorption, refraction, and interactions with the sea surface and seafloor [18, 26, 45].

Surface and bottom interactions can redirect acoustic energy and create additional propagation paths, while scattering and absorption reduce the amount of energy that continues toward the receiver. The magnitude of these losses depends on factors such as boundary roughness, bottom composition, and grazing angle [18, 26, 45].

1.3.1 Geometric Spreading

Geometric spreading represents the reduction in acoustic intensity as sound propagates away from a source. When acoustic energy spreads outward in all directions without significant interaction with boundaries, this is referred to as spherical spreading. Under these conditions, acoustic intensity decreases with the square of the distance from the source [45]. Spherical TL is expressed in Eq. (1.3), where R is the range from the source in meters.

$$TL_{spherical} = 20\log_{10}(R) \quad (1.3)$$

When the sea surface and seafloor limit vertical spreading, acoustic energy spreads primarily in the horizontal direction. This is referred to as cylindrical spreading and produces lower TL over a given range than spherical spreading [18, 45]. Cylindrical TL is expressed in Eq. (1.4).

$$TL_{cylindrical} = 10\log_{10}(R) \quad (1.4)$$

Acoustic propagation can vary between spherical and cylindrical spreading depending on water depth, the SVP, and boundary interactions [45]. Figure 1.2 illustrates these two spreading patterns.

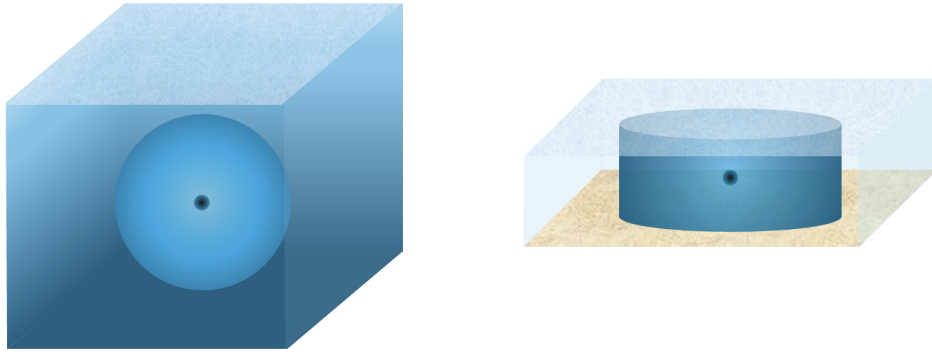


Figure 1.2. Illustration of spherical (left) and cylindrical (right) geometric spreading in underwater acoustics.

1.3.2 Absorption Loss

In addition to geometric spreading, acoustic energy is reduced through absorption in seawater. Absorption converts a portion of the acoustic energy into heat and increases with acoustic frequency [2, 18, 45]. At the 25 kHz operating frequency used in this study, absorption

contributes to TL as propagation distance increases. Absorption loss is expressed in Eq. (1.5), where α is the absorption coefficient (dB/m) and R is the propagation distance.

$$TL_{absorption} = \alpha R \quad (1.5)$$

1.3.3 Combined Transmission Loss

Total TL can be approximated as the combination of geometric spreading and absorption loss along a propagation path. This relationship is expressed in Eq. (1.6) [45], where k is the spreading factor, α is the absorption coefficient, and R is the propagation distance.

$$TL = k \log_{10}(R) + \alpha R \quad (1.6)$$

Refraction, boundary interactions, and multipath propagation can cause TL to vary from these simplified spreading models. BELLHOP was used in this study to estimate TL under the measured environmental conditions and evaluate how propagation changed with vehicle depth and source-receiver geometry [18, 33].

1.4 The Underwater Acoustic Channel

Acoustic signals can be affected by ambient noise, multipath propagation, Doppler effects, and acoustic shadowing as they travel between the transmitter and receiver [18, 45]. These effects can change received signal strength or distort the transmitted signal, reducing the ability of the acoustic modem to successfully decode a message.

1.4.1 Ambient Noise

Ambient noise consists of acoustic energy originating from sources other than the acoustic transmitter. Sources include wind-driven surface waves, precipitation, marine life, and vessel activity [18, 26, 45, 47]. Ambient noise reduces SNR and can interfere with detection and

decoding of the transmitted acoustic signal.

Ambient noise also varies with frequency. At lower frequencies, distant shipping and other anthropogenic sources can contribute to the acoustic environment, while wind and sea surface processes become more prominent at higher frequencies [18, 22, 45]. Biological sources can also produce acoustic energy within the 25 kHz operating band used in this study. Snapping shrimp generate broadband acoustic signals ranging from a few kHz to over 100 kHz and can produce persistent background noise in areas with high biological activity [46, 18, 47]. For this study, wind, vessel activity, and biological noise contributed to the ambient acoustic environment during the field experiments but were not independently measured or isolated.

1.4.2 Multipath Propagation

Multipath propagation occurs when reflections and refraction cause an acoustic signal to travel between the transmitter and receiver along more than one path. As a result, multiple copies of the transmitted signal can arrive at the receiver at different times and with different amplitudes and phases [18, 19, 35, 45].

Differences in arrival time and phase can produce constructive or destructive interference, causing variations in received signal strength. Delayed arrivals can also overlap with subsequent symbols and produce intersymbol interference (ISI), which can increase the likelihood of decoding errors [19, 36, 41]. The amount of multipath depends on water depth, boundary interactions, the SVP, and transmitter-receiver geometry [18, 35, 45]. During the depth and range assessment, the UUV operated in approximately 55 m water depth, where surface and bottom reflections may have contributed to the observed variations in received SPL.

1.4.3 Doppler Effects

The Doppler effect occurs when relative motion between the acoustic source and receiver causes a shift in the frequency of the received signal. When the source and receiver move toward each other, the received frequency increases, while movement away from each other decreases

the received frequency [18, 41, 45]. The resulting frequency and timing changes can interfere with signal detection, synchronization, and decoding [36, 41].

For a moving UUV, Doppler shift depends on vehicle motion and the relative velocity between the transmitter and receiver [35]. A UUV traveling at approximately 1–2 m/s can produce Doppler shifts on the order of tens of Hz at frequencies near the 25 kHz operating frequency used in this study [35, 41]. Vehicle and receiver motion were present during several field experiments and could therefore contribute to variability in acoustic communication performance.

1.4.4 Acoustic Shadowing

Acoustic shadowing occurs when acoustic energy is redirected or obstructed before reaching the receiver. Refraction can create shadow zones when acoustic rays bend away from a region, while physical obstructions can block the direct propagation path between the transmitter and receiver [18, 26, 45].

For the REMUS 100, the vehicle hull can obstruct the acoustic propagation path depending on the relative position of the receiver. The acoustic transducer used in this study was mounted beneath the forward section of the vehicle. When the receiver is positioned above the UUV, portions of the vehicle hull can lie between the transducer and receiver. The large acoustic impedance difference between seawater and the sealed, air-filled vehicle interior limits acoustic transmission through the hull, which can reduce signal strength in these directions [17, 18, 45].

Vehicle heading and receiver position can therefore change the amount of hull obstruction along the acoustic propagation path. This directional effect provides one possible mechanism for the differences in received SPL between broadside and nose-on or tail-on orientations evaluated in the relative heading assessment.

1.5 Signal-to-Noise Ratio (SNR)

Signal-to-noise ratio (SNR) represents the ratio of received signal power to background noise power at the receiver. Higher SNR increases the ability of the acoustic modem to detect

and decode a transmitted signal.

1.5.1 SNR Equation

In underwater acoustics, SNR can be expressed in decibels (dB) using the sonar equation, where SL is the source level (dB re 1 μPa @ 1 m), TL is the transmission loss (dB), NL is the noise level (dB re 1 μPa), and DI is the directivity index (dB) [18, 45]. The sonar equation shows how source level, TL, NL, and DI combine to determine SNR at the receiver.

$$SNR = SL - TL - NL + DI \quad (1.7)$$

1.5.2 Source Level

Source level (SL) represents the acoustic signal strength produced by the transmitter, referenced at a distance of 1 m from the source. Source level depends on transmitter power, transducer efficiency, and operating frequency [45]. The WHOI Micromodem-2 used in this study operated at 25 kHz, with the transmission power configuration described in Chapter 2.

1.5.3 Transmission Loss

TL reduces the acoustic signal strength between the transmitter and receiver. As described in Section 1.3, TL depends on range, absorption, refraction, and boundary interactions. Changes in TL with vehicle depth and range were evaluated using received SPL measurements and BELLHOP modeling during the depth and range assessment.

1.5.4 Noise Level

Noise level (NL) represents the ambient acoustic noise measured at the receiver within the receiver bandwidth. Higher NL reduces SNR and can make the transmitted signal more difficult to detect or decode [18, 45]. Noise level can vary with local acoustic activity and the operating frequency of the receiver. Wider receiver bandwidths also capture more noise energy, increasing the total NL measured by the receiver.

1.5.5 Directivity Index

Directivity index (DI) describes how a directional receiver favors acoustic signals arriving from some directions while reducing noise arriving from others [18, 26, 45]. Higher DI can therefore increase SNR when the receiver is aligned with the incoming acoustic signal.

For the REMUS 100, transducer mounting location and hull shadowing can also affect received signal strength as the geometry between the UUV and receiver changes. Transducer mounting and hull shadowing were evaluated during the relative heading assessment described in Chapter 3. The following chapter describes the REMUS 100, acoustic communication hardware, and vehicle systems used to conduct these assessments.

Chapter 2

Unmanned Underwater Vehicle (UUV) Platform and Communication Systems

In the 1990s, the Office of Naval Research (ONR) funded Woods Hole Oceanographic Institution (WHOI) to develop a small untethered robotic underwater vehicle to support scientific research and military applications. The developers at WHOI named the vehicle family the “Remote Environment Monitoring UnitS,” commonly referred to as REMUS. The REMUS family includes multiple vehicle variants ranging from the REMUS 100 to the REMUS 6000, with the numerical designation corresponding to the vehicle depth rating in meters [3, 32]. A REMUS 100 was used throughout this research to evaluate the effects of vehicle position and orientation on underwater acoustic communication performance.

The REMUS 100 is classified as a small UUV with a length of approximately 1.3 m, a diameter of 0.19 m, and a dry weight of approximately 37 kg. The vehicle can support a variety of environmental and navigation sensors depending on mission configuration [25, 37, 39].

Sensors relevant to this research included a conductivity-temperature-depth (CTD) sensor used to measure the water properties required to calculate the sound velocity profile (SVP). A downward-facing ADCP functioned as a Doppler Velocity Log (DVL) to measure vehicle velocity and altitude above the seafloor. The vehicle also included an Environmental Characterization Optics (ECO) sensor, digital compass, and yaw rate gyro [25, 37, 39]. Figure 2.1 shows the vehicle components and sensor locations, while Table 2.1 summarizes the primary characteristics

and sensor configuration of the REMUS 100 used in this research.

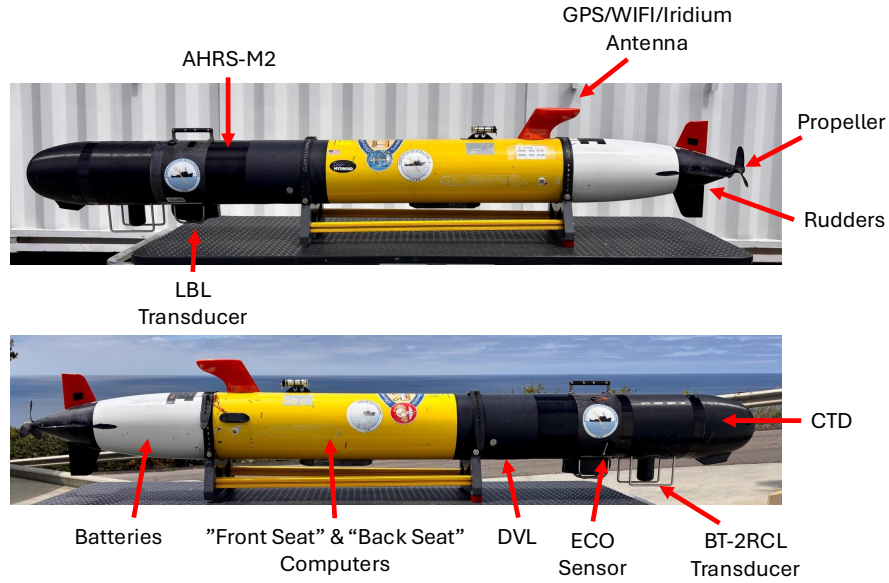


Figure 2.1. REMUS 100 vehicle components and sensors, CORDC configuration.

Table 2.1. REMUS 100 vehicle characteristics and representative sensor payloads, adapted primarily from [37] and supplemented with information from [25, 39].

Parameter	Description
Diameter	19 cm
Length	130 cm
Dry weight	37 kg
Depth rating	100 m
Energy	1 kW-hr internally rechargeable lithium battery
Propulsion	Direct drive brushless motor with open three-blade propeller
Maximum velocity	2.8 m/s
Navigation	GPS, LBL, USBL, DVL, digital compass, INS
Transponder frequencies	10–15 kHz and 20–30 kHz
Sensors	CTD, ECO sensor, digital compass, yaw rate gyro
Software	GUI-based laptop interface (WHOI VIP) for programming, maintenance, documentation, and troubleshooting
Communication	WHOI Micromodem-2, Wi-Fi, Iridium

2.1 REMUS 100 Navigation

The REMUS 100 uses GPS while surfaced and relies on an inertial navigation system (INS), Doppler Velocity Log (DVL), digital compass, and other onboard sensors to estimate vehicle position, heading, velocity, depth, and altitude while submerged. The DVL provides bottom-relative velocity and altitude measurements that support submerged navigation, while the INS combines these measurements with inertial and heading information to maintain an estimate of vehicle motion and position [25, 37, 20].

When available, Long Baseline (LBL) or Ultra-Short Baseline (USBL) acoustic navigation systems can provide external position updates and reduce accumulated navigation error during longer missions. When external updates are unavailable, the vehicle relies on onboard navigation and dead reckoning, which can accumulate positional error over time [20, 48].

For the experiments presented in this research, the navigation system provided the vehicle position, heading, depth, and altitude information required to evaluate acoustic communication performance as a function of vehicle location and orientation.

2.2 REMUS 100 Acoustic Communication System

2.2.1 Communication Architecture

The REMUS 100 uses a WHOI Micromodem-2 and a hull-mounted acoustic transducer to communicate with external acoustic communication nodes while submerged. WHOI VIP provides the surface operator interface for monitoring and controlling these communications. For this research, a BT-2RCL acoustic transducer was added to the REMUS 100 in addition to the standard LBL navigation transducer. The BT-2RCL was used for all acoustic communication experiments conducted during this study.

External communication systems used during this research included a Ranger transceiver, towfish, gateway buoy (GWB), and Wave Glider equipped with compatible WHOI acoustic communication hardware [17, 25, 37].

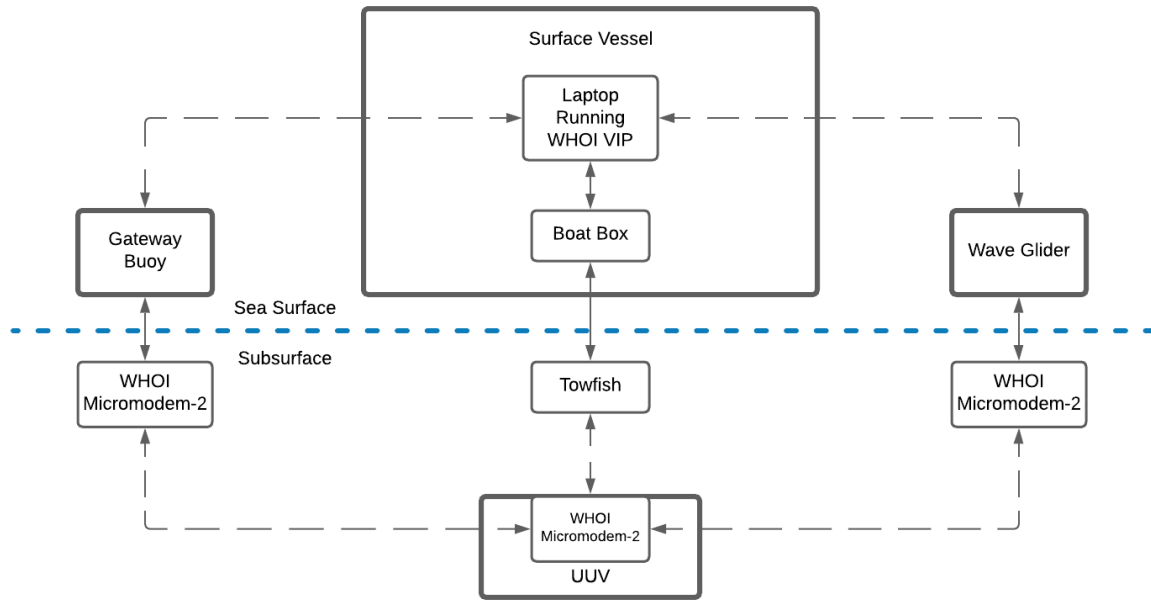


Figure 2.2. Acoustic communication platforms used throughout this research. The REMUS 100 communicated with gateway buoys (GWB), Wave Gliders (WG), and towfish deployed from a support vessel. These platforms enabled acoustic communication between the REMUS 100 and the WHOI VIP.

Communication with a manned surface vessel is typically performed using either a Ranger system or a towfish. The handheld Ranger provides an integrated acoustic communication and tracking capability, while the towfish positions the acoustic transducer below the sea surface to reduce surface noise and improve acoustic propagation. Fixed or mobile communication nodes, such as a GWB or Wave Glider, provide additional options for communicating with the UUV without requiring continuous support vessel repositioning [17, 25].

These acoustic communication systems can interface with the WHOI VIP, which serves as the primary graphical user interface for mission planning, vehicle programming, communication monitoring, data logging, maintenance, and post-mission analysis [37, 25]. Each of these communication components was used during this research. Figure 2.2 illustrates the communication pathways between the UUV and the external communication systems used during this study.

2.2.2 Vehicle Autonomy and Control Architecture

The REMUS 100 utilized in this research employs a layered control architecture consisting of two onboard computers: the standard REMUS frontseat computer and a programmable backseat computer [12, 14, 25]. The frontseat computer is responsible for safety-critical vehicle functions including navigation, propulsion, waypoint tracking, depth control, and execution of the mission plan generated before deployment. By maintaining responsibility for these low-level control functions, the frontseat computer ensures stable and reliable vehicle operation throughout the mission.

Higher-level autonomy is implemented through the backseat computer, which was developed by the Scripps Institution of Oceanography (SIO) Coastal Observing Research and Development Center (CORDC) as an additional onboard computing platform for research applications [12, 14]. The backseat computer interfaces with the standard REMUS frontseat computer through the REMUS RECON software interface, allowing custom autonomy software to access vehicle state information, navigation data, sensor measurements, and acoustic communication status while issuing high-level behavior commands. This architecture enables researchers to develop and integrate new autonomous capabilities without modifying the safety-critical frontseat software or vehicle control system [12, 14].

For this research, custom autonomy software was developed within the Robot Operating System (ROS) framework and executed on the SIO backseat computer. This approach enabled the vehicle to monitor acoustic communication performance in real time and modify high-level vehicle behaviors while allowing the frontseat computer to retain responsibility for vehicle safety, navigation, propulsion, and mission execution. The adaptive autonomous behaviors developed using this architecture are described in Chapter 4 [12, 14].

2.3 WHOI Micromodem-2

2.3.1 Overview of Acoustic Modems

Underwater communication is limited by the rapid attenuation of electromagnetic signals in seawater. As a result, acoustic signaling is commonly used for long-range underwater communication. Acoustic modems convert digital information into acoustic signals that can be transmitted through the water and reconstructed by a receiving modem [15, 43].

The WHOI Micromodem-2 is commonly used for acoustic communication in REMUS vehicles and was used throughout this research. The modem supports Frequency Shift Keying (FSK) and Phase Shift Keying (PSK) modulation, adjustable transmission power, multiple operating frequencies, and both acoustic communication and LBL navigation [9, 16, 17]. These capabilities allow the REMUS 100 to transmit vehicle telemetry and command data, including position, heading, speed, depth, altitude, battery status, and system faults [25, 44].

2.3.2 WHOI Micromodem-2 Components and Operation

The WHOI Micromodem-2 consists of internal modem electronics connected to an external acoustic transducer. For the REMUS 100 used in this research, the communication transducer was a BT-2RCL. During operation, the WHOI Micromodem-2 assembles packets from digital data provided by the vehicle control computer and encodes the data using modulation schemes such as FSK or PSK. The encoded signal is then converted into an acoustic waveform and transmitted through the water via the transducer. As the signal propagates through the acoustic channel, it is influenced by attenuation, multipath propagation, Doppler effects, and the local sound speed structure of the water column [16, 43, 51].

Once received, the acoustic signal is converted back into an electrical signal by the receiving transducer, digitized, and processed by a digital signal processor (DSP) for synchronization, detection, demodulation, and packet reconstruction [9, 16]. The decoded data is then displayed through the WHOI VIP. The end-to-end communication process is illustrated in Figure 2.3.

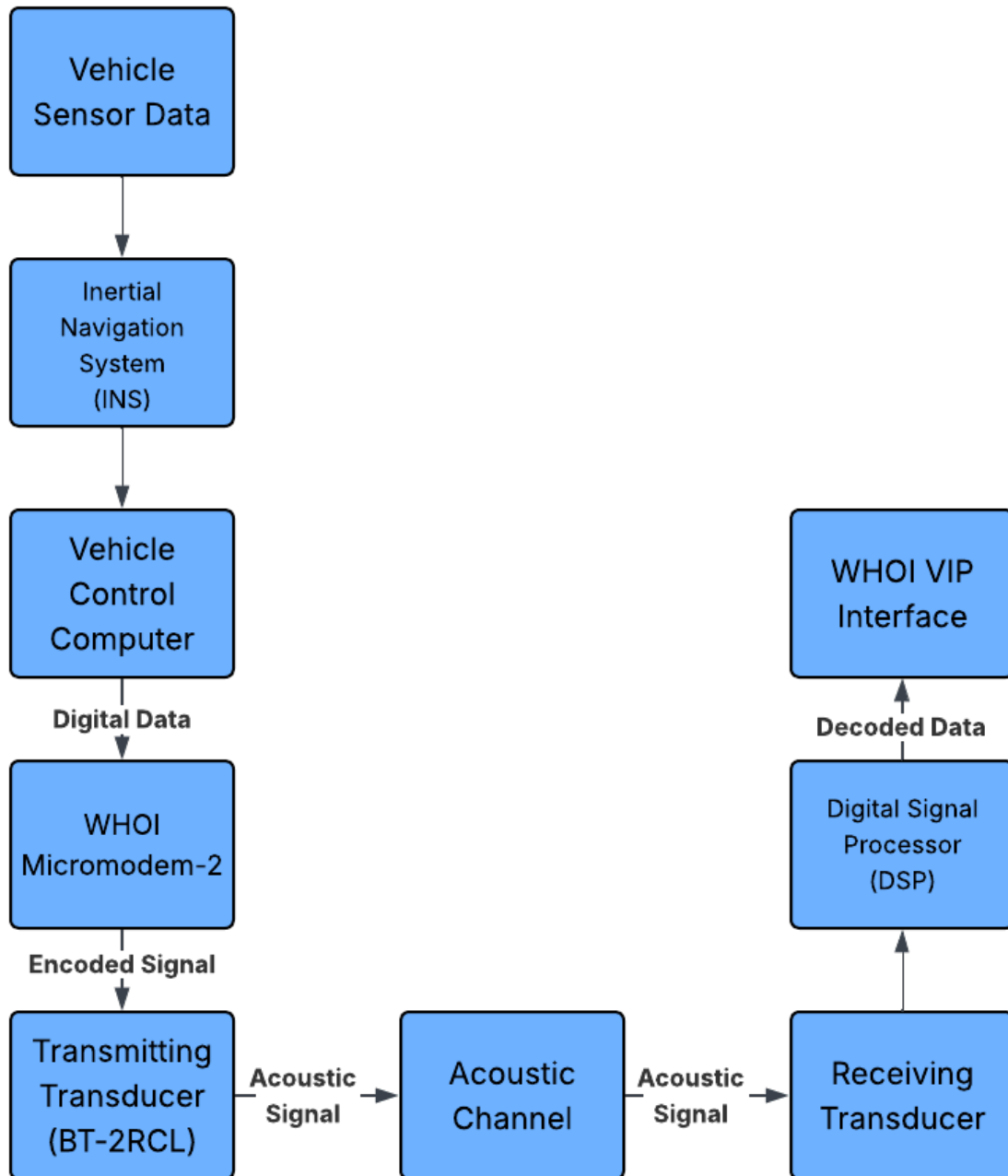


Figure 2.3. One-way acoustic transmission pathway from the REMUS 100 to a receiving acoustic communication system using the WHOI Micromodem-2. Vehicle sensor data are processed by the inertial navigation system and vehicle control computer, encoded by the micromodem, and transmitted as an acoustic signal through a BT-2RCL transducer. The signal propagates through the water, which forms the acoustic channel between the transmitter and receiver. The received signal is processed by a digital signal processor (DSP) and decoded for display in the WHOI Vehicle Interface Program (VIP).

2.3.3 REMUS 100 Transducers

For this research, a BT-2RCL acoustic transducer was added to the REMUS 100 in addition to the standard LBL navigation transducer. Although both transducers remained installed on the vehicle, the BT-2RCL was used instead of the LBL transducer for the acoustic communication experiments conducted during this study. The BT-2RCL is designed for broadband underwater acoustic communication systems and is compatible with the WHOI Micromodem-2. In contrast, the standard LBL transducer is optimized primarily for navigation and transponder interrogation of fixed acoustic beacons.

The BT-2RCL was mounted beneath the forward section of the REMUS 100 hull. Figure 2.4 shows the vertical beam pattern of the transducer at 20, 25, and 30 kHz. The strongest acoustic response occurs in the horizontal plane, while the response decreases in the vertical directions. This beam pattern indicates that vertical separation between the UUV and receiver can influence acoustic communication performance [1, 17].

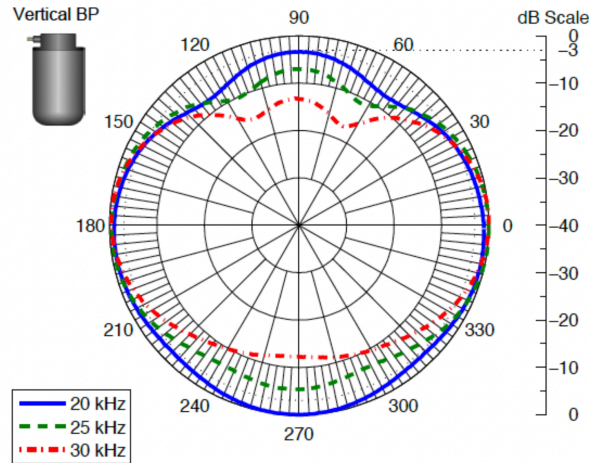


Figure 2.4. Vertical beam pattern of the BT-2RCL acoustic transducer at 20 kHz, 25 kHz, and 30 kHz. The strongest acoustic response occurs in the horizontal plane, with reduced response in the vertical directions. Adapted from BTech Acoustics [1].

2.3.4 Transmission Power and Source Level

The WHOI Micromodem-2 acoustic communication system used in this research operated at 25 kHz with a maximum source level of approximately 184 dB re 1 μ Pa at 1 m when transmitting at full power. The 25 kHz configuration was selected because it provides higher data rates for transmitting vehicle telemetry, including position, heading, depth, altitude, battery status, and system faults. The 25 kHz operating band is supported by the REMUS acoustic communication and navigation hardware used in this study. While lower-frequency communication modes generally provide greater communication range, the trade-off is lower data rates, which limit the amount of information that can be transmitted during each communication cycle [9, 17, 43].

The WHOI Micromodem-2 power amplifier supports adjustable transmission power settings through the `pwramp.txlevel` parameter, allowing the source level to be reduced from the maximum output setting. Available power settings include reductions of approximately 4 dB, 6 dB, and 17 dB below maximum output. These power control settings allow communication range, power consumption, and acoustic interference to be balanced depending on mission requirements [9, 17]. The available transmission power settings and corresponding reductions in source level are summarized in Table 2.2.

Table 2.2. WHOI Micromodem-2 transmission power settings at 25 kHz. MAX denotes the maximum transmission power setting. Adapted from [17].

<code>pwramp.txlevel</code>	Approximate Source Level (dB re 1 μ Pa at 1 m)
0	183–185
1	MAX – 4
2	MAX – 6
3	MAX – 17

2.3.5 Modulation Techniques: FSK and PSK

Frequency Shift Keying (FSK)

FSK encodes digital data by shifting between discrete frequencies. Each frequency represents a binary symbol, making FSK less sensitive to noise, Doppler effects, and time-varying channel conditions. This makes FSK well suited for long-range communication and low signal-to-noise ratio (SNR) environments. However, the trade-off is a relatively low data rate [15, 41, 43].

Phase Shift Keying (PSK)

PSK encodes data through changes in the phase of a signal, allowing significantly higher data rates than FSK [15, 41, 43]. However, PSK is much more sensitive to acoustic channel impairments such as multipath propagation, Doppler shift, and relative motion between the transmitter and receiver, all of which can distort phase coherence and degrade decoding performance [10, 43, 51]. Field experiments evaluating WHOI Micromodem-2 PSK signaling in a mobile-transmitter environment demonstrated that transmitter motion and time-varying acoustic channels significantly degrade PSK performance [10].

Both FSK and PSK should therefore be considered during mission planning with attention to the trade-off between communication reliability and data rate. In general, FSK is better suited for long-range missions or degraded acoustic environments with low SNR, whereas PSK can be used when environmental conditions and vehicle geometry are favorable enough to support higher data rates.

A comparison between representative FSK and PSK transmissions is shown in Figure 2.5. Both signals are centered at the same operating frequency of 25 kHz. The FSK transmission consists of several discrete frequency tones, while the PSK transmission spreads its energy across a broader range of frequencies.

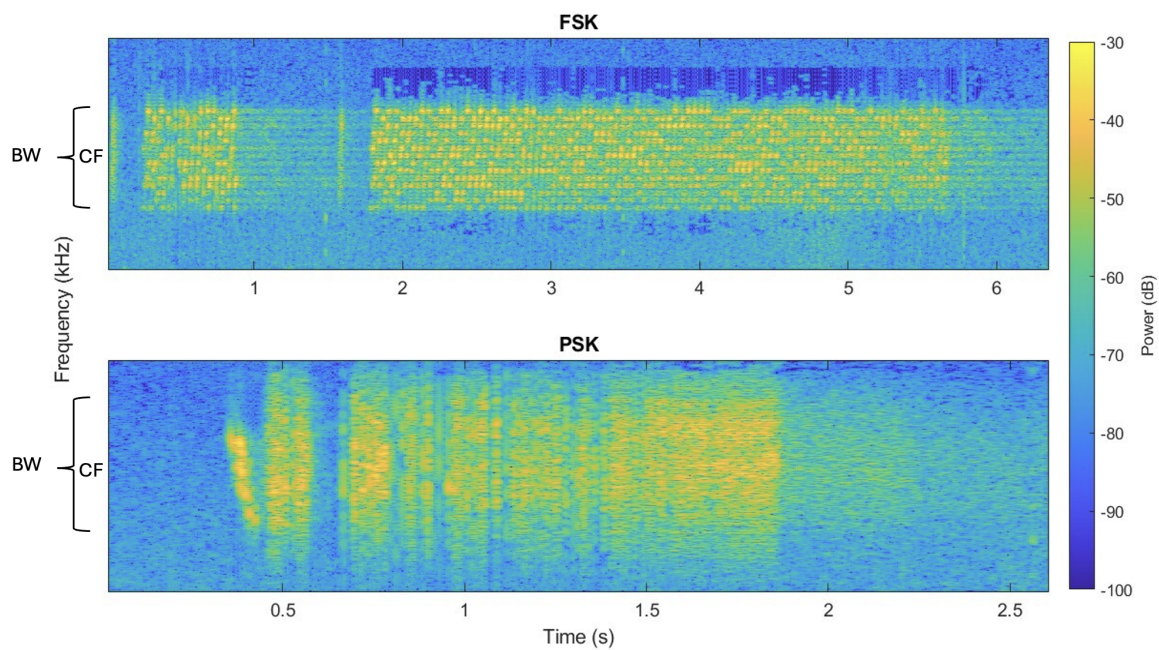


Figure 2.5. Spectrogram comparison of Frequency Shift Keying (FSK) and Phase Shift Keying (PSK) transmissions recorded from the WHOI Micromodem-2 at a center frequency of 25 kHz. The FSK signal (top) consists of discrete frequency tones, while the PSK signal (bottom) spreads across a broader range of frequencies. BW denotes bandwidth and CF denotes center frequency.

2.3.6 Packet Structure and Burst Transmission

Underwater acoustic communication is commonly transmitted in bursts rather than as a continuous data stream because of limited bandwidth, long propagation delay, and the need to manage interference and power consumption [17]. Each burst contains a packet that typically includes a synchronization header, addressing information, payload data, and error detection and correction fields. An example of a packet structure is shown in Figure 2.6.



Figure 2.6. Representative structure of an underwater acoustic communication packet. Packets typically include a synchronization header, address header, payload, cyclic redundancy check (CRC), and forward error correction (FEC). Adapted from [17].

The synchronization header is a known signal pattern that allows the receiver to detect the transmission and align timing with the incoming signal. Addressing information identifies the transmitting and intended receiving nodes, while the payload contains the vehicle information being transmitted, such as position, heading, depth, altitude, battery status, and system health.

The packet also includes error detection and correction fields, including cyclic redundancy checks (CRC) and forward error correction (FEC). CRC allows the receiver to determine whether errors occurred during transmission, while FEC introduces redundant information that allows certain errors to be corrected without retransmission. These techniques improve communication reliability in underwater environments where noise, multipath propagation, and Doppler effects can degrade acoustic signals [15, 16, 19, 43, 51].

2.3.7 Data Rates and Information Content

The data rates for the WHOI Micromodem-2 are relatively low, ranging from tens of bits per second for FSK modes to several kilobits per second for higher-rate PSK modes [9, 42].

REMUS modem messages typically contain telemetry or command data within packets ranging from tens to a few hundred bytes and lasting approximately three to five seconds [17, 25]. The packet data rates and signal characteristics for the available transmission modes are summarized in Table 2.3.

Table 2.3. WHOI Micromodem-2 packet data rates and signal characteristics. Reproduced from [17].

Mode	Burst Rate (bps)	Frames / Packet	Frame Size (bytes)	Signal Length (s)
PSK Rate 6	490	6	32	3.25
PSK Rate 5	5,388	8	256	3.34
PSK Rate 4	1,301	2	256	3.45
PSK Rate 3	1,223	2	256	3.65
PSK Rate 2	520	3	64	3.25
PSK Rate 1	498	1	64	3.38
FSK Rate 0	80	1	32	5.00

Table 2.3 shows the relationship between transmission mode, packet size, and data rate for the WHOI Micromodem-2. PSK Rate 5 provides the highest data rate at over 5 kbps using eight 256-byte frames per transmission, while FSK Rate 0 transmits a single 32-byte frame at 80 bps over a 5 s transmission.

Although signal duration remains relatively similar across the available modes, the amount of information transmitted within each packet varies substantially. Higher-rate PSK modes therefore allow more vehicle information to be transmitted during each communication opportunity, while lower-rate modes provide reduced data throughput in exchange for improved communication performance in degraded acoustic conditions [10, 43].

2.3.8 Time Division Multiple Access (TDMA)

Underwater acoustic communication networks commonly utilize Time Division Multiple Access (TDMA) protocols to reduce message interference and manage shared use of the acoustic channel. In TDMA systems, communication time is divided into discrete time slots, with each node assigned a specific transmission window during which it is allowed to transmit. By

separating transmissions in time, TDMA helps prevent multiple acoustic communication nodes from transmitting simultaneously on similar frequencies [9, 11, 31].

For the modem-message experiments conducted in this research, the communication network was configured with a repeating two-minute TDMA cycle divided into four 30-second transmission slots. One slot was assigned to the REMUS 100 and one was assigned to the primary acoustic communication node, which varied between the towfish, GWB, and Wave Glider depending on the experiment. The remaining two slots were intentionally left unassigned, allowing additional communication nodes or manual operator communications when required.

During experiments using a GWB or Wave Glider as the primary communication node, a support vessel monitored acoustic communications using a towfish and Ranger system. Although the towfish was not assigned a dedicated transmission slot, operators could manually transmit messages during the unused TDMA slots when necessary. This configuration allowed operators to communicate with the UUV without interfering with the experimental communication schedule.

2.3.9 Acoustic Communication Timing and Message Sequence

Typical underwater acoustic communication requires the exchange of multiple messages between the transmitter and receiver. The communication sequence often begins with a Request-to-Send (RTS) message transmitted by the UUV, followed by a Clear-to-Send (CTS) response from the receiver. The UUV then transmits the data packet, after which the receiver returns an acknowledgment (ACK) message indicating the packet was successfully received [9, 44]. Each message requires time for transmission and propagation through the water, making the total communication time significantly longer than the duration of the data packet alone.

Propagation delay is one of the primary factors affecting communication time because acoustic signals require time to travel between the transmitter and receiver. As communication range increases, additional time is required for each message to propagate through the water. The total communication time therefore increases with range, even when packet length remains unchanged [19, 43].

Communication timing is also influenced by the TDMA schedule described in the previous subsection. During this research, modem messages could only be transmitted during their assigned TDMA transmission slots. During the ping-based assessments, acoustic pings were transmitted every 10 seconds, but pinging was paused for 30 seconds every five minutes to allow a modem message to be transmitted and an ACK to be received from the Wave Glider. If a modem message was not successfully exchanged during the available transmission window, communication generally had to wait until the next assigned transmission slot before another attempt could be made. As a result, the time required to exchange messages depended on packet duration, propagation delay, and the assigned TDMA schedule. These timing constraints are important when evaluating underwater acoustic communication performance because communication opportunities are constrained by the TDMA schedule [9, 17, 31].

2.4 Relevant Work

2.4.1 Autonomous Adaptive Ocean Sampling and Observing

Since the 1990s, UUVs have evolved from pre-programmed survey platforms into autonomous systems capable of adapting their behavior in response to in situ environmental conditions. The Autonomous Ocean Sampling Network (AOSN) initiative established a foundational framework for adaptive ocean observing by combining autonomous vehicles with predictive ocean models and real-time environmental feedback systems [4, 5, 38].

The AOSN-II experiment conducted in Monterey Bay during 2003 demonstrated adaptive ocean sampling using autonomous underwater gliders and REMUS UUVs operating alongside buoys, aircraft, HF radar systems, and research vessels [38]. Adaptive sampling in the context of AOSN-II referred to modifying vehicle trajectories and sensing behaviors in response to environmental observations and ocean model predictions rather than relying solely on pre-programmed survey tracks [8, 24].

Autonomous gliders demonstrated coordinated adaptive behaviors through real-time

formation control, gradient tracking, and environmental feature tracking [8, 38]. In one demonstration, three gliders dynamically adjusted their formation to improve estimation of temperature gradients and upwelling events within Monterey Bay [38]. These experiments demonstrated that autonomous underwater vehicles could adapt their positioning and sampling behaviors in response to evolving oceanographic conditions.

2.4.2 Sense-React Autonomy Frameworks

As autonomous underwater vehicle capabilities have matured, research efforts have increasingly focused on developing onboard autonomy frameworks capable of modifying vehicle behavior in response to real-time sensor observations. Rather than relying solely on preplanned missions, these systems enabled vehicles to autonomously interpret sensor data and execute adaptive behaviors while underway.

Gallimore et al. (2018) developed a Robot Operating System (ROS) based autonomy framework for the REMUS 100 UUV that provided a flexible "backseat driver" architecture capable of integrating custom sensors and autonomous behaviors through the REMUS RECON interface. The framework allowed onboard software modules to process sensor data in real time and command vehicle behaviors while maintaining the standard REMUS frontseat computer for safety and mission execution [12].

Building upon this autonomy architecture, Gallimore et al. (2020) demonstrated autonomous sense-react behaviors using a REMUS 100 equipped with a scalar magnetometer for underwater archaeological surveys. Real-time magnetic target detection algorithms were executed onboard the vehicle, allowing the UUV to autonomously identify targets of interest and perform reacquisition maneuvers without human intervention. The system combined onboard sensing, classification, and autonomous mission replanning to improve survey efficiency and target localization. In addition, Gallimore et al. demonstrated cooperative multi-vehicle autonomy in which detections identified by one vehicle were transmitted acoustically to a second vehicle that autonomously performed target reacquisition using different sensors [13].

These studies demonstrated that autonomous underwater vehicles could move beyond passive data collection and execute closed-loop sense-and-react behaviors driven by onboard processing of sensor observations. This concept of autonomous decision making based on real-time sensor feedback provides a foundation for subsequent environmentally aware vehicle behaviors and adaptive communication strategies.

2.4.3 Environmentally Informed Navigation and Vehicle Behaviors

Environmentally informed navigation has been explored for autonomous underwater systems as a means of improving mission efficiency in ocean environments. Davis et al. investigated routing strategies for underwater gliders operating in strong ocean currents [6]. This work demonstrated that vehicle performance and sampling effectiveness could be improved through adaptive navigation strategies that incorporated real-time environmental information related to ocean current magnitude and direction [6].

Subsequent work extended environmentally informed autonomy into adaptive depth-seeking behaviors for improving UUV transit efficiency and endurance. Young et al. developed a greedy depth-seeking behavior that utilized vertical ocean current gradients to identify operational depths that reduced vehicle energy consumption during long-range transits [50]. Building upon this work, Kwan et al. implemented an onboard depth optimization behavior for a REMUS 100 using real-time ADCP measurements and demonstrated successful environmentally reactive navigation during field experiments conducted offshore of La Jolla, California [23].

2.4.4 Underwater Acoustic Communications and Environmental Awareness

The application of environmental awareness was later expanded beyond navigation and energy efficiency to address underwater acoustic communication challenges. McCarthy et al. investigated environmentally aware acoustic decision aids for autonomous underwater vehicles operating in changing ocean conditions [29, 28]. The underlying concept was to provide au-

onomous vehicles with awareness of the surrounding acoustic propagation environment. Rather than relying solely on a fixed depth communication plan, the vehicle would use environmental observations to estimate how transmission loss varied with depth and range. This enabled identification of locations more favorable for acoustic communications.

McCarthy et al. developed reduced-order transmission loss prediction models trained using BELLHOP acoustic simulations and in situ sound velocity profile observations. Environmental measurements were decomposed into reduced-order representations and used as inputs to machine learning models capable of rapidly predicting acoustic propagation conditions [29]. The objective was to provide autonomous systems with near real-time estimates of transmission loss that could support adaptive repositioning behaviors designed to improve communication performance.

Field experiments conducted offshore of San Diego, California, evaluated acoustic communications between a REMUS 100 UUV and a Wave Glider equipped with WHOI Micro-modems operating at 25 kHz [28]. Results demonstrated that reduced-order machine learning models could predict locations of favorable transmission loss with accuracy comparable to BELLHOP while significantly reducing computational requirements and prediction times [28]. These studies demonstrated the feasibility of providing autonomous vehicles with environmental awareness of the acoustic propagation field and established a foundation for communication-aware autonomous behaviors.

While McCarthy et al. demonstrated that autonomous vehicles could identify favorable acoustic propagation conditions, they did not investigate adaptive vehicle behaviors that adjusted vehicle orientation or experimentally evaluate communication-aware behaviors using real-time communication feedback.

2.4.5 Research Gap and Thesis Contribution

Previous studies have explored adaptive ocean sampling, environmentally informed navigation, and acoustic propagation prediction, yet few studies have investigated adaptive

autonomous vehicle behaviors designed to improve underwater acoustic communication performance in real time. Existing work has primarily focused on improving sampling efficiency, navigation performance, or energy consumption rather than communication-aware autonomous behaviors.

This research extends environmentally informed autonomy into the underwater acoustic communication domain by investigating how vehicle depth and relative orientation influence acoustic communication performance between a REMUS 100 UUV and external acoustic communication systems. Adaptive depth-seeking and broadside deviation behaviors are then developed and evaluated to determine whether real-time communication feedback can improve acoustic connectivity and communication reliability during autonomous operations.

The REMUS 100 platform, acoustic communication system, transducer geometry, and previous work presented in this chapter provide the foundation for the experimental assessments in Chapter 3. Based on these considerations, three primary factors were selected for evaluation: vehicle self-noise associated with propulsion RPM, acoustic propagation effects associated with vehicle depth, and relative vehicle orientation with respect to the receiver. Chapter 3 evaluates each of these factors to determine which may be suitable for exploitation through adaptive vehicle behavior.

Chapter 3

Experimental Assessments of Acoustic Communication Performance

3.1 Overview

The objective of this chapter is to experimentally evaluate factors affecting underwater acoustic communication performance for a REMUS 100 UUV. Three factors were investigated: vehicle self-noise, acoustic channel propagation effects, and relative vehicle orientation. Laboratory and field experiments were conducted to measure how each factor affected acoustic communication performance and to identify variables that could be exploited through autonomous vehicle behavior. Field testing allowed these factors to be evaluated under realistic operating conditions.

During field testing, depth, range, heading, and receiver motion could not always be isolated from one another. Environmental conditions also varied between test locations, including SVP and bottom depth. The influence of these variables is discussed in the individual experiment sections. Table 3.1 summarizes the experimental assessments conducted during this study.

Table 3.1. Summary of the experimental assessments conducted in this chapter. Approximate test-site water depths are reported in meters of seawater (msw).

Experiment	Objective	Variable	Experimental Configuration	Primary Finding	Limitation	Confidence
Open-Water RPM Test	Assess UUV self-noise underway	RPM	Towfish; Offshore (~400 msw)	Minimal RPM effect at 25 kHz	Receiver motion	Moderate
RPM Tank Test	Assess propulsion noise	RPM	icListen hydrophone; Saltwater tank	Minimal RPM effect at 25 kHz	No flow noise	High
Depth Assessment	Assess ACOMMs vs. depth	Depth	Wave Glider; Nearshore (49–55 msw)	Ping reception and received SPL varied with depth	Moving receiver; depth and range changed together	Moderate
Heading Assessment	Assess orientation effects	Heading	GWB; Nearshore (49–55 msw)	Broadside aspect increased median received SPL by 5–8 dB	Depth and range effects not fully isolated	Moderate

Confidence levels in Table 3.1 were assigned based on the level of experimental control, repeatability of the observed trend, and the ability to isolate the primary variable from other factors. High confidence indicates that the primary variable was well controlled and produced a consistent result under repeatable conditions. Moderate confidence indicates that a consistent trend was observed, but other variables could not be completely isolated during testing.

3.2 Data Processing

3.2.1 Data Synchronization

For each mission, the vehicle and receiver log timestamps were converted to epoch time using UTC as a common time reference. Nanoseconds were not included in the epoch conversion used for timestamp matching. Acoustic records were matched using a nearest-neighbor timestamp comparison with a maximum allowable time difference of 2 seconds. Vehicle and receiver positions were not interpolated to the exact transmission timestamp. The synchronized data were then used to associate vehicle position, heading, depth, receiver position, and additional telemetry data with each acoustic transmission.

Transmitter-receiver range was calculated as the geodesic distance between the matched GPS positions of the UUV and receiver. Relative vehicle orientation was calculated from the bearing to the remote acoustic node expressed in the UUV body-fixed frame of reference.

3.2.2 Communication Processing

Communication logs generated by the WHOI Micromodem-2 were processed to identify transmitted acoustic messages and received ACKs. The communication metric used in the analysis depended on the experiment and included ping reception, received SPL, or ACK reception. Communication attempts that did not result in the required reception or ACK were classified as unsuccessful when communication success was evaluated.

3.2.3 Sound Pressure Level Processing

SPL measurements were obtained from the Sonar Signal Tracker (SST) software using the `in_water_spl_db` output field. The WHOI Micromodem-2 documentation defines this field as the received SPL in units of dB re. $1 \mu\text{Pa}$ [49]. Transmissions that were not received did not have an associated received SPL measurement and were therefore not included in received SPL analyses.

3.2.4 Data Binning and Filtering

Communication data were grouped into range or relative orientation bins when needed to compare performance across similar operating conditions. Bin widths, bin edges, and experiment-specific filtering criteria are provided within the corresponding experiment sections.

Minimal filtering was applied to the experimental data. Communication attempts that occurred during temporary receiver repositioning were retained in the dataset. Failed or partial communication attempts were retained when evaluating communication success and were classified as unsuccessful when the required reception or ACK was not completed. No additional filtering was applied specifically to duplicate or corrupted communication records.

The acoustic communication configurations used during the experiments are summarized in Table 3.2.

Table 3.2. Acoustic message configuration used during each experiment.

Experiment	Signal Type	Transmit Interval	Modem Mode / Packet Type	Payload	Success Metric	Notes
Open-Water RPM	Modem message	30 s	PSK Rate 5	Variable	SST noise level	Towfish receiver; noise compared across RPM settings
Tank RPM	Acoustic recording	N/A	N/A	N/A	PSD near 25 kHz	Fixed hydrophone; no modem transmission
Depth/Range	Ping; modem message	10 s; 5 min	PSK Rate 5	None; 32 bytes	Ping reception	Inbound transits used for reception analysis
Heading	Ping	10 s	PSK Rate 5	None	Received SPL	GWB transmitted; received SPL measured at UUV
Behavior Tests	Status message + ACK	30 s	PSK Rate 5	Vehicle status	ACK reception	Described in Chapter 4

The following sections present the experimental assessments used to evaluate the primary factors affecting acoustic communication performance using these processing methods.

3.3 Vehicle Self-Noise

3.3.1 Sources of Vehicle Self-Noise

Vehicle self-noise is acoustic energy generated by the UUV during operation that contributes to the local noise floor surrounding the acoustic modem transducer. Sources of self-noise include mechanical, electrical, and hydrodynamic noise. Mechanical noise can originate from the propulsion motor, propeller, control surfaces, and drivetrain components, while electrical noise may be generated by onboard electronics and power systems. Hydrodynamic noise is produced

by water flow over the vehicle hull and appendages and can increase with vehicle speed.

Propeller-induced noise is a potential contributor to vehicle self-noise. [40] investigated propeller cavitation on small craft and found that increasing vessel speed and propeller RPM resulted in tip vortex cavitation and increased underwater radiated noise. However, their study used an outboard propulsion system operating near the water surface. Cavitation and bubble generation may therefore differ from those of a submerged, electrically powered UUV. The outboard system also discharged exhaust through the propeller hub, introducing bubbles that are not present in the propulsion system used in this study.

Based on these findings, it was hypothesized that reducing UUV propeller RPM would reduce vehicle speed and hydrodynamic flow noise, resulting in a lower local noise floor near the 25 kHz acoustic modem operating frequency. An open-water RPM variation experiment was conducted to evaluate this relationship.

3.3.2 Open-Water RPM Variation Experiment

Test Objective

The objective of this experiment was to determine whether changes in propeller RPM affected the local acoustic noise environment surrounding the UUV.

Experimental Design

The experiment was conducted approximately 11 km west of La Jolla, California in water approximately 400 m deep. This location was selected to reduce surface-bottom multipath interactions. Within this test area, the vehicle mission had the UUV continuously transit along a 300 m east-west track while maintaining a constant operating depth of 50 m. Propeller RPM was varied in 100 RPM increments from 1,000 to 1,500 RPM. Each RPM setting was maintained for 20 minutes.

Acoustic communications were received from the UUV using a WHOI 25 kHz transducer towfish equipped with a four-element HTI-96-MIN (CM) spatial diversity array. The towfish

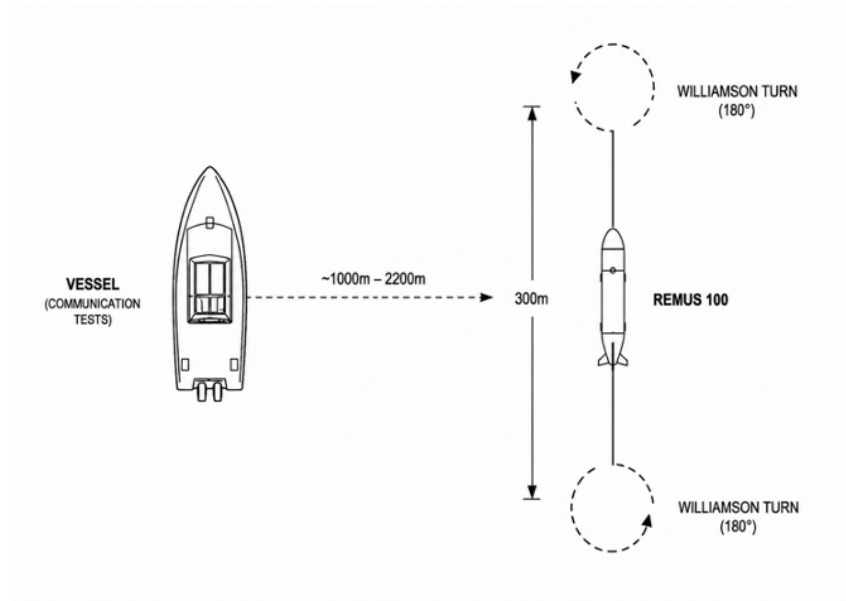


Figure 3.1. Experimental configuration for the open-water RPM variation test. The UUV executed repeated 300 m east-west transits while communicating with a towfish receiver located approximately 1,000–2,200 m from the vehicle.

was deployed to a depth of approximately 7 m from a 9 m Hewescraft 270 Alaskan support vessel. Acoustic transmissions and received SPL measurements were recorded throughout the experiment for comparison across RPM settings. The experimental configuration is shown in Figure 3.1.

Results

Figure 3.2 shows the SST summary median noise level recorded for each acoustic transmission throughout the open-water RPM test. Each colored point represents the SST summary median associated with a transmission while the UUV operated at the indicated RPM setting. Maroon points represent the SST summary median noise measurements recorded by the towfish receiver during the same period. The steady RPM test periods contained between 115 and 167 SST measurements per propulsion setting. UUV noise measurements remained clustered between approximately 88 and 89 dB across the 1,000–1,500 RPM range, with no consistent increase or decrease as RPM changed.

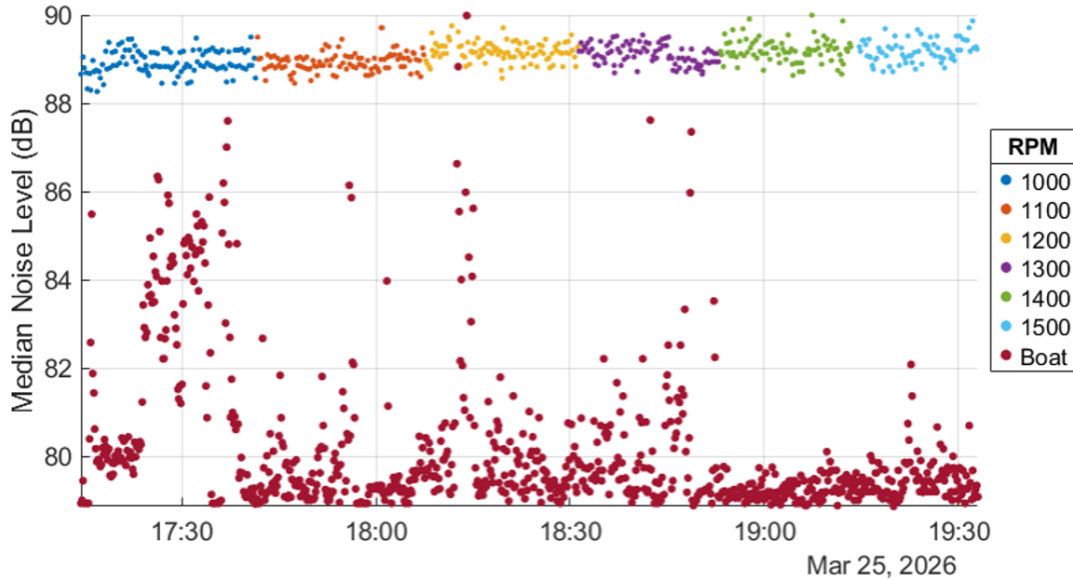


Figure 3.2. Median noise levels measured during the open-water RPM variation experiment. Colored data points represent measurements collected by the UUV at propulsion settings ranging from 1,000 to 1,500 RPM. Maroon data points represent noise measurements recorded by the towfish receiver system.

The measured noise level at the UUV was approximately 9 dB higher than that measured by the towfish while the support vessel remained at idle. Several increases in towfish noise level were also observed, reaching approximately 88 dB when the support vessel engaged propulsion to regain station after drifting due to winds and surface currents. A 9 dB difference corresponds to a range ratio of approximately 2.8 under idealized spherical spreading conditions. This comparison does not represent a measured reduction in modem communication range, but illustrates the potential effect of a higher local noise floor on acoustic detection.

The data provide moderate confidence that propulsion RPM between 1,000 and 1,500 RPM did not substantially change the measured noise level during this experiment. The consistent result across 115–167 measurements per RPM setting indicates that the observed lack of RPM dependence was not based on a limited number of samples. However, ambient ocean noise, support vessel motion, receiver motion, and other environmental sources could not be separated from vehicle-generated noise. Because these factors limited the ability to isolate the effect of RPM, a controlled tank experiment was conducted to evaluate propulsion-related noise under

fixed conditions.

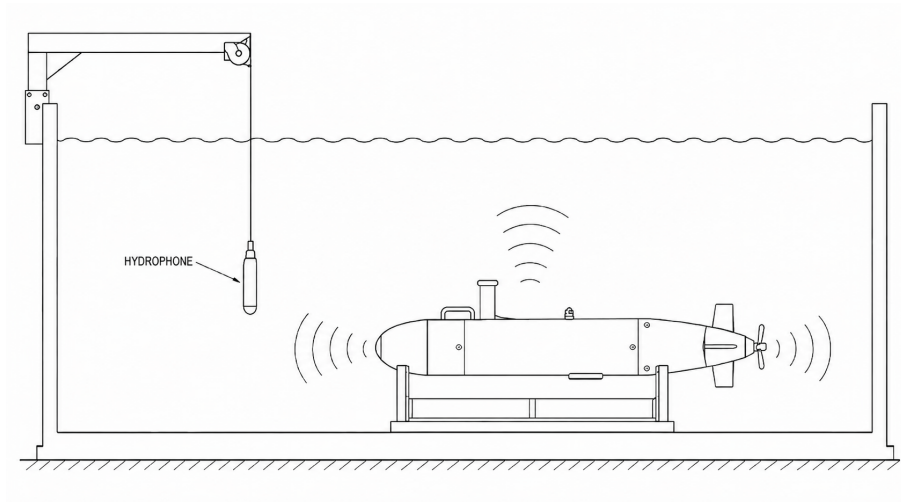
3.3.3 Controlled Tank Evaluation

Experimental Design

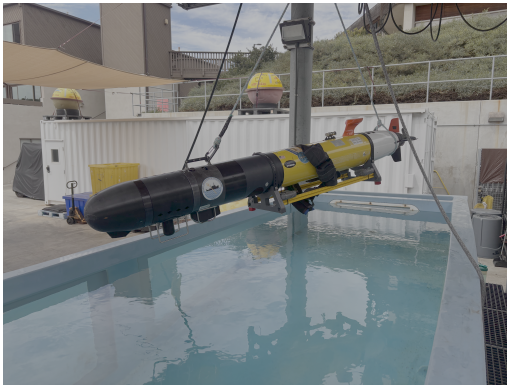
The tank experiment used the same UUV secured in a saltwater test tank. An icListen HF hydrophone was positioned approximately 1 m in front of the vehicle to record acoustic emissions generated during operation. The UUV was secured in a cradle and operated at propulsion settings of 0, 500, 1,000, 1,100, and 1,200 RPM. Each RPM setting was maintained for approximately three minutes while acoustic measurements were continuously recorded.

Acoustic spectra were recorded at a sample rate of 128 kHz using a 1,024-point FFT, corresponding to a frequency-bin width of 125 Hz. A Hann window with 50% overlap was applied, and each reported spectrum represented the mean of 63 accumulations. The number of spectra recorded with the hydrophone positioned in front of the vehicle was 720, 721, 732, 874, and 876 for the 0, 500, 1,000, 1,100, and 1,200 RPM conditions, respectively. The fixed vehicle and hydrophone geometry reduced variability associated with range and orientation and allowed changes in vehicle-generated acoustic energy to be compared across RPM settings.

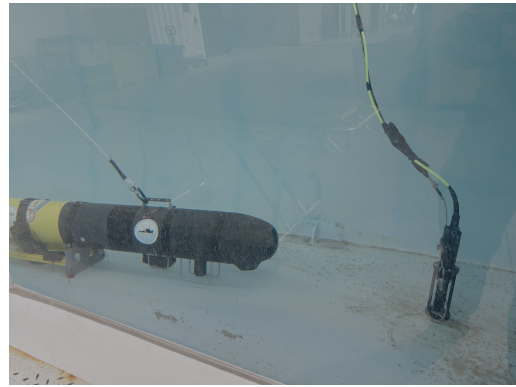
The experimental configuration is shown in Figure 3.3.



(a)



(b)



(c)

Figure 3.3. Stationary UUV RPM tank testing conducted to estimate vehicle-generated acoustic noise under controlled conditions. (a) Schematic of the tank test configuration. Figure created by the author with assistance from OpenAI ChatGPT (b) UUV being lowered into the saltwater tank before stationary RPM testing. (c) UUV secured within the saltwater tank while an icListen hydrophone recorded acoustic measurements approximately 1 m in front of the vehicle.

Tank Test Results

Figure 3.4 shows the measured power spectral density for each propulsion setting tested during the stationary tank experiment. Acoustic power increased with RPM at lower frequencies, with the largest separation between propulsion settings occurring below approximately 5 kHz. The 0 RPM condition generally produced lower acoustic power in this portion of the spectrum than the powered conditions, demonstrating that changes in propulsion RPM produced

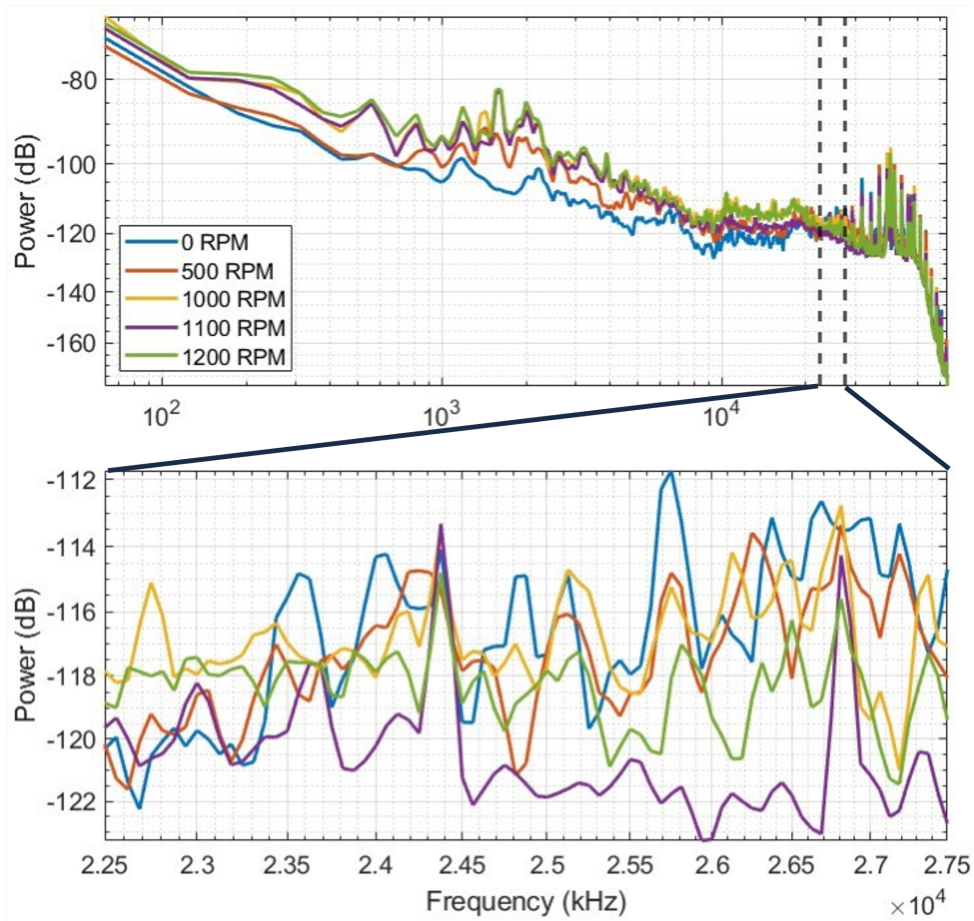


Figure 3.4. Power spectral density measured during stationary UUV RPM tank testing at propulsion settings ranging from 0 to 1,200 RPM. The dashed lines indicate the frequency band surrounding the 25 kHz WHOI Micromodem-2 operating frequency. The lower panel provides an expanded view of this frequency range.

measurable changes in vehicle-generated acoustic energy.

The separation between RPM settings decreased as frequency increased. Within the frequency range surrounding the 25 kHz WHOI Micromodem-2 operating frequency, the spectra overlapped substantially and did not show a monotonic increase in acoustic power with RPM. The expanded view in Figure 3.4 shows that the relative ordering of the RPM conditions changed throughout this frequency range. In particular, the 1,100 RPM condition produced some of the lowest measured values despite being one of the highest propulsion settings tested.

These results indicate that increasing propulsion RPM did not produce a corresponding increase in vehicle-generated acoustic noise near the modem operating frequency under stationary conditions. The clear RPM-dependent differences observed at lower frequencies demonstrate that the measurement system was capable of detecting propulsion-related changes, while the absence of a similar trend near 25 kHz suggests that propulsion-related noise was not a dominant contributor within the modem frequency band.

Confidence in this result is high because vehicle position, hydrophone position, and measurement geometry remained fixed while propulsion RPM was varied. The primary limitation of the experiment was that the UUV remained stationary. The test therefore isolated propulsion-related and mechanical noise but did not include hydrodynamic flow noise generated during forward vehicle motion. Reflections from the tank boundaries may also have influenced the measured acoustic field.

Although these limitations prevent direct comparison with underway acoustic conditions, the tank experiment provides high confidence that propulsion RPM alone did not substantially increase acoustic energy near 25 kHz over the tested range from 0 to 1,200 RPM. Combined with the open-water RPM assessment, these results showed limited RPM dependence near the WHOI Micromodem-2 operating frequency. Propulsion RPM was therefore not selected as a primary control variable for the communication-aware behaviors developed later in this study.

3.4 Acoustic Channel Effects

The next assessment focused on how acoustic propagation conditions affected communication performance as the UUV changed depth and range from the receiver. SVP, transmitter-receiver geometry, boundary interactions, and multipath propagation can produce differences in transmission loss throughout the water column. A field experiment was conducted at multiple vehicle depths and ranges to evaluate these effects on communication performance.

3.4.1 Depth and Range Experiment

Test Objective

The objective of this experiment was to determine how acoustic communication performance varied with UUV depth and range from the receiver. It was hypothesized that communication performance would vary throughout the water column due to depth-dependent changes in acoustic propagation and transmission loss.

Experimental Design

The experiment was conducted approximately 2 km offshore of La Jolla, California using a Wave Glider equipped with a WHOI Micromodem-2 as the acoustic receiver. The Wave Glider maintained a 200×100 m box pattern throughout the mission. Prior to the communication assessment, the UUV conducted a conductivity-temperature-depth (CTD) profile from the surface to approximately 50 m depth and back to the surface. Data collected during the profile were used to characterize the local SVP for subsequent acoustic propagation analysis.

Following the CTD profile, the UUV conducted repeated outbound and inbound transits at discrete depths of 5, 10, 20, 30, 40, and 50 m. Each depth was maintained for approximately 38 minutes. The UUV transmitted acoustic pings at 10-second intervals, with pings paused during a 30-second communication window every 5 minutes to allow modem-message transmissions. Ping reception by the Wave Glider was used to evaluate communication performance as a function of depth and range. Range between the UUV and Wave Glider varied from approximately 750 to

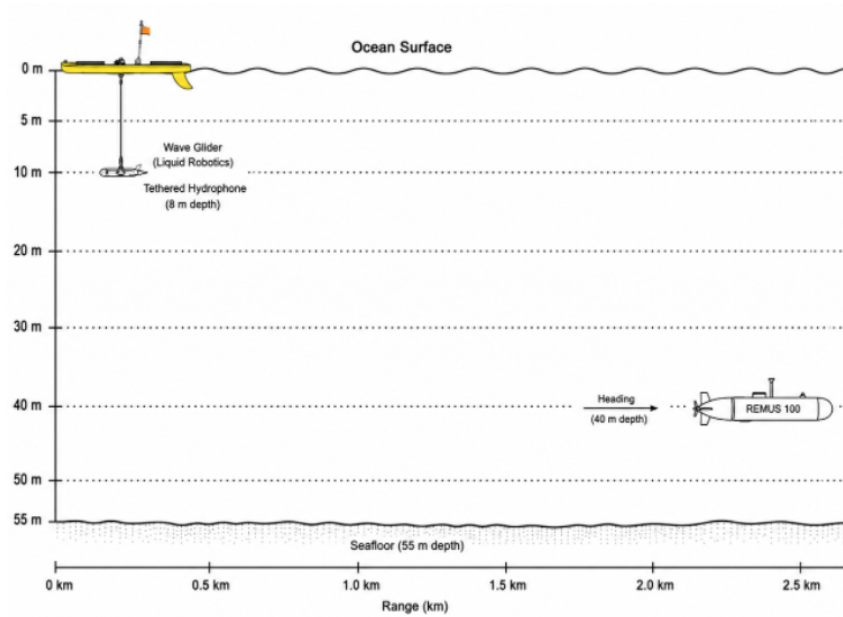


Figure 3.5. Experimental configuration for the depth and range acoustic communication assessment. A Wave Glider equipped with a tethered hydrophone at approximately 8 m depth acted as the acoustic receiver while the UUV operated at discrete depths from 5 to 50 m and ranges extending to approximately 2,600 m. Figure created by the author with assistance from OpenAI ChatGPT

2,600 m throughout the experiment. Water depth within the test area was approximately 55 m. The experimental configuration is shown in Figure 3.5.

Communication Success Results

Pings received by the Wave Glider were compared against the pings transmitted by the UUV. A transmitted ping received by the Wave Glider was classified as successful, while a ping that timed out without a corresponding reception was classified as unsuccessful. Timed-out transmissions were retained in the ping reception analysis.

Only inbound UUV transits were included in this analysis to maintain a consistent vehicle direction. A heading filter of 160° – 175° was used to isolate inbound transits and exclude northbound transits and vehicle turns.

For the individual ping analysis shown in Figure 3.6, each measurement was assigned to the nearest commanded operating depth of 5, 10, 20, 30, 40, or 50 m. The resulting dataset

covered ranges from approximately 750 to 2,600 m.

Figure 3.6 shows the individual ping transmissions as a function of UUV depth and range from the Wave Glider. Ping reception generally decreased as range increased, with unsuccessful receptions becoming more frequent at greater ranges. Reception also varied between operating depths, indicating that range alone did not account for the observed differences in communication performance.

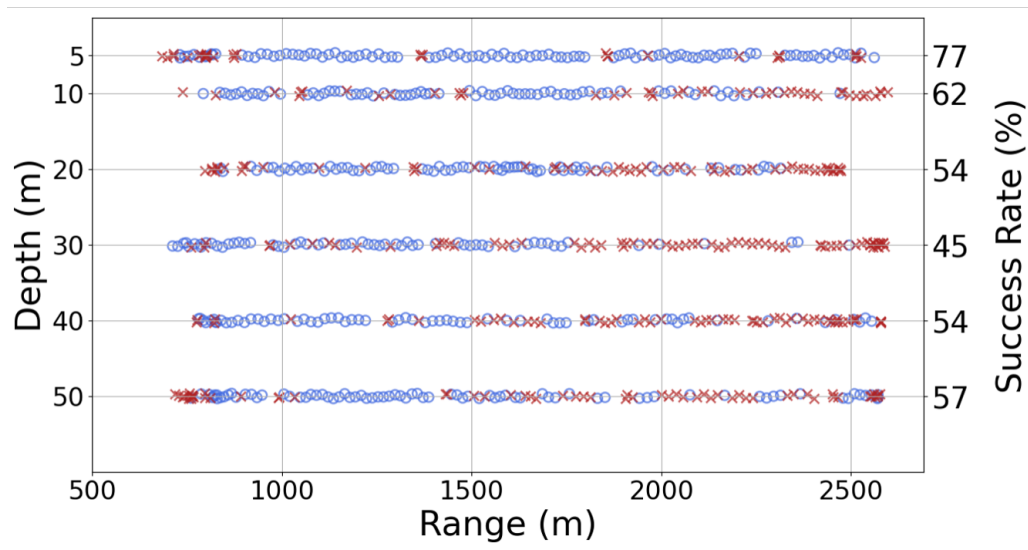


Figure 3.6. Individual acoustic ping transmissions during inbound UUV transits as a function of vehicle depth and range from the Wave Glider. Measurements were assigned to the nearest commanded operating depth. Blue markers indicate pings successfully received by the Wave Glider, while red markers indicate transmitted pings that were not received.

For the binned analysis shown in Figure 3.7, transmissions were grouped into 250 m range bins with bin edges extending from 750 to 2,750 m. Vehicle depth was divided into six equal bins across the 55 m water column, with bin edges at approximately 0, 9.2, 18.3, 27.5, 36.7, 45.8, and 55 m. Ping reception success rate was then calculated within each depth-range bin.

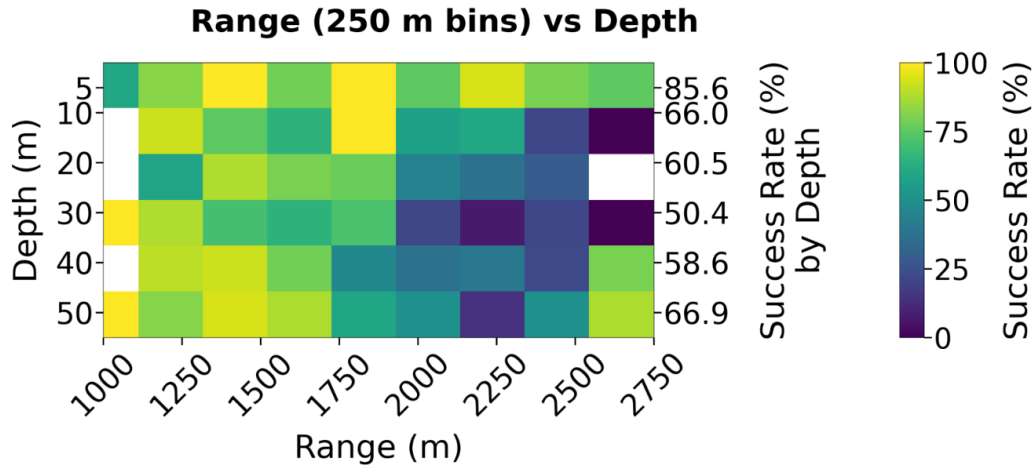


Figure 3.7. Ping reception success rate during inbound UUV transits as a function of vehicle depth and range from the Wave Glider. Success rates were calculated using 250 m range bins and six equal depth bins across the 55 m water column and are represented by the color scale.

Figures 3.6 and 3.7 use different depth-grouping methods and range limits. The success rates derived from the two analyses are therefore not directly comparable. Figure 3.7 was used to evaluate relative changes in ping reception across depth and range rather than to reproduce the success rates associated with the discrete operating depths shown in Figure 3.6.

Figure 3.7 shows that ping reception varied between depth and range intervals. These results indicate that communication performance was influenced by both range and UUV depth and are consistent with depth-dependent differences in acoustic propagation. However, depth and range did not vary independently, and the Wave Glider moved throughout the experiment. Based on the consistency of the observed trend and these experimental limitations, confidence in the depth-dependent communication effect is moderate. Received SPL and acoustic propagation modeling were examined next to determine whether the observed differences in ping reception corresponded with changes in received signal level and predicted transmission loss.

Received Signal Level Results

Further analysis investigated received SPL as a function of UUV depth and range from the Wave Glider. Unlike the success or failure classification used for ping reception, received

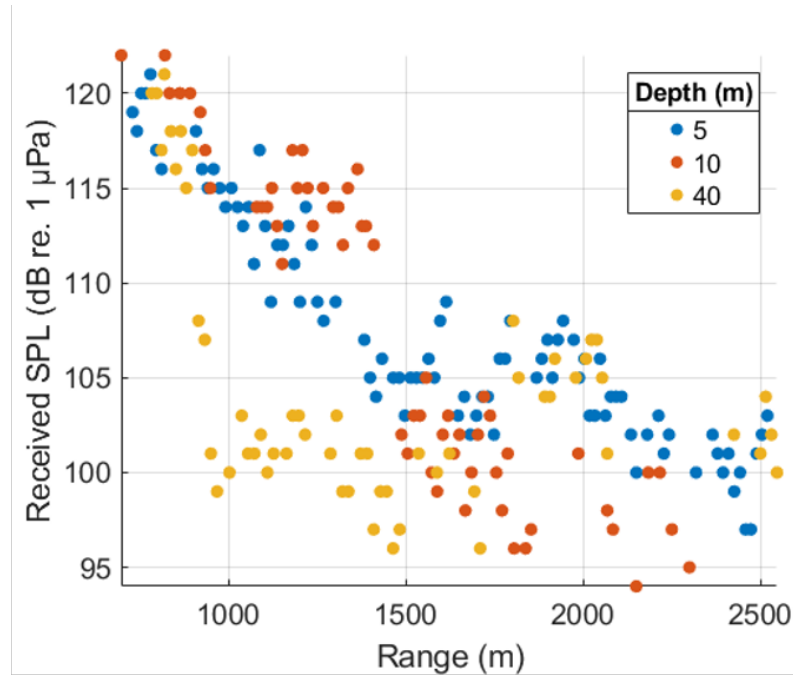


Figure 3.8. Received SPL as a function of range from the Wave Glider for UUV operating depths of 5, 10, and 40 m.

SPL provides a continuous measure of received signal strength. Because received SPL was only available for transmissions received by the Wave Glider, the SPL dataset did not include the unsuccessful transmissions shown in Figure 3.6.

Figure 3.8 shows received SPL for the 5, 10, and 40 m operating depths. Received SPL generally decreased as range increased. At ranges near 750 m, received SPL was approximately 120 dB re. 1 μ Pa for all three depths. At ranges approaching 2,500 m, measurements were generally near 100 dB re. 1 μ Pa. The largest separation between the 5, 10, and 40 m measurements occurred between approximately 1,000 and 1,500 m range. Within this interval, the 5 and 10 m operating depths produced received SPL values of approximately 110–115 dB re. 1 μ Pa, while the 40 m measurements were closer to 100–103 dB re. 1 μ Pa. This produced a difference of approximately 10 dB between shallow and deeper operating depths within this range interval. Beyond 1,500 m, the separation between depths became less consistent. The 5 and 40 m measurements became more similar at several ranges, while the 10 m measurements declined more rapidly and more frequently fell below 100 dB re. 1 μ Pa beyond approximately

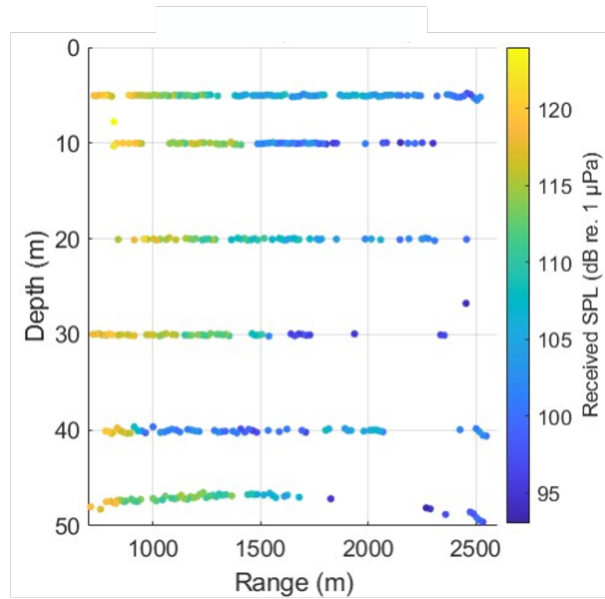


Figure 3.9. Received SPL as a function of UUV depth and range from the Wave Glider. Marker color indicates the received SPL measured by the Wave Glider receiver.

2,000 m.

Figure 3.9 shows the received SPL measurements across all tested depths. Received SPL near the 20 m operating depth was often higher than at the neighboring 10 and 30 m depths. One possible explanation is multipath interference within the water column in the test area, where surface- and bottom-reflected acoustic paths may have produced locally higher received signal levels. This explanation was not directly measured and is examined further using acoustic propagation modeling in the following section.

Received SPL varied with both range and UUV depth and generally followed the observed ping reception trends. Lower received SPL occurred more frequently at ranges and depths associated with reduced ping reception. However, depth, range, and Wave Glider motion did not vary independently. Based on the consistency of the observed trend and these experimental limitations, confidence in the depth-dependent received SPL effect is moderate.

Transmission Loss Modeling

To further examine the propagation conditions associated with the observed communication performance, the measured SVP was used as an input to the BELLHOP acoustic ray tracing model. The model estimated transmission loss as a function of depth and range throughout the test area.

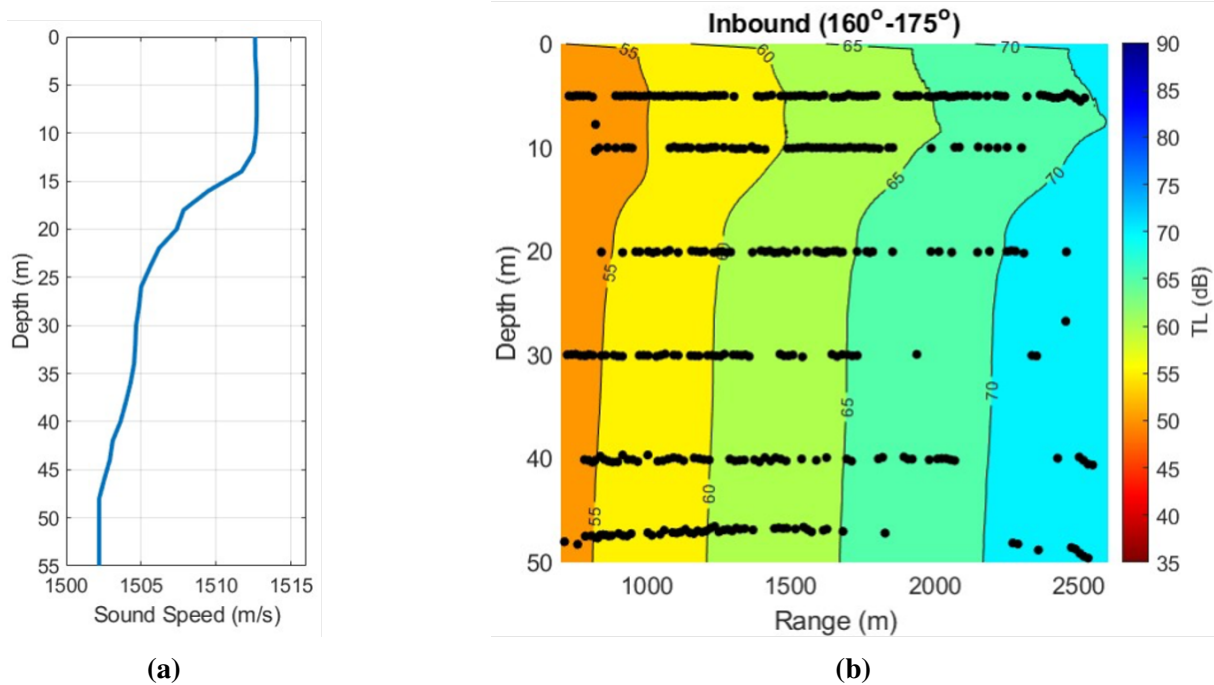


Figure 3.10. Environmental characterization and acoustic propagation modeling results. (a) Measured SVP. (b) BELLHOP-predicted transmission loss field with successfully received acoustic pings overlaid.

Figure 3.10(a) shows the SVP measured before the communication assessment. A well-mixed surface layer extended to approximately 12 m depth, below which sound velocity decreased with depth. This negative sound velocity gradient caused acoustic energy to refract downward and produced depth-dependent differences in the predicted propagation field.

Transmission loss was simulated using an omnidirectional source at 8 m depth and an operating frequency of 25 kHz. The source depth represented the Wave Glider transducer depth, with acoustic reciprocity used to evaluate transmission loss between the Wave Glider and UUUV

operating depths. The model extended to a range of 3 km and used a 50 m water column with a flat sandy bottom and flat sea surface. Model resolution was 10 m in range and 1 m in depth. The BELLHOP-predicted transmission loss field is shown in Figure 3.10(b).

Transmission loss increased with range and also varied with depth. Lower transmission loss was predicted within the upper portion of the water column, while higher transmission loss was generally predicted at deeper operating depths over much of the test range. The modeled transmission loss field generally followed the ping reception and received SPL trends presented in Figure 3.6 and Figure 3.9. Operating depths within or near the mixed layer generally produced stronger received SPL at the Wave Glider and more successful ping receptions than several deeper operating depths. The 5 m operating depth corresponded with relatively low predicted transmission loss over most of the test range.

One discrepancy between the BELLHOP model and the received SPL measurements occurred near the 20 m operating depth. At this depth, received SPL was often higher than at the neighboring 10 and 30 m depths, but a similar feature was not clearly present in the modeled transmission loss field. One possible explanation is multipath interference caused by surface and bottom reflections within the approximately 55 m water column. However, this explanation was not directly measured and cannot be confirmed from the available data.

Despite this discrepancy, the BELLHOP results support the observed dependence of communication performance on both range and UUV depth. The model reproduced the general increase in transmission loss with range and the more favorable propagation conditions observed at several shallower operating depths. However, it did not explain all localized variations in received SPL. Based on the similar trends observed in the modeled transmission loss field, ping reception, and received SPL measurements, confidence that acoustic propagation contributed to the observed depth-dependent communication performance is moderate.

3.5 Relative Vehicle Orientation Effects

As previously discussed, vehicle orientation can influence acoustic communication performance through transducer directivity and shadowing by the vehicle hull. Previous measurements conducted by WHOI showed direction-dependent variations in acoustic response associated with REMUS vehicle geometry. These measurements provided the basis for a field experiment to determine whether a similar orientation dependence could be observed under field conditions.

3.5.1 WHOI REMUS Transducer Beam Pattern Evaluation

The transducer mounted on a REMUS 100 is designed to provide near-omnidirectional coverage in the horizontal plane. However, the vehicle hull can alter the effective beam pattern. To evaluate this effect, WHOI conducted a beam pattern characterization study in 2007 using a REMUS 100 equipped with a standard LBL transducer.

The evaluation was conducted at the Lake Seneca Acoustic Calibration Facility operated by the Naval Undersea Warfare Center (NUWC). The REMUS 100 was mounted to a rotating fixture and rotated through 360° in the horizontal plane while transmitting acoustic signals. A calibrated receiver was positioned at vertical angles of -20° , -10° , 0° , $+10^\circ$, and $+20^\circ$ relative to the transducer. Acoustic measurements were collected throughout the full horizontal rotation at each receiver elevation to characterize the transmit voltage response (TVR) beam pattern. The results are shown in Figure 3.11.

Figure 3.11 shows that the acoustic response varied with both horizontal vehicle orientation and vertical receiver position. The strongest response generally occurred when the vehicle presented a broadside aspect to the receiver, corresponding to the port (0°) and starboard (180°) directions in the WHOI measurement convention. Reduced response was observed near the nose ($+90^\circ$) and tail (-90°) orientations, particularly when the receiver was positioned above the transducer.

As the receiver was lowered relative to the transducer, the beam pattern became more

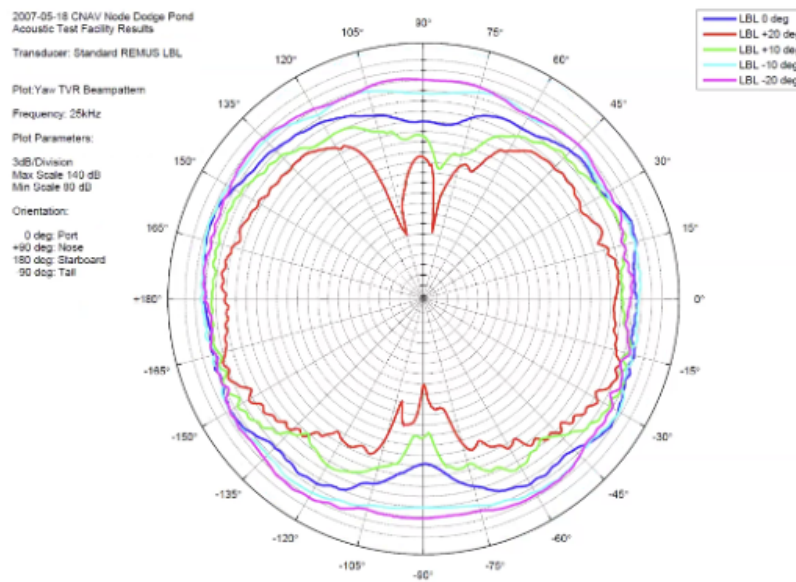


Figure 3.11. REMUS 100 LBL transducer beam pattern measurements collected by WHOI at multiple vertical receiver offsets relative to the transducer.

uniform. This trend is consistent with reduced obstruction by the vehicle hull as the acoustic path between the transducer and receiver moved below the vehicle body.

These measurements show that the effective acoustic response of the REMUS 100 transducer installation depends on both vehicle orientation and vertical receiver geometry. The stronger broadside response and reduced nose-on and tail-on response provided the basis for the relative heading experiment conducted in this study.

3.5.2 Relative Heading Experiment

Test Objective

The objective of this experiment was to determine whether relative vehicle orientation influenced acoustic communication performance under field conditions. Based on the WHOI beam pattern evaluation, it was hypothesized that received signal level would be reduced when the UUV was oriented nose-on or tail-on to the GWB and increased when the UUV presented a broadside aspect.

Experimental Design

The experiment was conducted approximately 2 km offshore of La Jolla, California using a GWB equipped with a WHOI Micromodem-2. The GWB transducer was deployed at a depth of 30 m, and water depth within the test area ranged from approximately 49–55 m.

The UUV executed repeated $160\text{ m} \times 160\text{ m}$ clockwise box patterns centered approximately 1,750 m from the GWB. The box pattern was conducted at nominal depths of 10, 20, 30, 40, and 50 m. A 5 m minimum-altitude constraint prevented the UUV from approaching the seafloor and limited the deepest operating depth to approximately 45 m. This mission geometry repeatedly exposed the UUV to different orientations relative to the GWB while limiting the range variation associated with each box pattern.

Throughout the experiment, acoustic pings were transmitted from the GWB at approximately 10-second intervals, and received SPL measurements were recorded at the UUV. Transmissions that were not received by the UUV did not have an associated received SPL measurement and were therefore not included in the SPL analysis.

During post-processing, the UUV position and GWB position were used to determine transmitter-receiver geometry. Relative orientation was defined as the bearing to the GWB expressed in the UUV body-fixed frame of reference. The experimental configuration is shown in Figure 3.12.

Received Signal Level Results

Figure 3.13 shows received SPL measured at the UUV along the vehicle track for the tested operating depths. A repeated directional pattern is visible across the box patterns. Higher received SPL values generally occurred when the UUV presented a broadside aspect to the GWB, while lower values were observed during nose-on and tail-on orientations.

Received SPL was first examined at the individual operating depths. The broadside orientations generally produced higher received SPL than the nose-on and tail-on orientations across the tested depths, although the magnitude and distribution of received SPL varied with

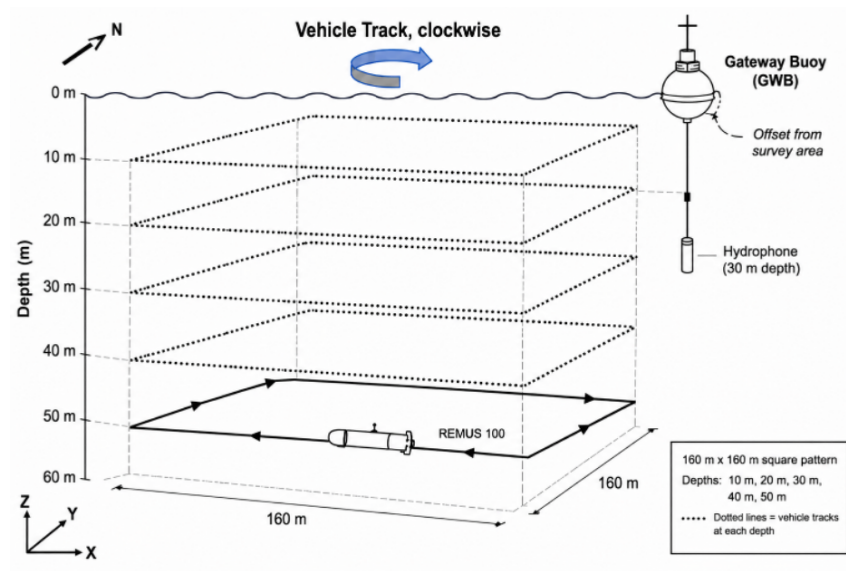


Figure 3.12. Experimental configuration for the relative heading assessment. The UUV executed repeated 160 m $\times$ 160 m clockwise box patterns at nominal operating depths from 10 to 50 m, with the deepest operating depth limited to approximately 45 m by the 5 m altitude constraint. The center of the box pattern was located approximately 1,750 m from the GWB. Figure created by the author with assistance from OpenAI ChatGPT

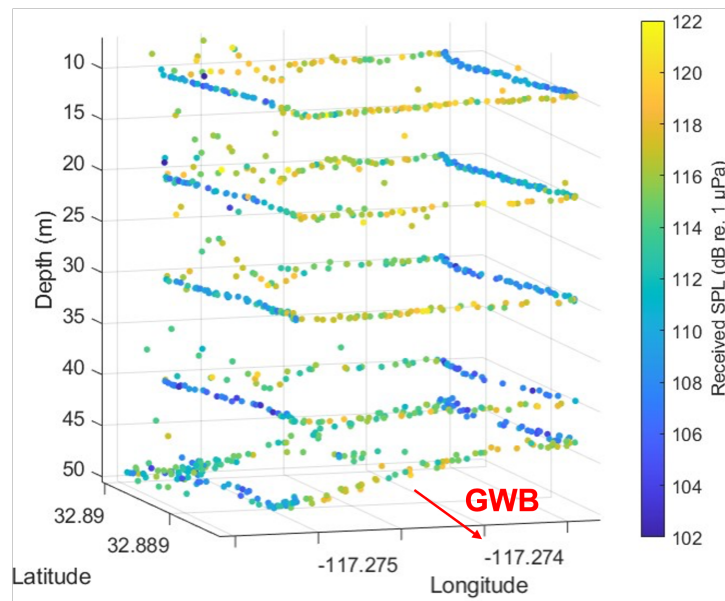


Figure 3.13. Received SPL measured by the UUV during the relative heading experiment. The colorbar indicates the received SPL associated with each received acoustic transmission. The red arrow indicates the direction from the UUV test area toward the GWB, located approximately 1,750 m from the center of the box pattern.

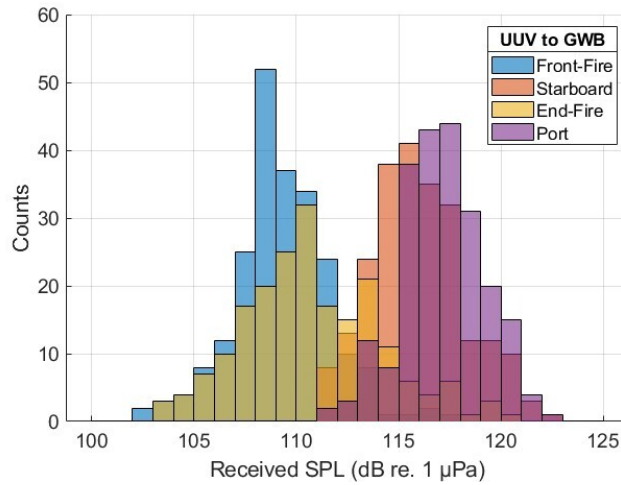


Figure 3.14. Distribution of received SPL measurements at the UUV grouped by relative bearing to the GWB in the UUV body-fixed frame. Measurements from the tested operating depths were combined and separated into port, starboard, front-fire (nose-on), and end-fire (tail-on) orientations.

depth. Measurements were then combined across depths to evaluate the overall orientation dependence.

For the four-orientation comparison, relative bearing to the GWB was divided into four sectors in the UUV body-fixed frame. Front-fire measurements included relative bearings greater than 330° or less than 30° , starboard measurements included bearings from 60° to 120° , end-fire measurements included bearings from 150° to 210° , and port measurements included bearings from 240° to 300° . Measurements within the 30° transition regions between these sectors were excluded from the four-orientation comparison. The resulting dataset contained 224 front-fire, 229 starboard, 203 end-fire, and 221 port observations.

The median received SPL was 117 dB re. $1 \mu\text{Pa}$ for the port orientation and 115 dB re. $1 \mu\text{Pa}$ for the starboard orientation, compared with 109 dB re. $1 \mu\text{Pa}$ for front-fire and 110 dB re. $1 \mu\text{Pa}$ for end-fire. The corresponding interquartile ranges were 115–118 dB for port ($n = 221$), 114–117 dB for starboard ($n = 229$), 108–110 dB for front-fire ($n = 224$), and 108–113 dB for end-fire ($n = 203$). The broadside orientations therefore produced median received SPL values approximately 5–8 dB higher than the nose-on and tail-on orientations.

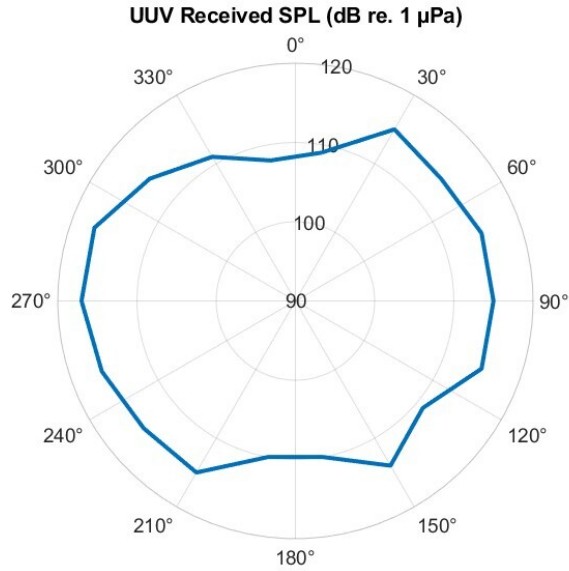


Figure 3.15. Average received SPL at the UUV as a function of relative bearing to the GWB in the UUV body-fixed frame. Data were averaged within 20° bins centered from 10° to 350°. The nose and tail of the UUV correspond to 0° and 180°, while starboard and port correspond to 90° and 270°, respectively.

Range was not identical between the two broadside legs of the box pattern. Based on the nominal test geometry, the nearer broadside leg was approximately 1,670 m from the GWB and the farther broadside leg was approximately 1,830 m from the GWB. A bounding calculation using spherical spreading predicted approximately 0.8 dB of additional transmission loss over this 160 m range difference, while cylindrical spreading predicted approximately 0.4 dB. Including frequency-dependent absorption produced similar differences over this range interval. The expected effect of range was therefore substantially smaller than the observed 5–8 dB difference between the broadside and nose-on or tail-on orientations. Range variation may explain part of the difference between the port and starboard distributions, but does not account for the larger difference between broadside and end-fire orientations.

The directional dependence is also shown in Figure 3.15. Received SPL was evaluated across the full 360° relative bearing to the GWB in the UUV body-fixed frame and averaged within 20° bins centered at 10°, 30°, and continuing in 20° increments through 350°.

Figure 3.15 shows higher average received SPL in the broadside directions and lower received SPL near the nose-on and tail-on orientations. The pattern is similar to the WHOI beam pattern measurements shown in Figure 3.11, although the angular conventions used in the two figures differ. Both datasets show stronger acoustic response when the vehicle presents a broadside aspect and reduced response near the longitudinal axis of the vehicle. This agreement supports vehicle geometry and hull shadowing as likely contributors to the observed orientation dependence.

The field measurements provide moderate confidence that relative vehicle orientation affected received SPL during the experiment. The 5–8 dB difference in median received SPL between broadside and nose-on or tail-on orientations was substantially larger than the estimated 0.4–0.8 dB effect associated with the range difference between the broadside legs. The same general directional dependence was observed when the operating depths were examined individually and was consistent with the independent WHOI beam pattern measurements. However, the magnitude of received SPL varied with depth, and environmental and acoustic propagation effects could not be fully isolated from vehicle orientation. These factors prevent complete isolation of the orientation effect and support a moderate confidence assessment.

3.6 Experimental Assessment Summary

This chapter evaluated vehicle self-noise, acoustic channel effects, and relative vehicle orientation as potential factors influencing underwater acoustic communication performance.

The self-noise experiments showed minimal RPM dependence near the 25 kHz modem operating frequency. The open-water test showed no consistent relationship between RPM and the UUV SST noise measurement across 115–167 measurements per RPM setting. The controlled tank test showed that propulsion-related acoustic energy increased at lower frequencies but did not show a corresponding monotonic increase near 25 kHz. Based on these results, propulsion RPM was not selected as a primary control variable for the adaptive behaviors.

The depth and range assessment showed that communication performance varied with both UUV depth and range. Ping reception, received SPL, and BELLHOP modeling supported the presence of depth-dependent propagation effects, although depth, range, and Wave Glider motion did not vary independently. Confidence in the depth-dependent communication effect was therefore moderate.

The relative heading assessment showed median received SPL values approximately 5–8 dB higher when the UUV presented a broadside aspect to the GWB compared with nose-on and tail-on orientations. The estimated effect of the approximately 160 m range difference between the broadside legs was only 0.4–0.8 dB. The directional pattern was also observed at the individual operating depths and was consistent with previous WHOI beam pattern measurements, supporting vehicle geometry and hull shadowing as likely contributors to the observed effect. Because depth-dependent propagation and other environmental effects could not be fully isolated from orientation, confidence in the orientation-dependent received SPL effect was moderate.

The experimental assessments identified vehicle depth and heading as the most promising control variables for communication-aware vehicle behavior. These findings provided the basis for the depth-seeking and broadside deviation behaviors developed and evaluated in the next chapter.

Chapter 4

Autonomous Behavior Development

4.1 Overview

Field testing was conducted to evaluate whether autonomous changes in vehicle depth and orientation could improve underwater acoustic communication performance following communication degradation. Two adaptive behaviors were evaluated: a depth-seeking behavior that modified vehicle depth and a broadside deviation behavior that modified vehicle heading relative to the receiver.

The depth-seeking behavior was evaluated during a 3 km transit on February 13, 2026, while the broadside deviation behavior was evaluated during a 6 km transit on April 30, 2026. Both experiments were conducted approximately 11 km offshore of La Jolla, California in water depths near 400 m. Two-way acoustic communication was established between a REMUS 100 and a towfish receiver positioned at a depth of 7 m. Successful ACK reception was used as the primary indicator of communication recovery.

The results were evaluated to determine whether communication could be re-established following activation of each behavior. The observed recoveries were also compared with the acoustic propagation and vehicle orientation effects identified during the experimental assessments. Vehicle depth, heading, range, and receiver geometry could not always be independently controlled during field testing. The results show whether each behavior was able to restore communication following communication loss, but the relative effects of these factors could not

be independently isolated.

4.2 Software Architecture

The adaptive behaviors were implemented within the Robot Operating System (ROS) architecture used aboard the REMUS 100. A custom behavior node monitored acoustic communication performance and issued temporary vehicle transit commands when communication degradation was detected. Figure 4.1 shows the architecture used during the experiments.

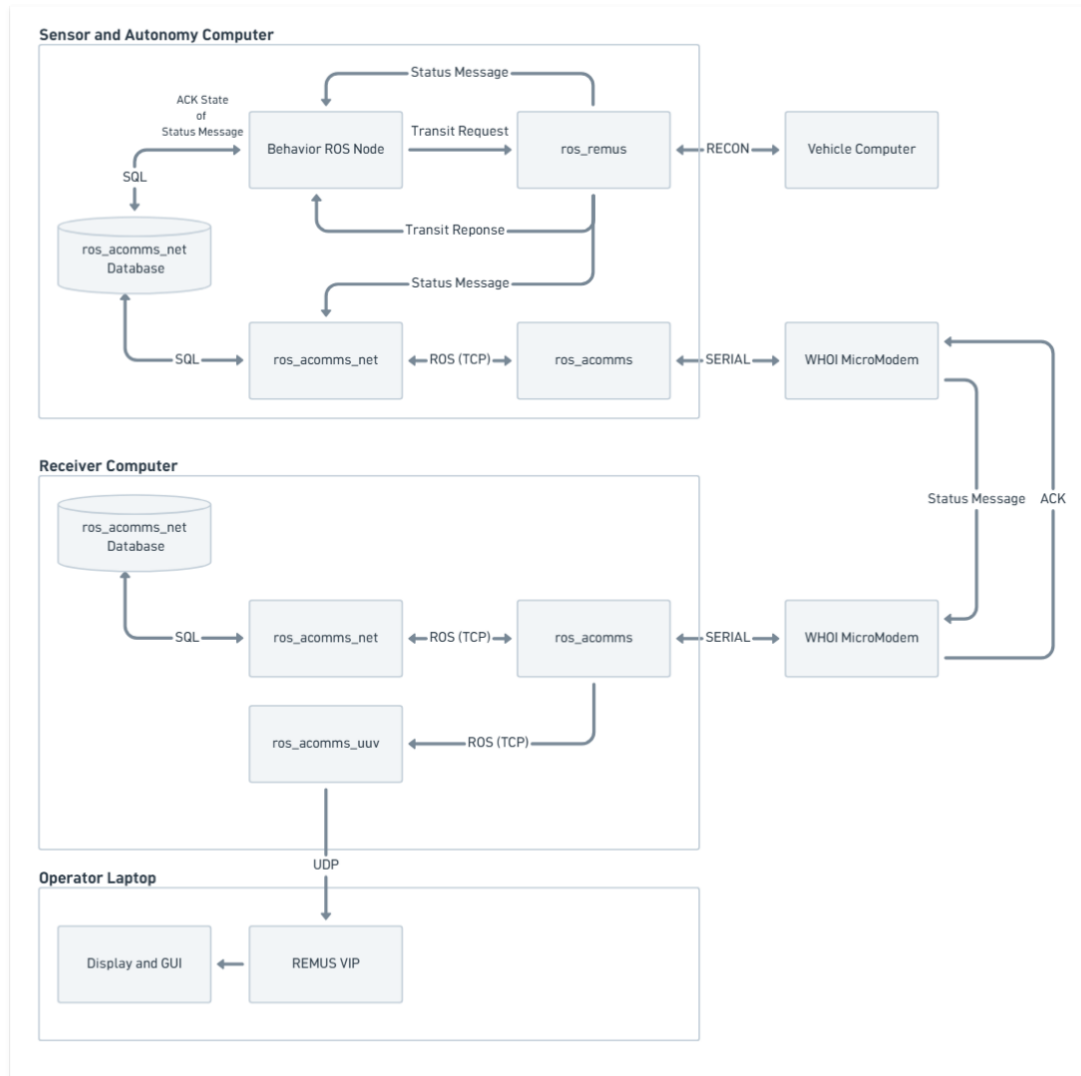
The behavior node interfaced with the vehicle through the `ros_remus` interface. Acoustic communication data were exchanged through the `ros_acomms` and `ros_acomms_net` processes. Vehicle status messages were transmitted through the WHOI Micromodem-2 to a remote receiver. When a status message was successfully received, the remote system generated an ACK message that was transmitted back to the UUV.

Transmitted status messages and received ACK messages were logged within the `ros_acomms_net` database. The behavior node accessed this database to determine the elapsed time since the most recent successful ACK reception. This approach allowed communication status to be monitored without modifying the acoustic modem firmware or the primary vehicle navigation software.

When the communication-loss threshold was exceeded, the behavior node generated a temporary transit request through the `ros_remus` interface. Depending on the behavior being evaluated, the transit request initiated either a depth profiling maneuver or a temporary heading deviation. After the adaptive maneuver was completed, the vehicle returned to the nominal mission plan.

4.3 Communication Loss Detection

Both adaptive behaviors used the same communication-loss detection algorithm. Rather than reacting to individual missed packets, the system monitored the elapsed time since the most



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Figure 4.1. Communication-aware autonomy architecture showing interactions between the REMUS vehicle software, acoustic communication network, and adaptive behavior node.

recent successful ACK reception.

Vehicle status messages containing navigation and mission information were transmitted every 30 seconds. Each message required a corresponding ACK from the receiving node. Successful ACK reception indicated that the acoustic link remained available, while extended periods without an ACK indicated degraded communication or communication loss.

A communication-loss condition was declared when no ACK message had been received for more than 120 seconds. This threshold required multiple consecutive missed ACK messages, representing multiple missed communication opportunities rather than a single packet loss, before an adaptive maneuver was initiated. The delay reduced unnecessary behavior activations caused by isolated packet losses while still allowing the vehicle to respond to sustained communication degradation.

For the behavior tests, communication recovery was defined as receipt of an ACK by the UUV following activation of an adaptive behavior. This metric indicates a successful two-way acoustic exchange. The remote receiver demodulated the UUV transmission, generated an ACK, and the UUV successfully received and demodulated the return message. A single ACK demonstrates communication recovery for that exchange, but does not by itself demonstrate sustained communication over multiple TDMA cycles.

Once the 120-second threshold was exceeded, the behavior node checked additional mission constraints before initiating an adaptive maneuver. These included confirmation that autonomous behavior overrides were enabled and that no conflicting adaptive transit commands were active. If these conditions were met, the appropriate adaptive behavior was initiated to restore communication.

4.4 Adaptive Depth-Seeking Behavior

4.4.1 Behavior Objective

The objective of the adaptive depth-seeking behavior was to restore acoustic communication following communication loss by temporarily changing vehicle depth. When the communication-loss threshold was exceeded, the vehicle conducted a vertical profiling maneuver while continuing to transmit status messages.

The behavior searched the water column for a depth where two-way communication could be re-established. Receipt of an ACK message indicated successful communication recovery and caused the vehicle to terminate the search at the current depth.

The depth-seeking behavior did not require environmental measurements, acoustic propagation models, or prior knowledge of a favorable communication depth. Instead, the behavior relied solely on ACK feedback received during the profiling maneuver.

4.4.2 Concept of Operations

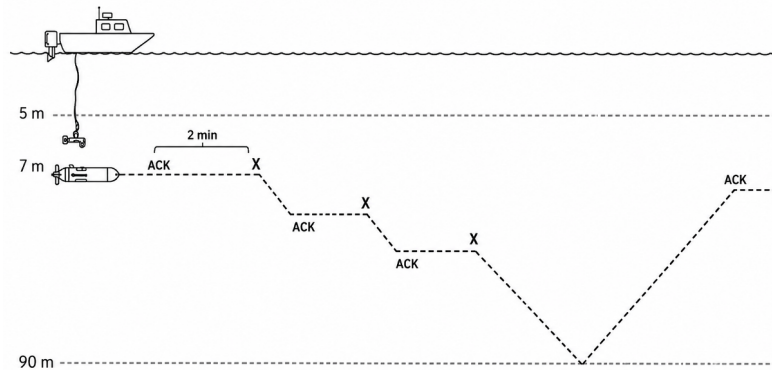


Figure 4.2. Conceptual representation of the adaptive depth-seeking behavior. Following a communication-loss condition, the vehicle conducts a profiling maneuver while continuing to transmit status messages. Figure created by the author with assistance from OpenAI ChatGPT

Figure 4.2 illustrates the operation of the adaptive depth-seeking behavior. An X indicates that no ACK message has been received for 120 seconds. Once this threshold is reached, the

vehicle begins a vertical depth excursion while continuing to transmit status messages and monitor returned ACK messages.

If an ACK message is received during the excursion, communication is considered re-established and the vehicle terminates the behavior at the current depth. If communication is not restored, the vehicle continues through the predefined depth range of 5 m to 90 m before reversing direction and searching back through the water column.

4.4.3 Behavior Logic

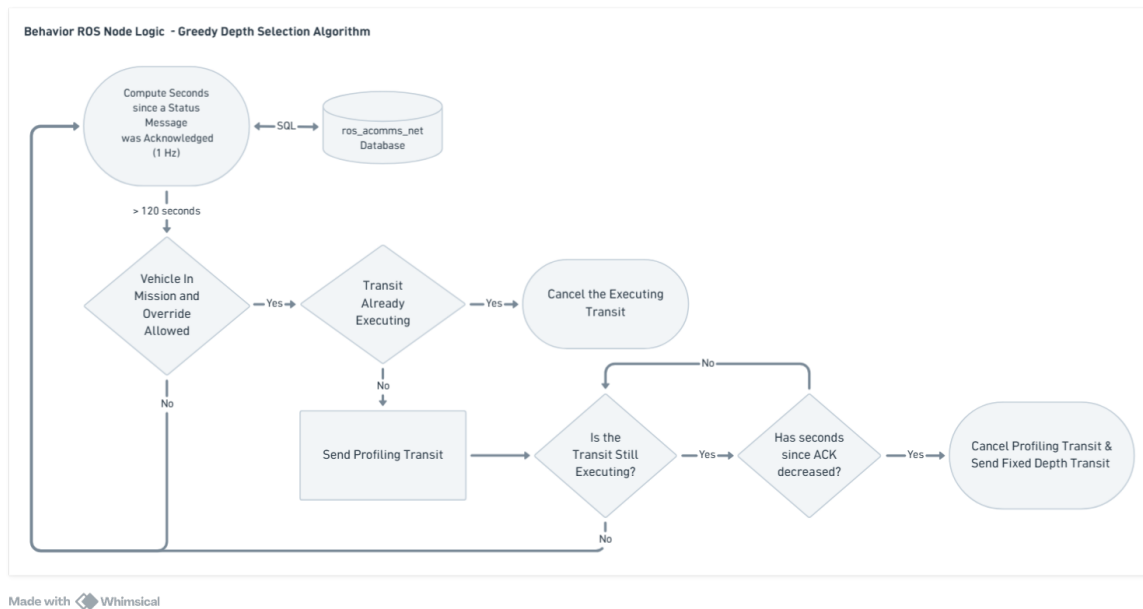


Figure 4.3. Logic used by the behavior node to implement the adaptive depth-seeking behavior.

Figure 4.3 shows the logic used to implement the adaptive depth-seeking behavior. During normal mission execution, the behavior node monitored the elapsed time since the most recent ACK reception. When this time exceeded 120 seconds, the node verified that the vehicle was operating in mission mode and that autonomous behavior overrides were enabled. It also checked whether an adaptive transit command was already active. If so, the existing transit was canceled before a new profiling command was issued.

During the profiling maneuver, the vehicle maintained forward motion at 1,400 rpm while ascending or descending at 18 m/min. The vertical rate was selected to balance two competing requirements. It provided enough time at changing depths for communication recovery while limiting the horizontal distance traveled during the search. The vehicle continued transmitting status messages and monitoring returned ACK messages throughout the maneuver.

When an ACK message was received, the profiling transit was canceled and a fixed-depth transit was issued at the depth where communication was restored. If no ACK was received, the vehicle continued profiling between the predefined depth limits.

The depth-seeking behavior used a greedy search strategy. Rather than sampling the full depth range and comparing communication performance at each depth, the behavior accepted the first depth where an ACK message was received. This reduced the amount of vehicle maneuvering required to restore communication and allowed the vehicle to resume its mission once the acoustic link was re-established.

4.4.4 Sound Velocity Profile and Transmission Loss Analysis

Measured SVP data and BELLHOP TL modeling were examined to characterize the acoustic environment during the February 13, 2026 experiment. This analysis was used to determine whether depth-dependent variations in acoustic propagation could potentially be exploited through adaptive vehicle depth changes.

Figure 4.4 shows the SVP and corresponding BELLHOP TL prediction for the experimental area.

The SVP exhibited a downward refracting structure, with sound speed decreasing from 1,516 m/s at the surface to 1,487 m/s at 400 m depth. These conditions cause acoustic energy to refract toward deeper water as range increases.

The TL model predicts increasing TL with range throughout the water column while also showing depth-dependent variation. Beyond 2 km range, lower TL regions are present at greater depths while higher TL regions persist near the surface. These differences suggest that changes

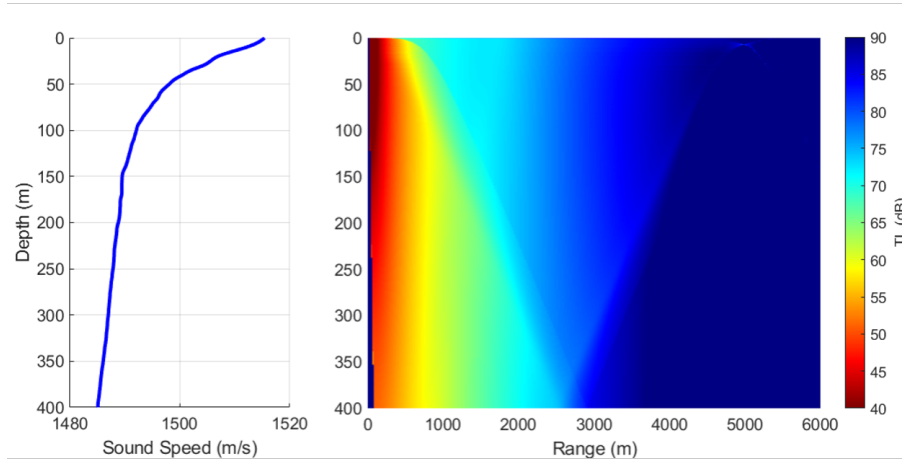


Figure 4.4. Measured SVP (left) and corresponding BELLHOP transmission loss prediction (right) for the depth-seeking behavior experiment.

in vehicle depth may produce measurable differences in acoustic communication performance at longer ranges.

4.4.5 Communication Recovery Performance

Figure 4.5 shows the vehicle depth profile and successful ACK receptions recorded during the experiment.

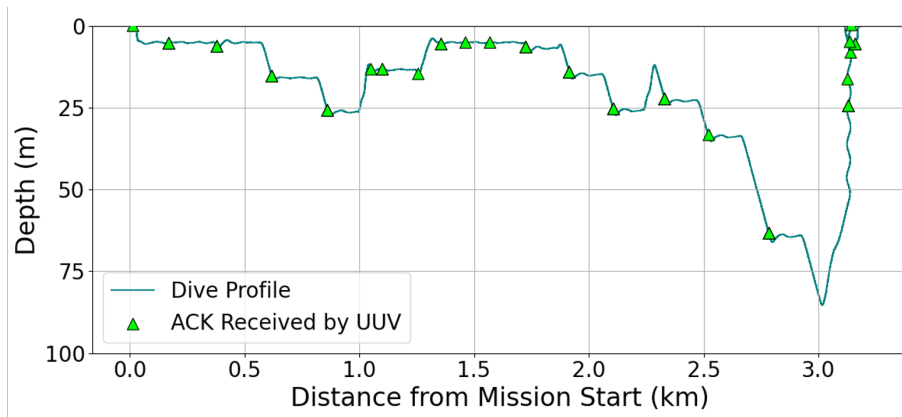


Figure 4.5. Vehicle depth profile and successful ACK message receptions during the depth-seeking behavior experiment. Green triangles indicate successful ACK messages received by the UUV.

Successful ACK receptions were recorded throughout most of the outbound transit. During the first 2.5 km of the mission, successful ACK receptions occurred while the vehicle

operated between 5 m and 35 m depth. Beyond approximately 2 km, ACK receptions became less frequent and the depth-seeking behavior was activated more often. The behavior initiated progressively deeper excursions, ultimately reaching a maximum depth of approximately 85 m near the end of the mission.

Most behavior activations were followed by successful ACK receptions, indicating that two-way communication had been re-established. These recoveries demonstrate that the behavior was able to restore communication following multiple periods of communication loss.

The observed communication recoveries are generally consistent with the depth-dependent propagation conditions predicted by the SVP and TL model. The field results support the potential use of vehicle depth changes to restore communication. However, depth was not independently isolated from changing range and vehicle orientation during the experiment. The results therefore support the effectiveness of the behavior but do not establish vehicle depth as the sole cause of the observed recoveries.

The environmental measurements and BELLHOP modeling were used to interpret the observed communication performance. The adaptive behaviors relied only on ACK feedback as the real-time trigger and measure of communication recovery.

At the end of the mission, the vehicle initiated a helical ascent to the surface for recovery. This maneuver was part of the nominal mission termination sequence and was not associated with the adaptive depth-seeking behavior. Several successful ACK receptions occurred during the ascent, but the vehicle was simultaneously changing both depth and orientation relative to the receiver. These receptions were therefore not considered when evaluating the depth-seeking behavior.

4.5 Adaptive Broadside Deviation Behavior

4.5.1 Behavior Objective

The objective of the adaptive broadside deviation behavior was to restore acoustic communication following communication loss by temporarily changing vehicle heading. The behavior was designed to exploit the relationship between vehicle orientation and acoustic communication performance observed during the relative heading assessments.

By changing heading, the vehicle could achieve a more favorable orientation relative to the receiver and increase the likelihood of restoring communication. The behavior did not require environmental measurements, acoustic propagation models, or knowledge of the receiver location. Instead, it relied solely on returned ACK messages to determine whether communication had been restored.

The behavior did not calculate bearing to the receiver. Instead, it used a fixed 90° deviation from the planned track to sample a different vehicle aspect and potentially move the transducer away from an unfavorable nose-on or tail-on orientation.

4.5.2 Concept of Operations

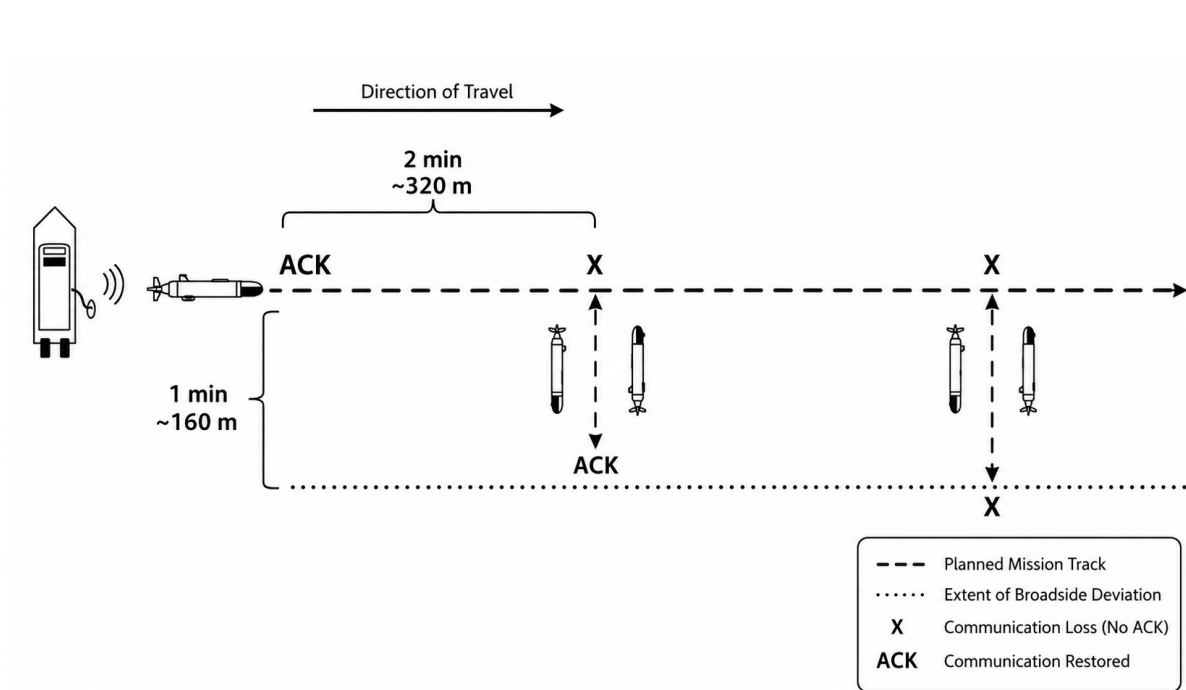


Figure 4.6. Conceptual representation of the adaptive broadside deviation behavior. Following a communication-loss condition, the vehicle temporarily deviates from the planned mission track while continuing to transmit status messages. Figure created by the author with assistance from OpenAI ChatGPT

Figure 4.6 illustrates the operation of the adaptive broadside deviation behavior. An X indicates that no ACK message has been received for 120 seconds. Once this threshold is reached, the vehicle executes a 90° deviation from the planned track while continuing to transmit status messages and monitor returned ACK messages.

If an ACK message is received during the deviation, communication is considered re-established and the behavior is terminated. The vehicle then returns to the planned track and resumes the nominal mission. If communication is not restored, the vehicle continues the deviation for 60 seconds, traveling approximately 160 m before reversing course and returning to the planned track.

4.5.3 Behavior Logic

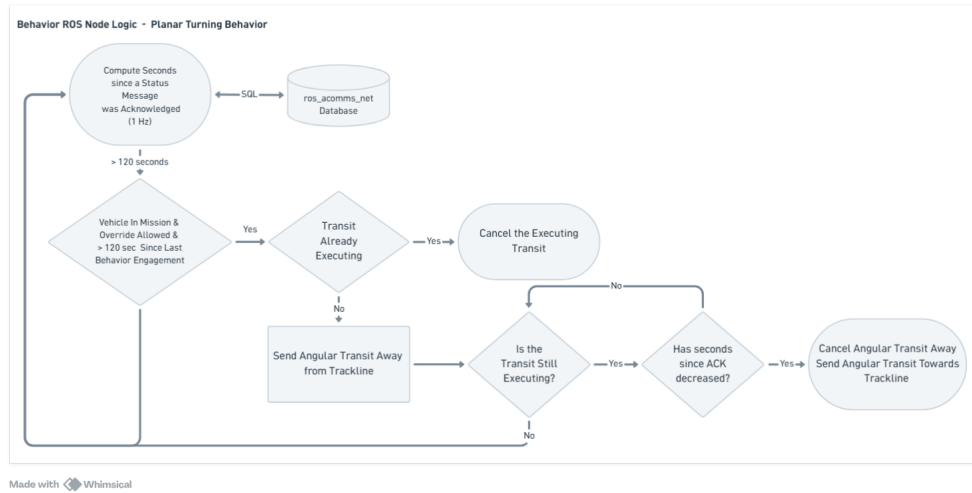


Figure 4.7. Logic used by the behavior node to implement the adaptive broadside deviation behavior.

Figure 4.7 shows the logic used to implement the adaptive broadside deviation behavior. During normal mission execution, the behavior node monitored the elapsed time since the most recent ACK reception. When the communication-loss threshold was exceeded, the node verified that the vehicle was operating in mission mode, that autonomous behavior overrides were enabled, and that no conflicting adaptive transit command was active.

Once these conditions were met, the behavior node issued a temporary transit command that turned the vehicle 90° from the planned trackline. ACK messages continued to be monitored throughout the deviation. Receipt of an ACK caused the deviation to terminate early and directed the vehicle back to the planned trackline.

If no ACK message was received, the vehicle continued the deviation for the full 60-second limit before reversing course and returning to the planned trackline. The 60-second limit kept the deviation to approximately 160 m and reduced the amount of time the vehicle spent away from the planned mission track.

4.5.4 Communication Recovery Performance

Figure 4.8 shows the vehicle track and successful ACK receptions recorded during the broadside deviation experiment. The vehicle began slightly southwest of the mission start point and transited northeast, corresponding to movement from left to right in the figure.

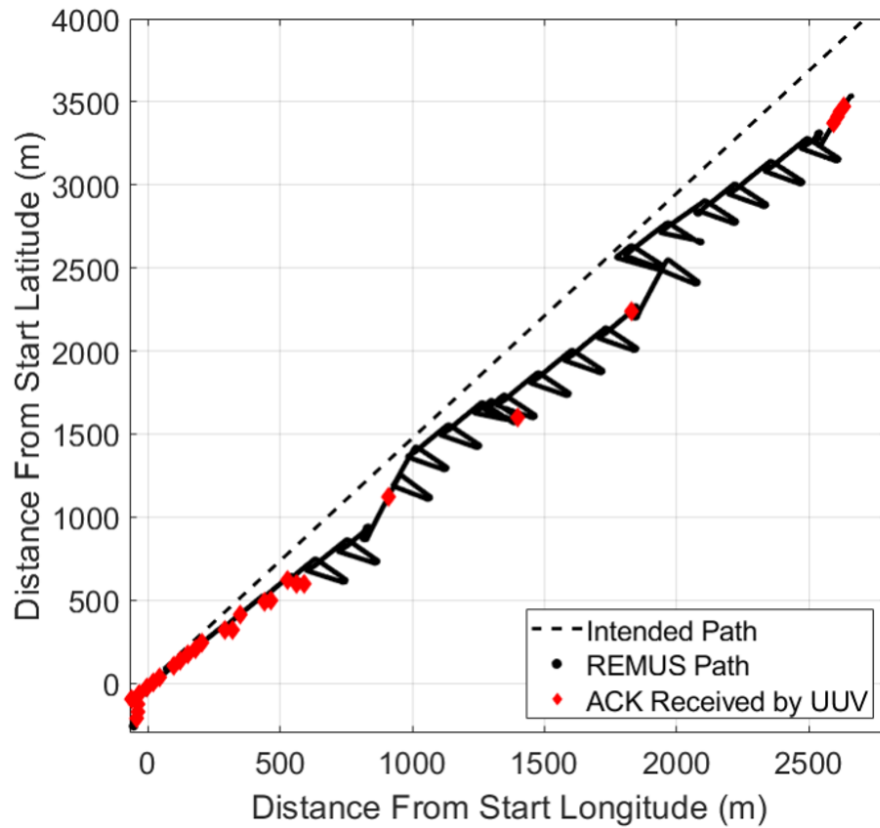


Figure 4.8. Vehicle track and successful ACK message receptions during the broadside deviation behavior experiment. The dashed line represents the planned mission trackline, the solid line represents the actual vehicle trajectory, and red diamonds indicate successful ACK messages received by the UUV as it transited from southwest to northeast.

Successful ACK receptions became less frequent as range increased. The majority occurred within the first 1.3 km of the transit, with additional successful communications recorded out to approximately 3 km. As ACK receptions became less frequent, the broadside deviation behavior was repeatedly activated, producing frequent departures from the planned trackline beyond approximately 1 km.

The first three behavior activations were terminated early following successful ACK receptions. Figure 4.9 provides a closer view of these communication recoveries.

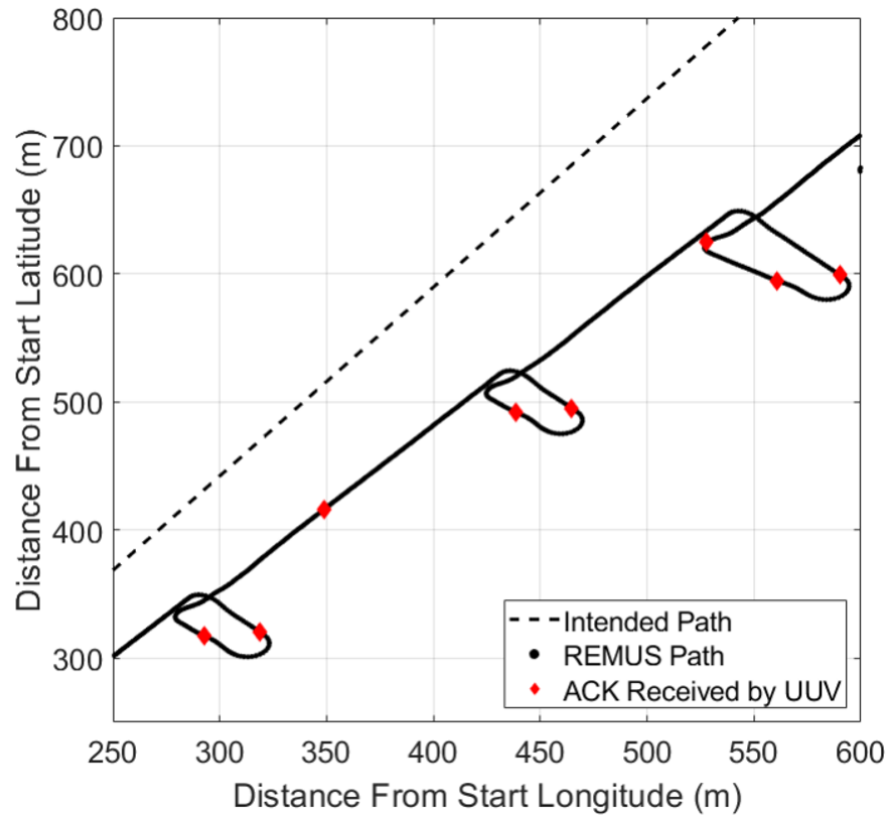


Figure 4.9. Expanded view of the first three broadside deviation maneuvers. Successful ACK receptions resulted in early termination of the behavior and return to the planned mission trackline.

During the first two activations, ACK messages were successfully received after the vehicle deviated approximately 50 m from the planned trackline. During the third activation, the vehicle traveled approximately 75 m before receiving an ACK. In each case, communication was restored during the deviation and the vehicle returned to the planned trackline.

Later behavior activations did not result in immediate communication recovery. The vehicle therefore completed the full 60-second deviation and traveled approximately 160 m before returning to the planned trackline.

The communication recoveries observed during the first three deviations are consistent with the orientation-dependent communication trends identified during the relative heading

assessment. Successful ACK receptions occurred after the vehicle initiated the broadside maneuver, supporting the use of temporary heading changes as a potential method for restoring communication. However, later deviations did not produce the same result. The field test therefore demonstrates that the behavior was capable of restoring communication during several activations, but does not show that a broadside deviation will consistently restore the acoustic link.

Receiver availability introduced additional uncertainty during the experiment. Strong winds and surface currents periodically displaced the support vessel and towfish from the intended receiver position, requiring the towfish to be recovered while the vessel repositioned. ACK messages could not be transmitted to the UUV during these periods, which typically lasted 2–3 minutes. Some behavior activations may therefore have resulted from temporary receiver unavailability rather than degraded acoustic communication. Additional testing using a fixed receiver platform, such as a gateway buoy, would provide a more controlled evaluation of broadside deviation performance.

4.6 Adaptive Behavior Test Summary

Table 4.1 summarizes the communication-loss response, observed field performance, and primary limitation associated with each adaptive behavior.

The Chapter 4 field tests showed that ACK-triggered depth and heading behaviors could be implemented on the REMUS 100 and could recover two-way acoustic communication during some field activations. The tests did not isolate the individual effects of depth, heading, range, and receiver availability, so the results should be interpreted as operational demonstrations rather than quantitative proof of communication improvement.

Table 4.1. Summary of adaptive behavior field test results.

Behavior	Behavior Initiation	Loss of Communication Behavior	Result	Limitation
Depth-Seeking	120 s with no ACK	Depth excursion until an ACK is received	UUV received fewer ACKs beyond 2 km	Depth, range, and vehicle orientation were not independently isolated
Broadside Deviation	120 s with no ACK	Up to 60-second, 90° deviation or until an ACK is received	UUV lost reliable ACK reception beyond 1.3 km	Support vessel periodically reset position

Chapter 5

Conclusion

5.1 Research Summary

This research investigated whether adaptive UUV behaviors could improve underwater acoustic communication reliability. Experimental assessments were conducted using a REMUS 100 to evaluate the influence of vehicle self-noise, vehicle depth, and vehicle orientation on communication performance.

The results showed that RPM-dependent vehicle self-noise was not a primary factor affecting communication performance near the 25 kHz communication frequency under the conditions tested. In contrast, vehicle depth and vehicle orientation were identified as controllable parameters capable of influencing communication performance. Based on these findings, a communication-aware autonomy framework was developed and integrated into the REMUS 100 software architecture. The framework monitored ACK message reception and initiated adaptive behaviors when communication degradation was detected.

Field testing demonstrated the successful implementation of the depth-seeking and broadside deviation behaviors during autonomous mission operations. In both cases, the vehicle responded to communication degradation by modifying its behavior and then returning to the planned mission trackline. ACK reception resumed following adaptive maneuvers in multiple instances. These results demonstrated that communication-aware behaviors can be incorporated into an operational UUV platform and used to adapt vehicle motion in response to changing

communication conditions.

5.2 Research Contributions and Engineering Implications

This research demonstrated that vehicle depth and orientation can be treated as controllable parameters within a communication-aware autonomy framework. Instead of treating acoustic communication performance as a fixed mission constraint, the framework used communication status to influence autonomous vehicle behavior.

The depth-seeking and broadside deviation behaviors provided two approaches for modifying vehicle motion in response to communication degradation. Their successful field implementation showed that communication performance can be incorporated into UUV autonomy while allowing the vehicle to continue its primary mission. This approach provides a foundation for more advanced communication-aware behaviors that account for acoustic conditions during mission execution.

5.3 Limitations

Several limitations should be considered when interpreting the results of this research. Environmental variability, support vessel motion, and receiver repositioning introduced additional uncertainty during portions of the field testing. These variables limited the ability to isolate individual factors affecting communication performance. The experiments were also conducted using a single acoustic modem frequency and transmission configuration over a limited range of test conditions.

The adaptive behavior demonstrations were intended to evaluate operational feasibility rather than provide a comprehensive statistical assessment of communication performance improvement. Additional testing with greater experimental control and repeated trials across a broader range of environmental and operational conditions would be required to quantify the effectiveness of the adaptive behaviors.

5.4 Future Work

Future testing should evaluate communication-aware behaviors across a broader range of environmental conditions, communication ranges, and mission geometries. Repeated field trials with greater experimental control would also help quantify the communication performance improvements associated with individual adaptive behaviors.

Future behavior development could incorporate real-time environmental sensing, acoustic propagation modeling, or communication performance prediction. These capabilities could allow the vehicle to adjust its behavior before communication is lost rather than waiting for communication degradation to trigger a response.

Communication-aware autonomy could also be extended to multi-vehicle operations involving UUVs, gateway buoys, and surface vehicles. Coordinated vehicle positioning and communication-aware mission planning could provide additional opportunities to improve network connectivity during autonomous operations.

5.5 Final Remarks

This research demonstrated that communication performance can be incorporated into autonomous UUV decision-making through controllable changes in vehicle depth and orientation. The field implementation of the depth-seeking and broadside deviation behaviors demonstrated the feasibility of using adaptive vehicle control to respond to underwater acoustic communication degradation during mission execution.

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