

## **Numerical Investigation and Design of an Acoustic Communication System for a Deep-Sea Autonomous Underwater Vehicle (AUV) in Oil and Gas Applications**

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### **Abstract**

Autonomous Underwater Vehicles (AUVs) operating at extreme depths face substantial challenges in maintaining reliable data communication due to high pressure, strong absorption, and environmental noise. This study presents a numerical analysis and system-level design of an acoustic communication framework for a deep-sea AUV operating at 6000 meters. Transmission Loss (TL), Received Power (Pr), and Signal-to-Noise Ratio (SNR) are evaluated across frequencies from 5–30 kHz and communication ranges up to 10 km. Results indicate that low-frequency signals (5–10 kHz) enable significantly longer communication distances due to reduced absorption. Practical implementation considerations including transducers, hydrophones, and signal-conditioning are also discussed to support real-world deployment. Unlike many existing studies that focus on shallow or mid-depth underwater communication, this work specifically addresses acoustic system design constraints for ultra-deep operations at depths up to 6000 meters in offshore oil and gas environments. Findings offer quantitative and practical guidelines for selecting acoustic frequencies and designing robust communication systems for deep-sea AUV missions.

**Keywords:** Autonomous Underwater Vehicle; Acoustic Communication; Deep-Sea; Signal-to-Noise Ratio; Oil and Gas Applications

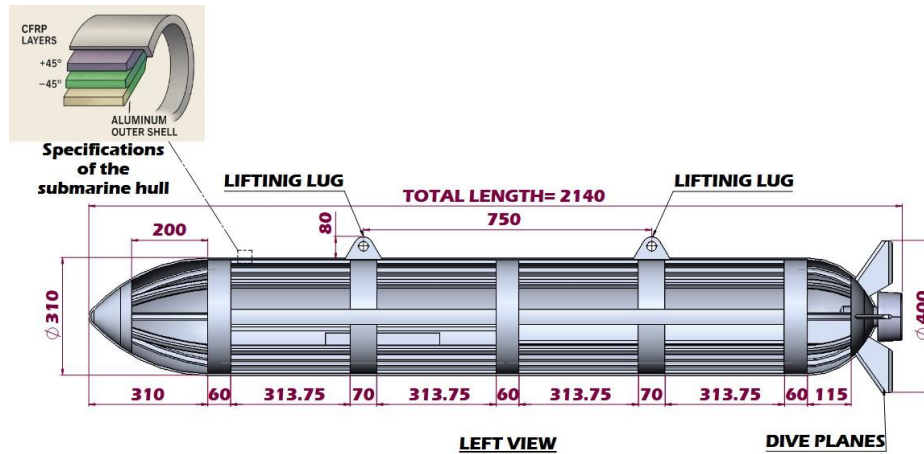
## 1. Introduction

In this study, the term autonomous underwater vehicle (AUV) is used to describe an unmanned, self-propelled underwater platform, which may also be informally referred to as an autonomous submarine in industrial contexts.

Autonomous Underwater Vehicles (AUVs) have become essential tools in the oil and gas industry, performing complex tasks in extreme underwater environments[1, 2]. These vehicles are deployed for missions such as subsea pipeline inspection, offshore infrastructure monitoring, environmental data collection, and maintenance support[3], where direct human intervention is either limited or impossible. Operating at depths up to 6000 meters, AUVs encounter significant challenges including high hydrostatic pressure, low temperatures, limited communication bandwidth, and restricted accessibility[4].

Among the various AUV platforms, the HUGIN 6000 AUV stands out as a reference system due to its proven deep-sea operational capabilities and integrated acoustic communication system[5]. Acoustic communication is widely recognized as the most effective method for maintaining data transmission under extreme underwater conditions, outperforming radio frequency and optical methods where water absorption and scattering significantly attenuate signals. [6]

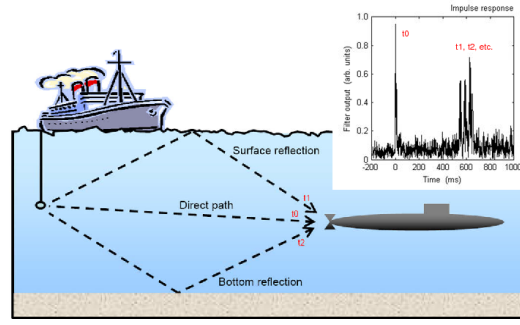
This study numerically investigates the performance of an acoustic communication system designed specifically for deep-sea AUV operations. Using validated acoustic propagation models and MATLAB-based simulations, the work provides insights into frequency selection, communication range prediction, and system component design for high-pressure subsea environments.



**Figure 1.** Preliminary hull and structural concept of an autonomous deep-sea vehicle.



**Figure 2.** Schematic of a deep-sea AUV performing subsea oil and gas operations, illustrating typical underwater acoustic communication links between the AUV, surface vessels, and subsea infrastructure.[7]



**Figure 3.** Conceptual diagram of underwater acoustic communication, illustrating signal transmission between a deep-sea AUV and a remote receiver under long-range propagation conditions.[8]

## 2. System Model

For deep-sea operations, AUVs require a reliable communication system capable of transmitting data over long distances under harsh environmental conditions. Acoustic communication is widely accepted as the most suitable solution for deep-sea missions due to its long-range capability and proven reliability in high-pressure underwater environments.[9]

### 2.1 Model Parameters

The acoustic communication system in the AUV is modeled as a point-to-point transmission link between the AUV and a remote station (or between multiple AUVs). The main parameters considered in the model include:

- **Carrier frequency (f):** The operating frequency of the acoustic signal.
- **Signal power (P<sub>t</sub>):** The transmitted acoustic power.
- **Propagation distance (d):** The depth and horizontal distance between transmitter and receiver.
- **Sound speed (c):** Speed of sound in seawater, typically ~1500 m/s, which may vary with depth, temperature, and salinity.
- **Environmental noise (N):** Background noise including ambient ocean noise and self-noise from the AUV

### 2.2 Acoustic Propagation Model

Received signal power (P<sub>r</sub>) is estimated using the transmission loss (TL) model:

$$P_r(d) = P_t - TL(d) \quad (1)$$

where transmission loss accounts for both spreading and absorption:

$$TL(d) = 10k \log_{10}(d) + \alpha(f).d \quad (2)$$

- **k** is the spreading factor (1 for cylindrical spreading, 2 for spherical spreading).
- $\alpha(f)$  is the absorption coefficient of seawater at frequency (f), typically expressed in dB/km (Urick, 1983).[10]

### 2.3 Signal-to-Noise Ratio (SNR)

In this study, the noise term  $N$  in Eq. (3) includes deep-sea ambient noise (shipping noise, turbulence, and thermal noise) with a representative noise level of **60 dB re 1  $\mu$ Pa**, consistent with typical deep-sea (6000 m) acoustic environments

The effective communication performance is characterized by the signal-to-noise ratio at the receiver.

$$SNR(d) = P_r(d) - N \quad (3)$$

This ratio determines the achievable data rate and reliability of the link. For deep-sea missions at 6000 m depth, SNR is critically affected by absorption, multipath propagation, and ambient noise levels.[11]

## 3. Numerical Simulation

The numerical simulation aims to evaluate the performance of an underwater acoustic communication system for a deep-sea autonomous underwater vehicle (AUV) operating at a depth of 6000 meters. The simulation was conducted to estimate key performance parameters such as transmission loss (TL), received acoustic power (Pr), and signal-to-noise ratio (SNR) under realistic deep-sea environmental conditions.

In this model, the underwater acoustic channel is characterized by high pressure, low temperature, and variable salinity, all of which influence sound propagation. The attenuation of acoustic waves in seawater depends on both geometric spreading and frequency-dependent absorption. To approximate real oceanic conditions, the Thorp empirical model for sound absorption was employed, which accurately represents attenuation effects for frequencies between 1 kHz and 100 kHz.

The communication link was modeled as a point-to-point system, representing transmission between the AUV and a remote surface station. The transmitted power (Pt), propagation distance (d), and operating frequency (f) were varied to determine their effect on received signal strength and SNR. The system assumes an omnidirectional transmitter and receiver pair, with propagation following a spherical spreading model.

The numerical implementation was developed in MATLAB, allowing flexible analysis of acoustic propagation and visualization of results in both spatial and frequency domains. By computing transmission loss, received power, and SNR over a wide range of frequencies and distances, this simulation provides a practical basis for selecting suitable communication parameters for deep-sea AUVs engaged in oil and gas exploration and inspection missions.[12]

### 3.1 Assumptions for Numerical Simulation

The following parameters were used in the simulation:

**Table 1.** Simulation Assumptions.

Parameter	Symbol	Value / Description
Depth	h	6000m, Constant
Temperature	T	2, C <sup>o</sup>
Salinity	S	35 PSU
AUV Speed	v	4.5 Knots, (2.3 m/s)
Frequency Range	f	5-30 KHz
Water Density	$\rho$	1027 Kg/m <sup>3</sup>
Ambient Noise Level	NL	60 dB, (typical deep-sea)
Source Level	SL	190, dB re 1 $\mu$ Pa @1m

These parameters reflect realistic deep-sea conditions that influence acoustic communication performance. Line-of-sight between transmitter and receiver is not required due to the omnidirectional propagation nature of acoustic waves underwater.

These parameters represent a realistic deep-sea environment typically encountered in oil and gas field operations.

### 3.2 MATLAB Implementation

The MATLAB simulation calculates the acoustic path loss using the following general expression:

$$TL(d) = 20 \log_{10}(d) + \alpha(f).d \quad (4)$$

where TL is the transmission loss (dB),  $r$  is the range (m), and  $\alpha(f)$  is the absorption coefficient (dB/m) as a function of frequency, determined by the Thorp equation. The received power  $P_r$  is computed from the source level SL and TL:

$$P_r = SL - TL \quad (5)$$

Finally, the signal-to-noise ratio (SNR) is obtained from:

$$SNR = P_r - NL \quad (6)$$

where NL is the ambient noise level (dB).

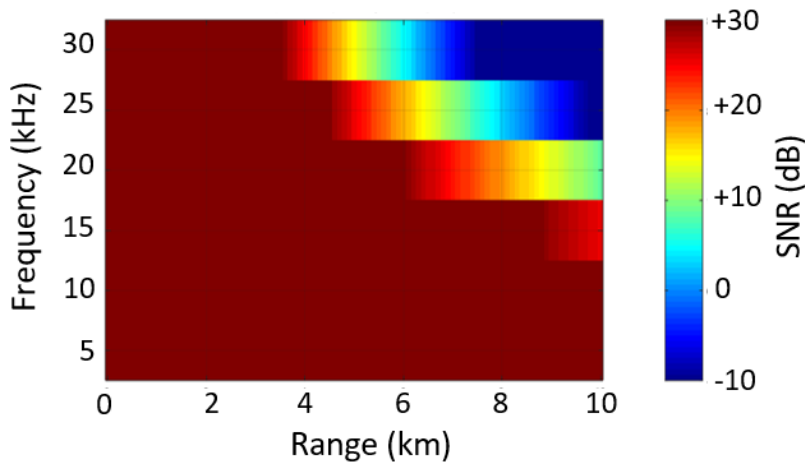
Simulation results include the variation of TL,  $P_r$ , and SNR over different ranges and frequencies. These outputs allow identifying optimal operational frequencies and communication limits for the AUV under the defined deep-sea conditions.

## 4. Results

This section presents the numerical results obtained from the simulation model. Graphical outputs including heatmaps, range–frequency plots, and SNR contours—are examined to determine optimal frequency bands, effective ranges, and communication limits. Each figure is accompanied by descriptive interpretation to ensure clarity.

### 4.1 Heatmap Analysis:

The SNR heatmap reveals that low-frequency signals (5–10 kHz) maintain higher SNR over long distances due to lower absorption, while higher frequencies (>20 kHz) experience significant attenuation in deep-sea environments (Figure 1).

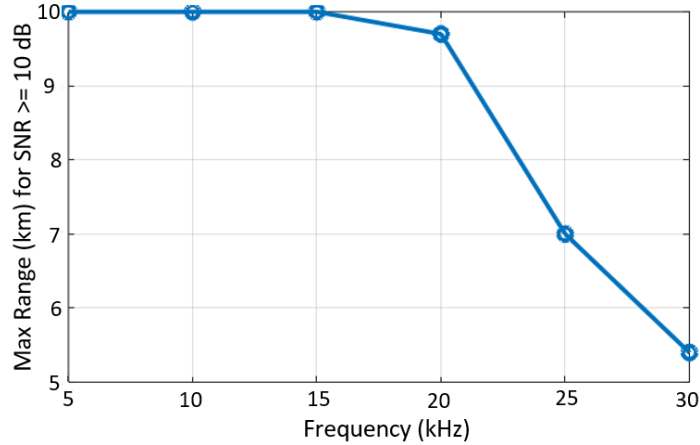


**Figure 4.** SNR (dB) Heatmap - Frequency. Lower frequencies (5-10 kHz) maintain higher SNR over long ranges, while higher frequencies attenuate quickly.

The heatmap provides a clear visualization of the frequency-dependent attenuation, highlighting the superior long-range performance of low-frequency acoustic signals.

### 4.2 Maximum Communication Range:

For an SNR threshold of (10 dB), the estimated maximum communication ranges are:



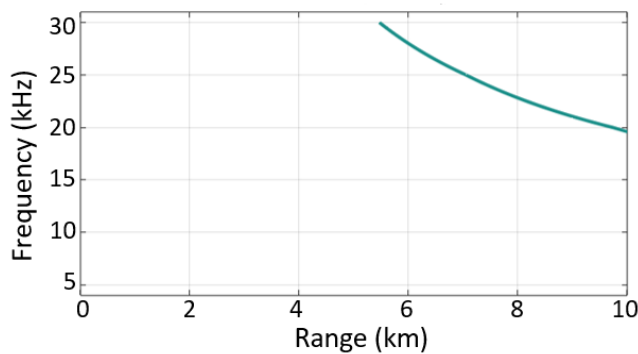
**Figure 5.** Maximum Communication Range - Frequency. Lower frequencies (~5 kHz) reach 8-9 km, while frequencies above 20 kHz are limited to 1-3 km.

- 5 kHz → ~8.9 km
- 10 kHz → ~6.2 km
- 15 kHz → ~4.4 km
- 20 kHz → ~3.2 km
- 25 kHz → ~2.3 km
- 30 kHz → ~1.7 km

The results indicate that operating at 5 kHz provides nearly a fivefold increase in maximum communication range compared to 30 kHz under identical noise and source level conditions.

These results indicate that low-frequency acoustic signals are more suitable for long-range, deep-water communication.[13]

### 4.3 SNR Boundary Contour

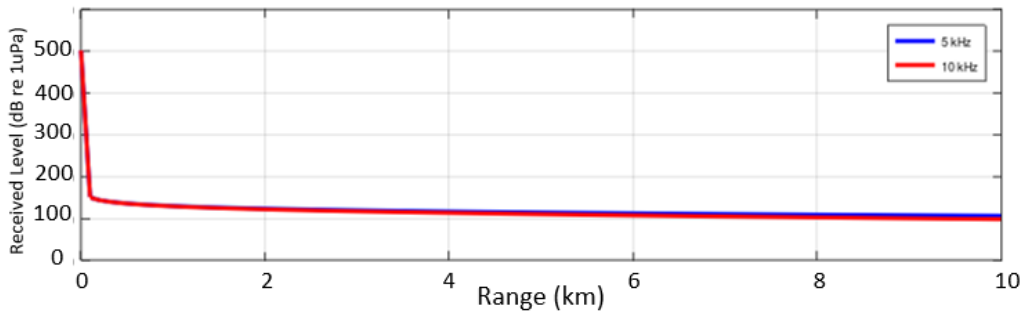


**Figure 6.** Contour SNR=10 dB (usable boundary) defines the usable communication region for reliable data transmission.

The SNR = 10 dB contour delineates the operational boundary for reliable underwater acoustic communication.

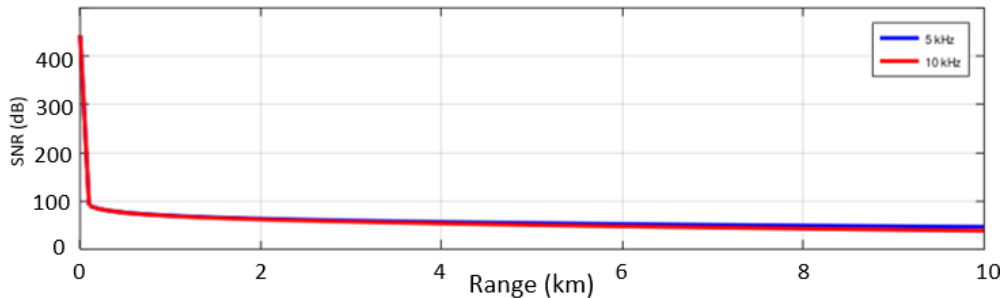
#### 4.4 Received Level and SNR vs. Distance:

A detailed analysis of received level ( $P_r$ ) and SNR over distance shows that low-frequency signals preserve both received power and SNR even at long ranges. Conversely, higher frequencies, although potentially providing higher data rates, decay rapidly and are thus better suited for short-range tasks such as local sensor networks or swarm AUV communications.[14]



**Figure 7.** Received Level – Range. The usable communication region for reliable data transmission.

The received level decreases monotonically with increasing propagation range due to geometric spreading and frequency-dependent absorption. The intersection between the received level curves and the ambient noise floor defines the practical communication limit, beyond which reliable data transmission is no longer feasible. As expected, lower-frequency signals maintain usable received levels over significantly longer distances compared to higher-frequency signals.



**Figure 8.** SNR versus distance illustrating rapid decay of higher-frequency energy.

The SNR versus range plot further illustrates the strong dependence of communication reliability on operating frequency. For low-frequency signals, the SNR remains above the 10 dB threshold over extended ranges, enabling reliable long-distance communication. In contrast, higher-frequency signals experience a rapid SNR degradation, limiting their effective use to short-range applications.

Together, the received level and SNR analyses clearly define the usable communication region for reliable data transmission in deep-sea AUV operations.

#### 4.5 Practical Implementation Insights:

- Piezoelectric transducers must be designed for the chosen low-frequency range to maximize emitted power.
- High-sensitivity hydrophones and signal-conditioning circuits are crucial for reliably detecting weak signals at long distances.

- These results inform the design of onboard modems, including frequency selection, encoding/decoding schemes, and SNR thresholds, to ensure reliable communication under high-pressure, deep-sea conditions.[5]

#### **4.6 Guidelines for Deep-Sea Operations:**

For an AUV moving at 4.5 knots (~2.3 m/s) in a typical deep-sea environment (temperature ~2°C, salinity 35 PSU), low-frequency acoustic communication is essential to maintain robust data links. Mission planners can utilize the calculated SNR and maximum range values to optimize route planning, communication scheduling, and sensor data collection.

Overall, this study provides both quantitative and practical guidance for designing, implementing, and operating reliable acoustic communication systems for deep-sea AUVs in offshore oil and gas applications, effectively bridging numerical modeling with real-world deployment. [4]

#### **4.7 System Components and Practical Implementation**

The AUV communication system is composed of:

- **Transducer (Acoustic Projector):** Converts electrical signals into acoustic waves, typically using a piezoelectric ceramic for deep-sea operation.
- **Hydrophone (Receiver):** Converts incoming acoustic waves into electrical signals; high sensitivity is essential for deep-water detection.
- **Signal Conditioning Unit:** Amplifies and filters received signals to improve SNR.
- **Controller / Modem:** Manages encoding/decoding, modulation (e.g., FSK, PSK), and timing, often integrated into the AUV's onboard industrial computer.
- **Mounting / Isolation:** Mechanically couple's transducers and hydrophones to the hull with vibration-isolating mounts to minimize self-noise.

#### **4.8 Installation Notes:**

- Transducers are usually installed in forward-facing or omnidirectional arrays to optimize coverage and reduce shadow zones.
- Depth-rated components are required, capable of operating at 6000 meters (~600 bar).
- Reference system: HUGIN 6000 AUV acoustic modem (Kongsberg Maritime), which uses piezoelectric projectors and hydrophones for deep-sea telemetry.

### **5. Discussion**

These findings are consistent with previous studies on deep-sea acoustic propagation, particularly the work of Stojanovic [1], which highlights the dominant role of frequency-dependent absorption in limiting long-range underwater communication.

simulation results confirm that low-frequency acoustic communication is significantly more effective for deep-sea AUV missions. Although higher frequencies can support greater data rates, their limited propagation range restricts their application to short-range operations.

hermore, the SNR thresholds derived from the numerical model provide practical design guidelines for assessing link reliability and optimizing communication scheduling in real-world deep-sea AUV missions.

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