Integration of the ahoi Modem into the MOLA Seafloor Lander System: Concept, Realization and Real-World Trials

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Abstract

Seafloor landers are used for various marine research and exploration applications. Most available ocean landers are large, heavy and expensive, and their operation requires vessels with heavy-duty cranes for deployment and recovery. We present the Modular Ocean LAnder (MOLA), a small and low-cost ocean lander system, which integrates an *ahoi* modem to enable low-cost underwater acoustic communication. We first describe the hardware and software integration of the *ahoi* modem in the MOLA system. Due to the limited operation depth of the *ahoi* modem's default transducer, we explore alternative transducers with different specifications for the system. We present the results of a real-world, deep-sea evaluation of our system offshore Sicily in the Mediterranean Sea. Using transducers with appropriate depth ratings, we achieved stable vertical communication links up to 1000 m depth. Furthermore, we deployed a network of three MOLAs at 165 m to 185 m depth on the seafloor. The communication link was stable for most communication baselines and we successfully triggered the release mechanism for coming up with an acoustic packet and recovered all MOLAs. Finally, we outline the next steps of our development.

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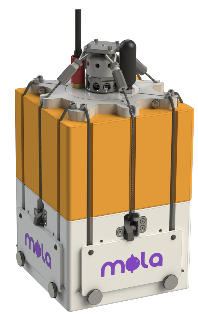


Figure 1: CAD model of the Modular Ocean LAnder (MOLA).

1 Introduction

71 % of the Earth's surface is covered by water of the oceans, which contain 97 % of the Earth's water [14]. Although better knowledge of the ocean is key to understanding the effects of climate change, understanding marine life or assessing natural hazards, only a fraction of the seabed has been explored because the equipment needed to explore the ocean is expensive and requires research vessels with high personal cost. However, during the last years the research on low-cost underwater modems and localization allowed novel concepts for distributed underwater data acquisition [3, 11]. Our research contributes to the field of low-cost underwater communication and measurement equipment. In this paper, we discuss the integration of the *ahoi* modem [18] into the MOLA system. The initial development of the MOLA system (see Fig. 1) was motivated by the idea of building a low-cost ocean-bottom seismometer (OBS). Currently used OBSs are large and expensive, which restricts the number of OBSs in a measurement setup and thereby limiting spatial resolution and network extents. Furthermore, current OBSs record the data passively, and data analysis and processing only

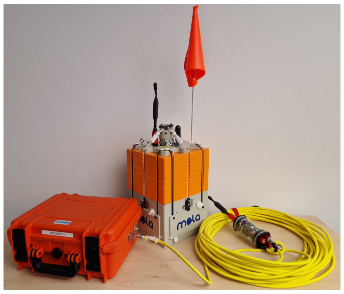


Figure 2: MOLA with deck box and *ahoi* modem.

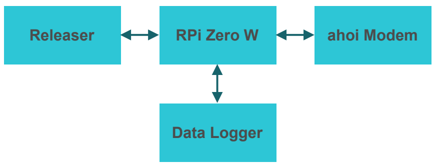


Figure 3: Actual MOLA electronic hardware structure. It is planned to combine data logger and RPi and use a lightweight MCU.

occur after the recovery of the systems, often months to years after the deployments. While conventional OBS systems can operate in up to 6000 m depth for up to a year (or longer), the MOLA system is designed for water depths of up to 1000 m and measurement durations of weeks to a few months (depending on sensor type and settings). This reduces the material and production cost significantly, thus allowing a higher sensor density or network size with the same budget. This increases the spatial resolution and reduces the financial access barriers access to seafloor measurement technology significantly. The MOLA system is designed to be equipped with various sensor types, including temperature, pressure, tilt, and chemical sensors. Furthermore, the integrated *ahoi* modem allows research on underwater communication and networking protocols. The MOLA was already used in [21] to evaluate a novel acoustic frequency shift chirp modulation (FSCM) implementation. Moreover, it is planned to integrate onboard artificial intelligence (AI) for data processing and event detection. An AI-based earthquake detection for the MOLA is currently under development [23].

Integrating an acoustic underwater modem is essential to enable communication between a base station or the landers in an underwater wireless sensor network (UWSN). For example, an acoustic packet triggers the release system of the MOLA for recovery or the transmission of sensor readings to a base station. We decided to integrate the *ahoi* modem. Several low-cost and low-power acoustic underwater modems have been developed over the last years. Reviews of these modems are given in [3, 4]. Recent examples of other modems are the *Nanomodem* [19], *FAU modem* [9], or *Xiamen University modem* [5]. The Nanomodem has an horizontal range of up to 2 km. The data rate depends on the modulation scheme and hardware version of the modem and is 40 bit/s respectively 640 bit/s. A data rate of 100 bit/s provides the FAU modem with a maximum horizontal range of 50 m. Finally, the Xiamen University modem has up to 300 bit/s data rate and a 500 m horizontal communication distance. However, most acoustic underwater modems have been evaluated over a horizontal communication link. For the MOLA system, a vertical and horizontal communication link is required.

In general, the requirements for underwater communication in the MOLA system are: (1) Low power consumption for long-term measurement campaigns. (2) Up to 1000 m vertical communication and depth rating. (3) Applicable as an UWSN. (4) Highly reliable communication link. (5) Low component costs compared to the overall cost of the lander.

Table 1: Physical dimensions of the MOLA.

Parameter	Value
Size	220 mm × 220 mm × 310 mm
Weight before release	14.1 kg (air)
Weight after release	10.7 kg (air)
Depth rating	1000 m

Contributions and Organization

We present MOLA and the integration of the *ahoi* modem into the system. We compare four different transducers for acoustic underwater communication with depth ratings between 200 m and 2000 m, different transmission frequency ranges and directivity patterns.

Moreover, we describe the MOLA system architecture, the hard- and software for underwater communication, and future communication networks. Finally, we evaluate our system during a scientific cruise with the research vessel RV Meteor. We show that a reliable communication link is achievable down to a water depth of 1000 m.

2 Concept

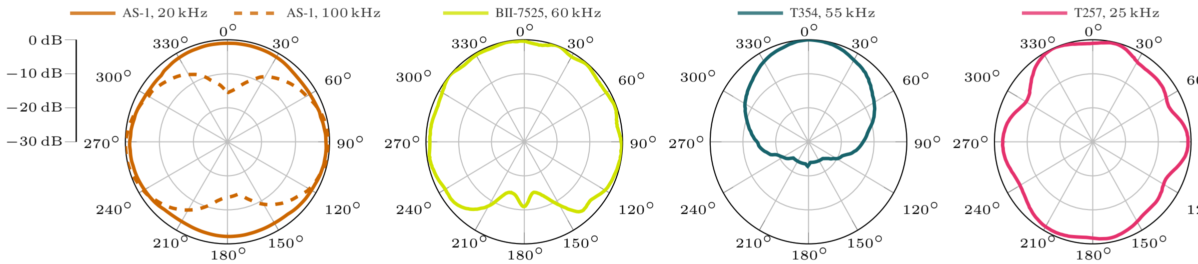
Next, we introduce the MOLA system and the *ahoi* modem. Each MOLA carries an *ahoi* modem for communication in a network of MOLAs or to a base station. Figure 2 shows a MOLA and deck box with an external *ahoi* modem.

2.1 MOLA Lander

The physical dimensions of the MOLA lists Table 1. All electronic components and batteries are placed inside a watertight pressure housing. The hardware structure is shown in Fig. 3 and consists of a data logger, Raspberry Pi (RPi) Zero W, releaser, and *ahoi* modem. The GEOLOG data logger records the samples of three geophones (in XYZ-directions) and a hydrophone on an SD card. The system has already been used in many OBS measurement campaigns. It is equipped with a high-precision real-time clock, synchronized at the beginning and end of a measurement campaign with the GPS. Assuming a linear clock drift, the drift can be removed based on the difference between the synchronizations at the beginning and end. The data logger runs independently of the RPi.

The releaser electronic controls the release mechanism of the MOLA for recovery. The mechanism drops additional weight, fine gravel in this case, and the MOLA returns to the sea surface. It has a dedicated, low-power microcontroller unit (MCU). If the releaser receives a release command from the RPi, it triggers the release mechanism. As a backup system, the releaser has an independent clock and a pre-programmed time-based trigger to enable the release mechanism.

The RPi connects all components and runs the control software for the releaser and *ahoi* modem. For example, if the *ahoi* modem receives a release command, the software on the RPi processes the command and forwards it to the releaser. Outside the water, the RPi is connected to a wireless local area network (WLAN) to configure releaser and data logger, to upload the data from the SD card, and



(a) Aquarian Scientific AS-1 **(b) Benthowave BII-7525** **(c) Neptune Sonar T354** **(d) Neptune Sonar T257**

Figure 4: Directivity pattern based on the datasheets [1, 2, 15, 16]. The damping factor is plotted on the left side.

Table 2: Comparison of different transducers, selected for the real-world trials. The FFVS and TVR are listed in dB re 1 µPa/V@1 m, respectively dB re 1 V/µPa. *BW* is the frequency range for transmission and *spacing* the spacing of the FSK symbols.

Transducer	Depth	Size	TVR	FFVS	Direc.	BW	Spacing
Aquarian Scientific AS-1 [1]	200 m	12 mm (d) x 40 mm (h)	132 dB at 60 kHz	−208 dB at 60 kHz	omni./toro.	50—75 kHz	781.250 Hz
Benthowave BII-7525 [2]	500 m	35 mm (d) x 38 mm (h)	147 dB at 60 kHz	−203 dB at 60 kHz	omni.	50—75 kHz	781.250 Hz
Neptune Sonar T354 [15]	1500 m	48 mm (d) x 36 mm (h)	156 dB at 55 kHz	−189 dB at 55 kHz	conical	45—70 kHz	781.250 Hz
Neptune Sonar T257 [16]	2000 m	55 mm (d) x 60 mm (h)	136 dB at 25 kHz	−191 dB at 25 kHz	toroidal	19—31 kHz	390.625 Hz

to control software on the RPi. It is planned to combine data logger and RPi in the future and use a lightweight MCU for logging and processing.

2.2 *ahoi* Modem

The *ahoi* modem [18] is a small, low-power and low-cost acoustic underwater modem, developed for the integration into micro autonomous underwater vehicles (μAUVs) or UWSNs. The modem consists of three stacked printed circuit boards (PCBs) with an overall size of 50 mm × 50 mm × 25 mm and approximately €200 component cost. The first PCB includes a CortexM4 MCU, power supply and external connections. The second PCB works as the receiver and involves amplifiers, a bandpass filter, and an analog-to-digital converter (ADC). The pre-amplifier and bandpass filter have a gain of 56.6 dB. The second amplifier gain can be adjusted by the MCU in the range from 0 dB to 36 dB in 2 dB-steps. A software-based automatic gain control (AGC) is used in the default setup to adjust the amplifier gains. The third PCB is the transmission board, which includes a digital-to-analog converter (DAC) converter and a power amplifier with 29 dB V_{rms} output. The power consumption in idle and receive mode is around 300 mW, and up to 5 W during data transmission. The default transducer is an Aquarian Scientific AS-1 broadband measurement hydrophone [1]. The *ahoi* modem was previously deployed in shallow-water scenarios with a horizontal communication link. A reliable communication link was established in these scenarios up to 200 m. Moreover, in [7], up to 300 m with a low packet reception rate (PRR) was observed.

Signal processing is realized in software on the MCU, which allows for a fast reconfiguration of frequency and coding setups. The *ahoi* modem uses a packet-based communication starting with a preamble and a starting frame delimiter (SFD) to apply a per-packet synchronization. Afterwards, a header of 6 B and optional payload are transmitted. The 6 B header contains the source, destination, packet type, sequence number, flag register, and payload length, each with a single byte. For transmission, a binary frequency shift keying (BFSK) parallel with different frequencies (similar to orthogonal frequency-division multiplexing (OFDM)) is implemented. Therefore, each symbol of 2.56 ms consists of four superimposed sinusoidal waveforms. To counter frequency fading caused by the multipath propagation channel (MPC), each symbol is repeated three times. In addition, frequency hopping spread spectrum (FHSS) is applied using a hopping scheme, which is adapted to the symbol repetitions. The combination of repetitions and FHSS distributes the bits over a wider bandwidth and addresses frequency cancellations. Overall, the modem has 25 kHz bandwidth with 781.25 Hz frequency spacing around a central frequency of 62.5 kHz. The default setup, in combination with an extended Hamming code, leads to a net data rate of 260 bit/s.

It is possible to use different transducers with the *ahoi* modem. The modem compensates for the frequency-dependent transducer characteristics based on pre-programmed lookup tables (LUTs). The compensation provides an equal frequency distribution at the receiver side.

2.3 Transducer Selection

Since the default transducer (Aquarian Scientific AS-1) has an operational depth rating of 200 m and a survival depth of 350 m, a different transducer compatible with the *ahoi* modem is required for deeper deployments. All evaluated transducers are listed in Table 2, directivity pattern and frequency characteristics are plotted in Figs. 4 and 5. The AS-1 comes with the lowest size and price. At 20 kHz it has an omnidirectional and at 100 kHz an toroidal directivity (see Fig. 4a). In the transmission bandwidth from 50 kHz to 75 kHz, the directivity characteristics are neither strictly omnidirectional nor toroidal. Compared to the other transducers, the AS-1 has the lowest free-field voltage sensitivity (FFVS) and transmission voltage response (TVR). The second tested transducer was the Benthowave BII-7525 [2] with 500 m depth rating. The BII-7525 has a nearly omnidirectional directivity. FFVS, TVR are in the middle between AS-1 and T354. Due to the small electrical impedance of the

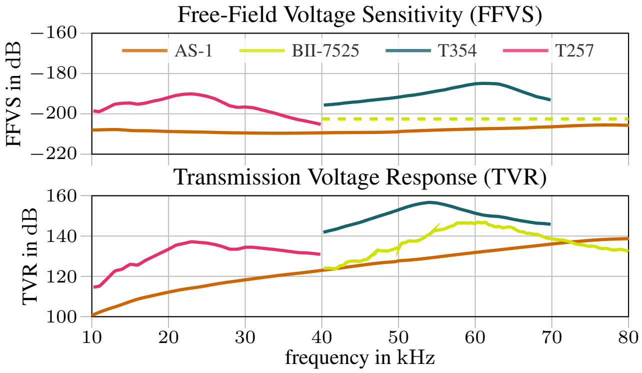


Figure 5: FFVS in dB re 1 µPa/V@1 m and TVR in dB re 1 V/µPa based on the data sheets [1, 2, 15, 16]. The manufacturer of the BII-7525 a single value for the FFVS, which is represented by the dashed line.

BII-7525, it is required to reduce power amplifier output by 6 dB to 23 dB V_{rms}. For communication, the frequency range from 50 kHz to 75 kHz is selected, which enables compatibility with modems with AS-1 transducers. The Neptune Sonar T354 [15][1] is rated for 1500 m depth and has a conical directivity pattern (see Fig. 4c). The T354 is selected for applications with huge depths where a stable up and downlink is required. Since the T354 has the highest TVR around 55 kHz, the transmission range is set to 45 kHz to 70 kHz. Finally, Neptune Sonar T257 [16] is the biggest transducer with the highest depth rating of 2000 m. It has toroidal directivity, which is nearly omnidirectional. The T257 is selected to evaluate the communication in a lower frequency range. The frequency-dependent attenuation increases with frequency [22], for example at 25 kHz the attention is 6.1 dB/km and 19.7 dB/km at 55 kHz. Therefore, lower frequencies are usually selected for long-range communication. To integrate the T257, the bandpass filter on the receiver PCB is modified. Due to the smaller bandwidth of the T257, the frequency spacing is reduced to 391 Hz and the transmission bandwidth is set to 19 kHz to 31 kHz. Another important aspect is the cost per transducer because the MOLA system is designed to be low-cost. In general, the availability of affordable transducers is limited. The AS-1 is the cheapest transducer. followed by the BII-7525, T354, and T257. The prices of BII-7525, T354, and T257 are in the same order and circa three times more than the AS-1.

2.4 *ahoi* Modem Integration

The PCBs of the *ahoi* modem are placed inside the pressure tube of the MOLA and the transducer on top of it. For the connection between transducer and *ahoi* modem, a underwater connector is used for simple change of the transducer type.

Inside the pressure tube, the *ahoi* modem is connected to the RPi via universal asynchronous receiver-transmitter (UART) (see Fig. 3). The *PyLib* [10], an open-source Python application programming interface (API) for the *ahoi* modem, was used to develop an application for the RPi inside MOLA. Different control commands, e. g., for release, flash the light on top of the MOLA, or sensor readings, were defined and implemented. For proof of the concept of sensor readings, the application reads the central processing unit (CPU) usage and temperature, memory and disk usage of the RPi and

[1]The reference is for the Neptune Sonar T204, but the T354 has identical characteristics to T204.

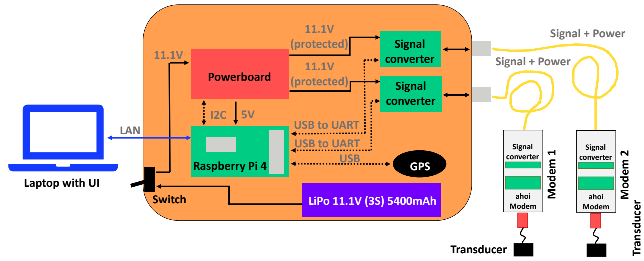


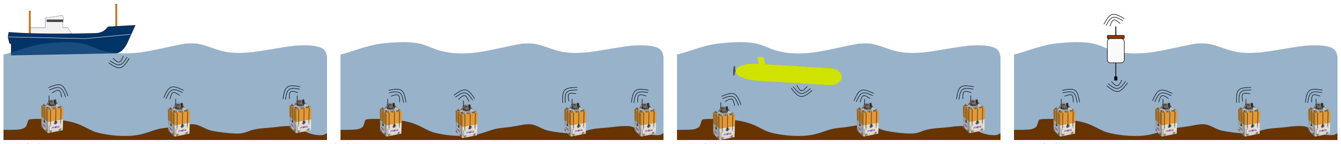
Figure 6: Structure of the deck box with two external *ahoi* modems. The second modem was used for evaluations with different transducers. In the final application, a single modem is required. The second modem can be used as a backup device.

transmit them to surface. Moreover, the application on the RPi logs all transmitted and received packages for further analysis, e. g., PRR or gain settings.

2.5 *ahoi* Modem Deck Box

In the following, the communication between the vessel and the submerged MOLAs is discussed. The concept is illustrated in Fig. 6. A small waterproofed deck box (orange case) is placed on deck of the vessel to forward the data packets from a laptop to a modem or vice versa. The concept in Fig. 6 consists of two *ahoi* modems. The second modem was used for evaluations with different transducers. In the final application, a single modem is required.

The *ahoi* modem and an additional signal converter PCB are placed inside a BlueRobotics 2"-Watertight Enclosure and connected with a 25 m long BlueRobotics Fathom ROV Tether to the deck box. The tether carries four unshielded twisted pairs of 26AWG wire. Two pairs (one for the ground and one for the supply voltage) are used for the modem's power supply. A single wire has circa 130 mΩ/m resistance. Since the setup uses two wires in parallel, the entire cable resistance (back and forth) over 25 m is 3.25 Ω. In the case of a transmission with the maximum transmission power of 5 W and 12 V at the modem, the cable loss is 1.35 V. The loss is still in the specifications of the voltage converters on the *ahoi* modem. Three capacitors on the signal converter PCB with 1000 µF per unit stabilize the supply voltage against fast voltage drops. It is important to note that a transmission power of 5 W is a peak value only in the actual configuration. For longer cable lengths, it might be useful to place the supply battery inside the submerged tube or to use cables with larger cross sections, and therefore, lower resistance. The *ahoi* modem has a UART for data exchange with 3.3 V logic level and 115 200 Bd. To avoid distortions over the 25 m cable, the UART signal is transmitted differentially over two twisted pairs. Inside the submerged modem, an Analog Devices MAX3490 on the signal converter PCB converts the signal to the standard UART of the modem. A high-power red green blue (RGB)-LED is installed on the enclosure, to get some basic information from the submerged modem. The LED changes the color if the modem transmits or receives an acoustic packet or the modem receives a packet from the host. Inside the deck box, two signal converter PCBs are used for the connection to the external modems. The PCBs generate the differential signal with a MAX3490 and provide protection functions like over-current, under-voltage, and digital isolators for the data lines. The interfaces of the converter PCBs, UART connections, are connected to the RPi. Transmission control protocol (TCP) servers



(a) Link between RV and MOLAs. (b) Communication between the MOLAs. (c) Data collection with an AUV. (d) Over-water data forwarding.

Figure 7: Underwater communication network structures for different use cases.

forward the serial connections over local area network (LAN) to a laptop with user interface (UI). The global positioning system (GPS) receiver in the deck box can be used for position tracking. Furthermore, a message queue telemetry transport (MQTT) broker runs on the RPi inside the deck box. MQTT is used to exchange messages in the LAN between different applications.

The entire setup is powered by a three cell lithium polymer (LiPo) battery with 11.1 V nominal voltage and 5400 mA h capacity. The operating time is dependent on the modems usage. On average, the battery can power the setup for more than 8 h. The battery is connected to the power board PCB inside the deck box for protection of the battery and the connected devices against short circuits, over current, under voltage. Furthermore, the power board generates a stable 5 V supply voltage for the RPi and measures internal temperature, and battery voltage and current. The measurements can be read with the RPi and displayed on a connected laptop to monitor the entire setup.

2.6 User Interface and Communication Concept

The actual UI is a command line interface (CLI) based on the *modem shell (MoSh)*, an application from the PyLib. The MoSh was developed to set up the *ahoi* modem and transmit packets from a CLI. It is planned to build a graphical UI for a better user experience.

For the communication with MOLAs, we defined packet types (see Section 2.2), e. g., for release, sensor readings, or test measurements. The packet destination byte inside the header allows to address a specific MOLA. As an example, the command to trigger the release mechanism of MOLA 1 is *mola-release 1*. The UI generates a packet with the specific type for release, destination of one and a flag, which ask for an acknowledgment (ACK). If MOLA 1 receives the packet, it transmits an ACK to the base station to confirm the packet reception. Otherwise, the command can be repeated.

For sensor readings, the measured value is inside the packet payload. It is important to keep the packet length as short as possible to avoid the channel being occupied for a long time. A packet without payload has a duration of 266 ms, and for example, with 8 B payload the duration is 573 ms. In addition to the commands for the MOLAs, the UI has functions for two-way ranging (TWR) and PRR evaluation. If the UI receives an acoustic packet from a lander, the information is forwarded to an MQTT broker (see Section 2.5) to share it with other applications or for displaying sensor readings or distances in an MQTT-based data visualization application.

2.7 Network Structures

It is considered to use numerous MOLAs inside a measurement topology. Different topologies require several underwater network structures and medium access control (MAC) protocols. Four examples are illustrated in Fig. 7. Until know, the setup works without MAC protocol. This section discusses future applications.

First, in Fig. 7a a direct communication link between research vessel (RV) and submerged MOLAs is established. Examples are the release commands, sensor readings, or system setup commands. In these examples, the user sends commands via the UI (see Section 2.6). Since the user enter a single command per time, an MAC protocol is not essential.

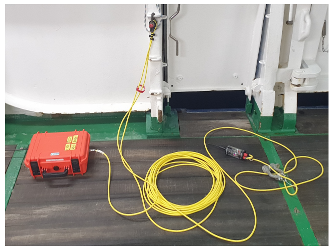
In Fig. 7b, a communication in a network of MOLAs is established. For example, an AI-based detection algorithm is running on all MOLAs for data processing. If a MOLA notices an event, the MOLA shares the event with the other MOLAs. Afterward, all MOLAs in the network could use the received events, e. g., to adjust the detection sensitivity or calculate the source of the event. In this case, a MAC protocol is required to avoid packet collisions. To remain with the example of event detection, if all MOLAs transmit a packet directly after detection, the packets might collide if the event occurs simultaneously (or with a time difference shorter than the packet duration and travel time). A solution could be unique or random waiting times before transmission, similar ALOHA with random backoff [17]. Another option is time division multiple access (TDMA), where a time slot is assigned to each MOLA.

Another application could be data collection with an autonomous underwater vehicle (AUV) or autonomous surface vehicle (ASV) (see Fig. 7c). In this example, the MOLAs are placed over a wide area, and it could be possible that the distance between the MOLAs is larger than the maximum communication distance. A vehicle is used to collect the data from the lander. An appropriate underwater protocol has already been presented [20] and evaluated in the real-world with *ahoi* modems [7].

For live monitoring, a router station between underwater and over-water communication is mandatory. In Fig. 7d, a buoy is equipped with an underwater modem and over-water radio frequency (RF) transceiver, e. g., LoRaWAN or satellite communication. Acoustic messages, e. g., sensor readings or detected events are forwarded over the RF link. Similarly to that, received RF messages, e. g., control commands or sensor reading requests, are forwarded to the submerged MOLAs via acoustic underwater communication. A real-world implementation of LoRaWAN-based over-water network and an acoustic underwater network is discussed in [12]. A simulation of underwater data collection with an AUV and forwarding over buoys with LoRaWAN is described in [13].

The selection of a MAC protocol dependents on the application and the topology of the network. It is planned to implement MAC protocols for the MOLA architecture. In the following evaluation, a scenario similar to Fig. 7a is considered. However, the results from the evaluation are essential for future network designs to identify the maximum throughput and communication range. In more advanced network configuration the concept of the deck box from Section 2.5 could be integrated into a surface buoy or vehicle. Results of a comparable setup have already been discussed in [7].

(a) RV Meteor in front of Mt Etna



(b) Lattice box w. MOLAs (c) Deckbox with external *ahoi* modem

Figure 8: RV Meteor in front of Mount Etna made from an RHIB, which was used to collect the MOLAs after the free-water trial and measurement setup on RV Meteor.

3 Practical Evaluation and Discussion

The practical evaluation took place during the expedition M198 on board of RV Meteor in February 2024 [8]. Key objective of M198 was to conduct geophysical measurements of Mt Etna's partly submerged Eastern flank. Therefore, the expedition was in the Mediterranean Sea in front of Mt Etna.

3.1 Transducer Comparison

For the comparison of different transducers, we placed MOLAs inside a lattice box and the deck box on the RV Meteor. To avoid reflections from the bottom of the lattice box, we selected a lattice box without metal base. A crane of the RV Meteor allowed lowering the lattice box with MOLAs to different depths to test the vertical up- and downlink with *ahoi* modems and the transducers from Section 2.3. Figure 8 shows pictures of the lattice box deployed with a crane and the deck box on RV Meteor. To measure the link quality, packets without payload and with requested ACK were transmitted to the submerged MOLA. The received packets were logged on the MOLAs and UI on RV Meteor. Both packets (downlink and uplink) have the same size. In previous evaluations, e. g., [7, 18], we noticed that the link performance can be estimated with the usage of header packets without payload.

The first test was a comparison of Aquarian Scientific AS-1 and Benthowave BII-7525. We placed two MOLAs in the box. The first MOLA was equipped with an AS-1 and the second with a BII-7525. Similar to that, we connected two modems with AS-1 and BII-7525 to the deck box. The results are depicted in Fig. 9, where we compared the PRR and the amplifier gain of the second adjustable amplifier of the *ahoi* modem (see Section 2.2) for different depths. The depths are the rope length under the water surface of the crane. For each depth and transducer, we transmitted 250 packets with ACK request. We did not compare cross-talk between the different transducers. We started with 50 m rope length. The MOLA with AS-1 received 83 of 250 packets (33.2 % PRR downlink) and the modem under the RV Meteor received 57 of 83 ACK packets (68.7 % PRR uplink). The BII-7525 had 62.8 % PRR for the downlink

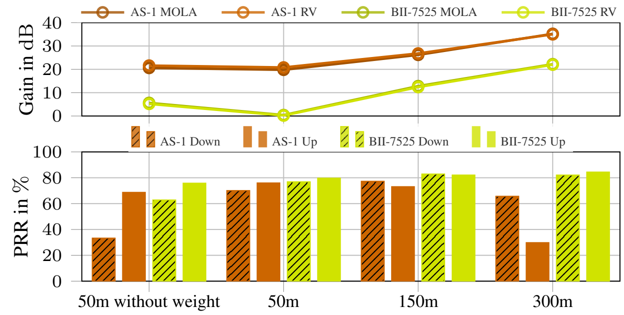


Figure 9: Comparison between Aquarian Scientific AS-1 and Benthowave BII-7525 inside the lattice box. The x-axis is the rope length of the crane under the water surface.

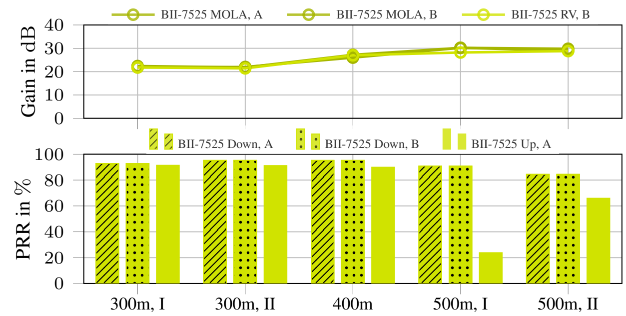


Figure 10: Evaluation of Benthowave BII-7525 inside the lattice box. The x-axis is the rope length of the crane under the water surface. The labels I and II indicate two trials at the same depth. MOLA A was the active part, and MOLA B listened to the packets only.

and 75.8 % PRR for the uplink. During the first trial at 50 m, we observed that the water current pushed up the modems from the RV Meteor near the water surface and ship hull. After adding some weight to the modems, the PRR for AS-1 and BII-7525 increased, e. g., from 33.2 % to 68.7 % (AS-1 downlink). The measured distance between modems under the RV Meteor and MOLAs with the built-in ranging function of the *ahoi* modem reduced from 42.6 m to 40.4 m (AS-1) respectively from 43.2 m to 36.6 m (BII-7525) at a constant speed of sound of 1513 m/s. Therefore, the modems had a more considerable distance to the water surface. For 50 m and 150 m, both transducers had comparable PRRs between 70.0 % to 82.8 %. At 300 m depth, the PRR of the AS-1 is reduced and shows an asymmetrical behavior (65.6 % downlink, 29.8 % uplink). However, 300 m was more than the given operating depth of 200 m (350 m survival depth, see Section 2.3). Moreover, Fig. 9 shows the receiving amplifier gains. The difference between the amplifier gains for AS-1 and BII-7525 is 15.7 dB on average in Fig. 9. The BII-7525 had 5 dB higher FFVS than the AS-1 and 15 dB higher TVR (see Table 2). Due to the low impedance of the amplifier output was reduced by 6 dB for the BII-7525 (see Section 2.3). In sum, the difference between AS-1 and BII-7525 was 14 dB, which matched the described difference of 15.7 dB in the amplifier gains. The remaining difference of 1.7 dB might result from the different directivity patterns (see Fig. 4) and frequency-dependent characteristics (see Fig. 5).

Afterward, we recovered the AS-1 transducer and replaced the AS-1 with a second BII-7525. The results are shown in Fig. 10. Compared to the previous trial (see Fig. 9), the PRRs for 300 m were slightly better. During the trial, we observed a lower water current

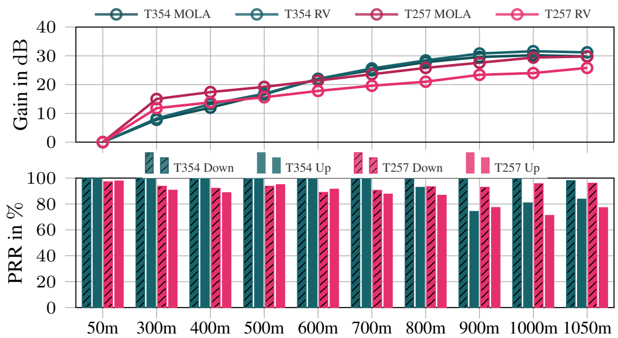


Figure 11: Comparison between Neptune Sonar T354 and Neptune Sonar T257 inside the lattice box. The x-axis is the rope length of the crane below the water surface.

and measured 282.6 m distance between MOLA and upper modem at 300 m rope length (17.4 m difference). Compared to that, the difference for the first trial with higher current was between 13.4 m to 15.0 m. Therefore, the modems had a more considerable distance to the water surface. The results for 400 m depth (379.8 m distance) were comparable to 300 m. But at 500 m depth (479.1 m distance) the uplink was significantly reduced to 23.8 %, respectively, 65.9 %, and showed an asymmetrical behavior (similar to the AS-1 at 300 m). This was unexpected because the BII-7525 has a rating of 500 m.

Finally, the Neptune Sonar T354 and Neptune Sonar T257 were compared in Fig. 11. First, we went down to 50 m. The PRRs for up- and downlink with T354 were both 100 %, and 97.0 % (downlink) and 97.9 % (uplink) for T257. The AGC adjusted the gain of the adjustable amplifier to 0 dB, which is circa 21 dB lower than the gain for the AS-1 at 50 m. However, the FFVSs are 19 dB (T354), 17 dB (T257), and the TVR 24 dB (T354), respectively 4 dB (T257) higher than the characteristics of the AS-1 (see Table 2). Down to 700 m (674.6 m distance with a constant speed of sound of 1516 m/s), we observed 100 % PRRs for up and downlink with T354 and PRRs above 87.6 % for T257. For more than 700 m, we noticed a slightly asymmetrical behavior (similar to the AS-1 at 300 m and BII-7525 at 500 m). But the PRRs are still above 74.2 % (T354) respectively 71.1 % (T257) in all cases. At 1050 m we transmitted 50 packets instead of 250, to show that it is possible to have communication distances of more than 1000 m. We measured distances of 1017.4 m (T354) and 1017.6 m (T257). The AGC values of both transducers showed an essential aspect of the different transmission frequencies. The *ahoi* modem with the T354 transmitted in the range from 45 kHz to 70 kHz and with the T257 from 19 kHz to 31 kHz (see Section 2.2). The FFVSs were almost similar, the FFVS of T354 was 2 dB higher than the FFVS of T257. The TVR of T354 was 20 dB higher than the TVR of T257. On the other hand, the frequency-dependent attenuation was 6.1 dB/km at 25 kHz and 19.7 dB/km at 55 kHz (see Section 2.3). For smaller distances, the AGC adjusted a higher gain level for the T257 than the gain for T354. For larger distances, the gain for T354 was higher than that of T257. In contrast to all other transducers, the gains of the AGC for T257 showed a larger difference between the gain at the MOLA and the gain at RV Meteor. The reason was unclear and needs further investigation. It could result from the ambient noise level, which is higher for lower frequencies [22]. In the region from 1 kHz to 100 kHz, sea state noise caused by wind and waves is the dominant noise source. It might be possible that

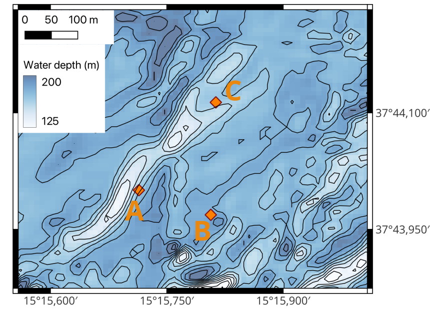


Figure 12: Bathymetry map with the position of the MOLAs on the seafloor. The bathymetry data is based on [6].

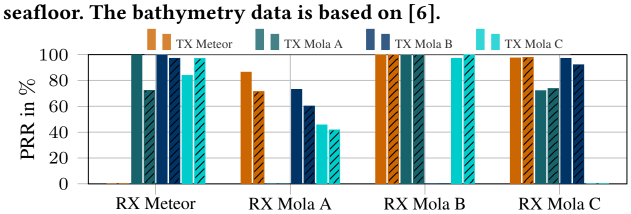


Figure 13: Results of the free-water trial with three MOLAs and RV Meteor. All *ahoi* modems were equipped with AS-1 transducer. Bars without shading are the PRRs from the first round, and bars with shading from the second.

the signal level at RV Meteor was higher due to additional noise, and the AGC selected a lower gain.

In summary, the AS-1 showed an high PRR down to 150 m. However, even at 300 m (100 m more than the operating depth in the data sheet) the AS-1 can be used for communication if a lower PRR is acceptable. Unfortunately, the BII-7525 showed a relevant performance reduction already before reaching its maximum depth rating of 500 m. For larger depths, the T354 and T257 showed convincing results with high PRRs down to 1000 m. According to the evaluations, we selected the AS-1 for shallow water and T354 or T257 for deep water applications.

3.2 Free-Water Test

In our last trial, we deployed three MOLAs (MOLA A, B, and C) on the seafloor at depths between 165 m and 185 m. Each MOLA was equipped with an AS-1 transducer for communication with the *ahoi* modem. A map of the setup shows Fig. 12. The distances between the MOLAs were circa 150 m (MOLA A to MOLA B), 255 m (MOLA A to MOLA C), and 270 m (MOLA B to MOLA C). We calculated the distances based on the way points of the RV Meteor. The deployment position might differ from the values.

After the deployment, we conducted two experiments. Before the experiments, the RV Meteor held position, which caused the *ahoi* modem under RV Meteor to be pulled to the maneuvering thruster, and thus we had a bad communication link. After turning off the thruster, the RV Meteor slowly drifted with the water current and we measured a better link to the submerged MOLAs. The distances between RV Meteor and the MOLAs were 235 m–275 m (MOLA A), 215 m–230 m (MOLA B), and 230 m–235 m (MOLA C) in the first round and 265 m–300 m (MOLA A), 225 m–240 m (MOLA B), and 235 m–250 m (MOLA C) in the second evaluation round. In each round, we transmitted 100 packets with ACK requests to each MOLA. The other MOLAs and the RV Meteor logged all received packets from all sources. For example, if the RV Meteor transmitted

100 packets to MOLA A and MOLA A responded with 90 ACK packets (90 % PRR in this example), the MOLA B and MOLA C were able to calculate the downlink from RV Meteor to themselves based on the packets for MOLA A and based on the ACK packets for RV Meteor, B and C were able to measure the link from MOLA A. The PRRs shows Fig. 13. The link quality was high for the communication between RV Meteor, MOLA B, and MOLA C. In all cases, the PRR was above 80 %. However, the PRRs between MOLA A and the other modems were lower and went down to 41.6 % (MOLA C to MOLA A). A topographic ridge between MOLA C and MOLA A may explain the reduced connection quality between these two landers, while there is no obvious explanation for the generally reduced performance of MOLA A.

At the end of the trial, we were able to trigger the release mechanism for all MOLAs from the RV Meteor without any problems and recover the three MOLAs with a rigid-hulled inflatable boat (RHIB).

4 Conclusion and Outlook

We introduced the MOLA, a small and low-cost lander platform for underwater sensors. The MOLA has an integrated *ahoi* modem for communication with a surface device and inside an underwater network of MOLAs. We discussed the selection of transducers for different applications described the hardware and software integration of the *ahoi* modem into the MOLA system. Finally, we evaluated the system during an expedition with the RV Meteor. We showed that providing a reliable vertical communication link down to 1000 m with transducers with an appropriate depth rating is possible. Furthermore, we demonstrated the use of low-cost transducers in a network on the seafloor at 165 m to 185 m water depth and communication distances inside the seafloor network between circa 150 m to 270 m.

The MOLA with integrated *ahoi* modem is an promising novel architecture and contributes to the trend of low-cost underwater research. We are convinced that the MOLA system is a versatile platform for the research on underwater networks and network protocols, as well as sensor networks for diverse ocean research applications. The reduced cost for the lander and deployment offers research groups with smaller budgets to carry out their own experiments. Another possibility is to increase the spatial measurement density with more sensor stations with the same budget. Our next steps are the implementation of an underwater network protocol to collect data from the submerged MOLAs and to forward the data via an over-water network. Furthermore, we want to integrate onboard AI event detection and reduce power consumption by replacing the RPi with an MCU and updating the electronic hardware.

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References

[1] Aquarian Scientific. [n.d.]. AS-1 Charts. https://www.aquarianaudio.com/AqAudDocs/AS-1_charts.pdf. last visited: 09/16/2024.

[2] Benthowave Instrument Inc. [n.d.]. Datasheet BII-7525. https://www.benthowave.com/products/Specs/BII7525Datasheet.pdf. last visited: 09/16/2024.

[3] F. Campagnaro, F. Steinmetz, and B.-C. Renner. 2023. Survey on Low-Cost Underwater Sensor Networks: From Niche Applications to Everyday Use. *J. of Marine Science and Eng. (JMSE)* 11, 1 (2023). https://doi.org/10.3390/jmse11010125

[4] F. Campagnaro, F. Steinmetz, B.-C. Renner, and M. Zorzi. 2023. Affordable underwater acoustic modems and their application ineveryday life: a complete overview. In *ACM International Conference on Underwater Networks & Systems (WUWNet)*. Shenzhen, China. https://doi.org/10.1145/3631726.3631734

[5] H. Chen, Y. Zhu, W. Zhang, K. Wu, and F. Yuan. 2022. Underwater Acoustic Micromodem for Underwater Internet of Things. *Hindawi Wireless Communications and Mobile Computing* 2022 (2022). https://doi.org/10.1155/2022/9148756

[6] F. L. Chiocci and D. Ridente. 2011. Regional-scale seafloor mapping and geohazard assessment. The experience from the Italian project MaGIC (Marine Geohazards along the Italian Coasts). *Marine Geophysical Research* 32 (2011), 13–23. https://doi.org/10.1007/s11001-011-9120-6

[7] E. Coccolo, C. Delea, F. Steinmetz, R. Francescon, A. Signori, C. N. Au, F. Campagnaro, V. Schneider, F. Favaro, J. Oeffner, B.-C. Renner, and M. Zorzi. 2023. System Architecture and Communication Infrastructure for the RoboVaaS Project. *Journal of Oceanic Engineering (JOE)* 48, 3 (July 2023), 716–739. https://doi.org/10.1109/JOE.2023.3234710

[8] German Research Fleet Coordination Centre. 2024. Weekly Reports and Short Cruise Reports. https://www.ldf.uni-hamburg.de/en/meteor/wochenberichte.html. last visited: 09/16/2024.

[9] J. Hermans, G. Sklivanitis, and D. A. Pados. 2022. A First-of-its-kind Low Size, Weight and Power Run-Time Reconfigurable Underwater Modem. In *6th Underwater Communications and Networking Conference (UComms)*. Lerici, Italy. https://doi.org/10.1109/UComms56954.2022.9905700

[10] Inst. for Autonomous Cyber-Physical Systems. [n.d.]. pylib. https://collaborating.tuhh.de/e-24/public/ahoi/pylib. last visited: 09/16/2024.

[11] Y. Jiang and B.-C. Renner. 2024. Low-Cost Underwater Swarm Acoustic Localization: A Review. *IEEE Access* 12 (2024), 25779–25796. https://doi.org/10.1109/ACCESS.2024.3357359

[12] G. J. Lowes, J. Neasham, B. Sherlock, and R. Burnett. 2023. Low-Power, Low-Cost LoRaWAN Gateway Buoy for use with Wireless Underwater Sensor Networks. In *MTS/IEEE Oceans Conference & Exposition (OCEANS)*. Limerick, Ireland. https://doi.org/10.1109/OCEANSLimerick52467.2023.10244344

[13] D. Magrin, A. Signori, D. Tronchin, F. Campagnaro, and M. Zorzi. 2020. Collaboration of LoRaWAN and Underwater Acoustic Communications in Sensor Data Collection Applications. In *MTS/IEEE Oceans Conference & Exposition (OCEANS)*. Biloxi, MS, USA (virtual). https://doi.org/10.1109/IEEECONF38699.2020.9389248

[14] National Oceanic and Atmospheric Administration (NOAA). [n.d.]. The Ocean. https://globalocean.noaa.gov/the-ocean/. last visited: 09/16/2024.

[15] Neptune Sonar Limited. [n.d.]. Datasheet T204. https://www.neptune-sonar.co.uk/downloads/758580c7-b062-4ddc-9a51-dfcdc9b983b8/T204.pdf. last visited: 09/16/2024.

[16] Neptune Sonar Limited. [n.d.]. Datasheet T257. https://www.neptune-sonar.co.uk/downloads/9eb8eb22-ab36-44f2-b640-f2d66005121f/T257.pdf. last visited: 09/16/2024.

[17] N. Parrish, L. Tracy, S. Roy, P. Arabshahi, and W. L.J. Fox. 2008. System Design Considerations for Undersea Networks: Link and Multiple Access Protocols. *IEEE Journal on Selected Areas in Communications (JSAC)* 26, 9 (2008), 1720–1730. https://doi.org/10.1109/JSAC.2008.081211

[18] B.-C. Renner, J. Heitmann, and F. Steinmetz. 2020. ahoi: Inexpensive, Low-Power Communication and Localization for Underwater Sensor Networks and μAUVs. *Transactions on Sensor Networks (TOSN)* 16, 2 (2020), 1–46. https://doi.org/10.1145/3376921

[19] B. Sherlock, N. Morozs, J. Neasham, and P. Mitchell. 2022. Ultra-Low-Cost and Ultra-Low-Power, Miniature Acoustic Modems Using Multipath Tolerant Spread-Spectrum Techniques. *MDPI Electronics* 11, 9 (2022). https://doi.org/10.3390/electronics11091446

[20] A. Signori, F. Campagnaro, F. Steinmetz, B.-C. Renner, and M. Zorzi. 2019. Data Gathering from a Multimodal Dense Underwater Acoustic Sensor Network Deployed in Shallow Fresh Water Scenarios. *Journal of Sensor and Actuator Networks (JSAN)* 8, 4 (2019). https://doi.org/10.3390/jsan8040055

[21] F. Steinmetz and B.-C. Renner. 2023. Practical Evaluation of Differential Frequency Shift Chirp Modulation for Acoustic Underwater Communication. In *ACM International Conference on Underwater Networks & Systems (WUWNet)*. Shenzhen, China. https://doi.org/10.1145/3631726.3631740

[22] M. Stojanovic and J. Preisig. 2009. Underwater acoustic communication channels: Propagation models and statistical characterization. *IEEE Communications Magazine* 47, 1 (2009), 84–89. https://doi.org/10.1109/MCOM.2009.4752682

[23] T. Zainab, J. Karstens, and O. Landsiedel. 2023. LightEQ: On-Device Earthquake Detection with Embedded Machine Learning. In *8th ACM/IEEE Conference on Internet of Things Design and Implementation (IoTDI)*. San Antonio, TX, USA. https://doi.org/10.1145/3576842.3582387