Short-Range Submarine Radio System for Localization of Remotely Operated Underwater Vehicles and Cave Divers in Fresh Water

Nicolas Troesch, Arnaud Vena, Benoît Ropars, Lionel Lapierre, Luc Rossi, Rémi Bouchard, and Brice Sorli

Abstract – This article presents the study of a new RF device operating in the high-frequency band for underwater localization of scuba divers and the development of exploration robots in karstic environments. The system, composed of a conductive breadcrumb thread connected to a signal generator for transmission and a mobile receiver based on a software-defined radio, is validated by experimental measurements in a real environment.

1. Introduction

The deployment of communicating devices is accelerating in homes, buildings, cities, and less-urbanized areas, but the marine world and freshwater reserves (karstic environment) are still little explored. However, understanding the evolution of these complex environments with the help of fixed or mobile communicating devices is of great interest. A karst environment consists of large cavities that form in the limestone. These cavities contain large reserves of fresh water but are difficult to access. Only cave divers can venture into them, and exploration is risky. To limit this risk, sending underwater exploration robots is an alternative, but the communication and geolocation solutions necessary for their development are rare in these extreme environments. It is not common to find studies on radio technologies for underwater environments. The main reason is that it is a difficult environment for electromagnetic waves, which cannot propagate over long distances due to the conductivity of water [1–5], unlike in free space. However, it would be a pity not to study the possibilities offered by radio waves in an underwater environment, especially considering the exceptional sensitivity performance offered by the latest radio modems or software-defined radios. For example, a LoRa node [6] can receive a signal down to –136 dBm and transmit with a power of 14 dBm, which offers us 150 dB of dynamic range. For applications of data transfer or localization at short distances (a few meters), radio systems can provide advantages over acoustic devices. Indeed, they are more energy-efficient, and the electromagnetic environment in the water is very little polluted. In this article, we study the possibility of setting up a radio localization system for underwater exploration robots and divers in karstic environments by using a conductive breadcrumb thread.

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2. Basic Principle and Design

2.1 EM Wave Propagation in Fresh Water and Seawater

The difficulty of transmitting a radio signal in water is related first to the strong reflection of waves at the interface between air and water. Second, an electromagnetic wave propagating in water is strongly attenuated due to the conductivity σ of the medium [1]. The attenuation factor α including the effect of σ can be calculated as

$$\alpha = \omega\sqrt{\varepsilon\mu}\left(\frac{1}{2}\left(\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}-1\right)\right)^{\frac{1}{2}} \tag{1}$$

In addition, as for free-space propagation, the energy from an electromagnetic source is distributed spherically, so that the signal strength (decaying at $1/d^2$, with d the distance) can be calculated as

$$L = 20\log_{10}\left(\frac{\lambda}{4\pi d}\right) \tag{2}$$

Finally, the following equation includes (1) and (2) to allow calculation of the received power in a lossy medium:

$$P_{rx} = P_{\tau x} + L + 10\log_{10}\left(e^{2\alpha d}\right) \tag{3}$$

The environment in which the system functions is fresh water, whose conductivity is close to 0.04 S/m—much lower than seawater's 4 S/m. As shown in Table 1, the attenuation (calculated with (1)) in fresh water is much more favorable to the propagation of radio signals and allows us to consider their detection at several tens of meters in the band from 1 MHz to 100 MHz.

Table 1. Theoretical attenuation of radio waves in water (dB/m) due to the conductivity of the medium (1)

Medium	1 MHz	10 MHz	100 MHz
Fresh water (0.04 S/m)	3.4	10.8	32.2
Seawater (4 S/m)	34.5	109.1	344.9

2.2 Localization System Based on a Submarine Bread-Crumb Thread

The system studied here is based on the use of a conductive bread-crumb thread, in which a continuous wave (CW) is injected with the help of a generator connected to one end. This wire is a source of radio waves distributed over the entire length of the cable, as shown in Figures 1a and 1b. Figure 1b shows a simulation result of the electric field (E-field) at 10 MHz generated by a 20 m long cable excited in the middle with a CW signal of power 1 W. Since the wire is not connected to any load, standing waves can be observed.

Simulation results shown in Figure 2 give the E-field strength at 10 MHz as a function of the distance from the cable up to 3 m. Results are given for three positions x along the cable (relative to the left end), according to the conductivity of fresh water and seawater. From 0 m to 3 m, we observe an attenuation of 50 dB for fresh water and 145 dB for seawater. Values obtained for $x = 0.5$ m, 1 m, and 1.5 m are similar, with a maximum difference of 5 dB in fresh water. This shows that we could detect a signal evenly along the cable.

The mobile receiver is composed of a short monopole antenna (50 cm long in an insulator) connected to a radio receiver inside a watertight cylinder, as shown in Figure 1a. Figure 3 shows S_{21} measurement results in fresh water (conductivity = 0.04 S/m) between the excitation port and the receiver according to horizontal and vertical orientation. Note that the radiating wire is 20 m long in this specific study, to ease the simulation step; for a real application, it is intended to be much longer. In the range from 0 m to 1.5 m from the cable, the horizontal orientation allows receipt of a larger signal, especially at 10 MHz, whereas the vertical orientation shows a curve almost flat after 3 MHz. From these results, one can see that a signal could be detected by a standard radio receiver up to at least 1.5 m for a radiating cable of length 20 m.

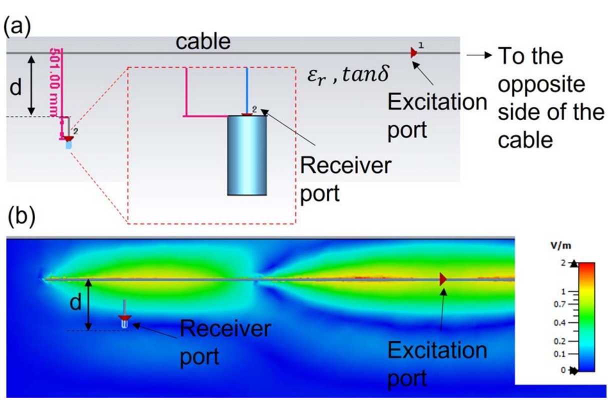

Figure 1. (a) Modeling of a radio receiver positioned near a radiating submarine wire. (b) Simulated distribution of an electric field generated by a continuous-wave signal fed into the middle of a 20 m long cable at 10 MHz.

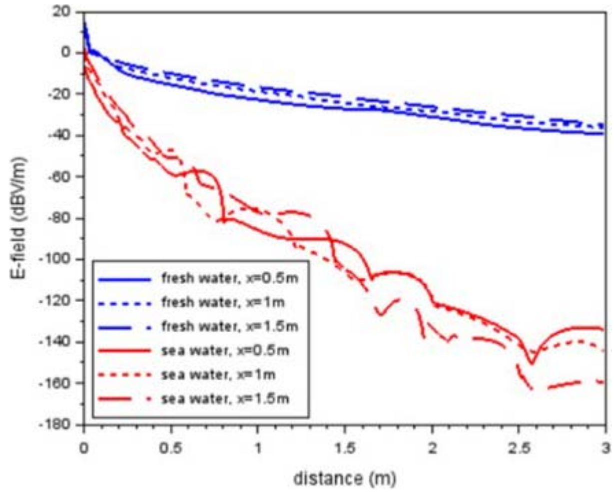

Figure 2. Simulated electric field at 10 MHz as a function of the distance to the radiating wire in water for various conductivities (from 0.04 S/m to 4 S/m). The radiating wire is 20 m long and the excitation port (power = 1 W) is placed in the middle.

2.3 Design of the Proposed Localization System

The system studied here is based on the use of a conductive bread-crumb thread with an isolation layer (galvanized stainless-steel wire) of several tens of meters connected to the inner conductor of the coaxial connector of the main 50 Ω output of a TTI TG2511A waveform generator located at the surface. The outer

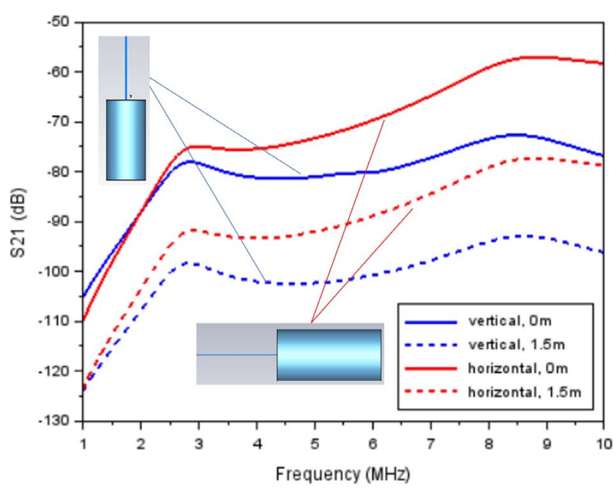

Figure 3. S_{21} simulation result between the excitation port and the receiver from 1 MHz to 10 MHz in fresh water for various distances from the radiating wire. The receiver is placed at $x = 2$ m from the left end of the radiating wire, and is rotated according to vertical or horizontal orientation.

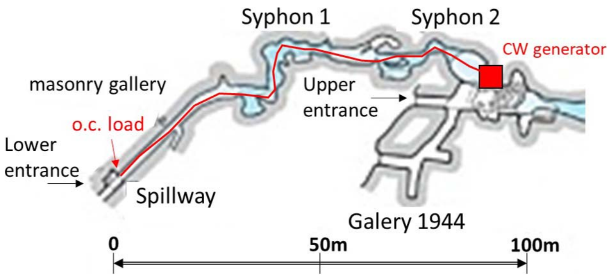

Figure 4. Topography and installation of the St-Antoine Spring.

conductor of the coaxial connector of the generator is connected to the earth with the help of a metallic rod. This wire was installed by cave divers in syphons 1 and 2 of the St-Antoine Spring (Toulon, France), as shown in Figure 4. Note that the end of the wire on the opposite side is left open-ended. On the receiver side, the system is composed of a 4 in. PMMA tube with two aluminum covers with external connectors, to ensure watertightness (Figure 5). The system itself is composed of a software radio (SDRPlay RSPDuo, band-pass 1 kHz–2 GHz), a Raspberry Pi 4, and, for the power supply, a lithium-ion 2S 5.2 A h battery. A 5 V voltage regulator (TSR-2-2450) is used to lower the battery voltage for the Raspberry. The radio logic has two inputs: a high-impedance one (1 kΩ) and one at 50 Ω. In this study we use the high-impedance input because we have experimentally obtained the best results for frequencies between 1 kHz and 20 MHz. The external antenna is a short monopole (50 cm) mainly intended to capture the electric field near the wire.

3. Validation

The on-site experimentation phase consisted of injecting a CW signal into the cable at 10 MHz. On the receiver side, a cave diver progresses along the cable from one end to the other with the watertight box containing the radio receiver that records the strength of the E-field generated by the radiating cable. The results concerning the magnitude of the radio signal measured as a function of the diver's progress are presented in Figure 6 for the forward direction and Figure 7 for the backward direction. We can observe in the forward direction that a signal can be detected over the first 30 m in syphon 2, with variations that are linked to a variation in distance between the radio receiver and the bread-crumb thread. As we approach the exit of syphon 2, the amplitude of the signal decreases to zero. The same behavior is confirmed for the backward direction when the cave diver returns to the generator. We think that this phenomenon is due to the hook that maintains the cable close to the cave wall bringing a large capacitance to the earth, so that a low-pass filtering effect is observed. Even though the system cannot be used beyond the first 30 m, the envelope of the recorded signal is similar in both figures, so that it is possible to

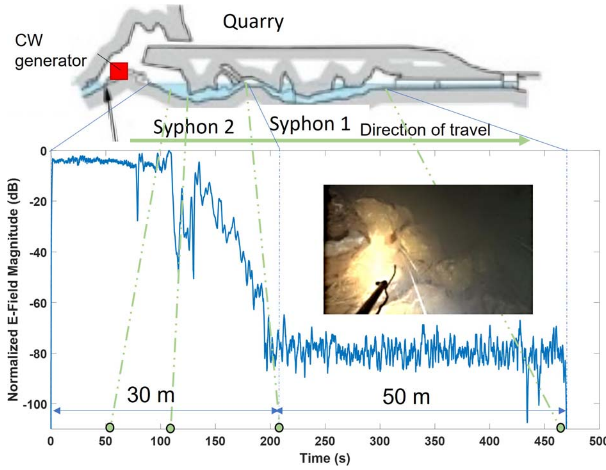

Figure 6. Measured radio signal at 10 MHz recorded along the bread-crumb thread in the forward direction.

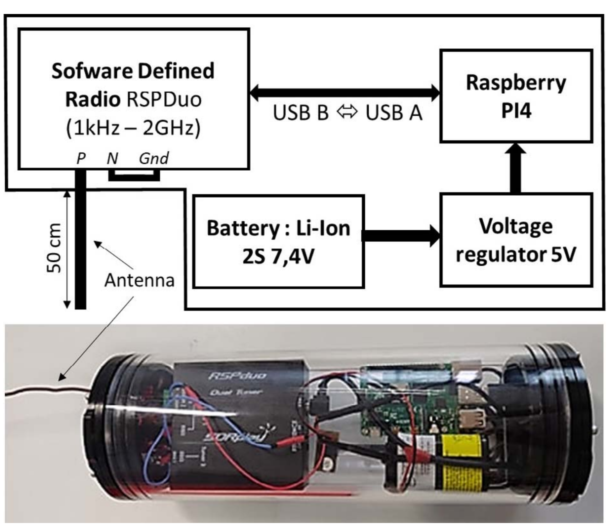

Figure 5. View of the waterproof radio receiver.

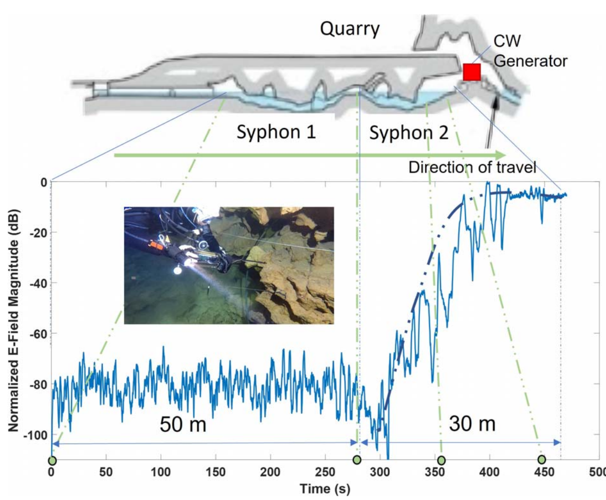

Figure 7. Measured radio signal at 10 MHz recorded along the bread-crumb thread in the backward direction.

correlate the signal magnitude with the specific position of the diver in syphon 2.

4. Conclusion

We have demonstrated through this study that it is possible to capture a 10 MHz radio signal generated by a conductive bread-crumb thread in a fresh-water underwater environment using a simple watertight software-defined radio. Preliminary results obtained at the St-Antoine Spring show that we can detect the presence of the transmitting cable over the first 30 m from the generator. In future work, various frequencies and signal waveforms will be tested to extend the operating range of the localization system. In addition, the variation of the E-field strength as a function of the distance to the cable will be studied to confirm the simulation results.

5. References

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