Sub-Bottom Scanning Sonar (SBSS) for buried target detection

Avec le soutien de la Wallonie

DEFENCE

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1.Introduction

- There are about 400,000 underwater unexploded **historical mines** and **UXOs** (**UneXploded Ordnances**) worldwide. These targets may be **buried**, and currently **there is no detection system** that can reliably and quickly map large underwater areas.
- Current detection systems have high sensitivity but also many **false positives**, and the identification and classification processes take a **long time.**
- The **Sub-Bottom Scanning SONAR (SBSS)** project aims to develop a low-frequency, high-speed SONAR system to detect currently hidden or buried targets.
- The use of SONAR for mine and UXO hunting is justified by the capacity of **acoustic waves** to propagate in the marine environment and by **their reflection on all types of objects**.

a. Manta **b.** Cylindrical **c.** Moored **d.** PDM2

Figure 1: Most common mines

2. Specific problem

As part of the SBSS project, two phases will be carried out: (i) **acoustic modeling** to understand the response of buried objects; and (ii) **detection** and **classification** of these targets.

Detection consists of determining the existence of objects present on the seabed, and the classification can be, for example, a **binary class prediction (mine like / non-mine like).** Acoustic modeling is essential to understand the interaction between the buried target and the sediment, as well as the target response and internal resonances, since these phenomena will give specific features for the classification of buried mines and UXO .

Therefore it is necessary to model the **acoustic response** of objects with different **geometries** and **materials** buried at **different depths** on the seabed with different types of **sediments**.

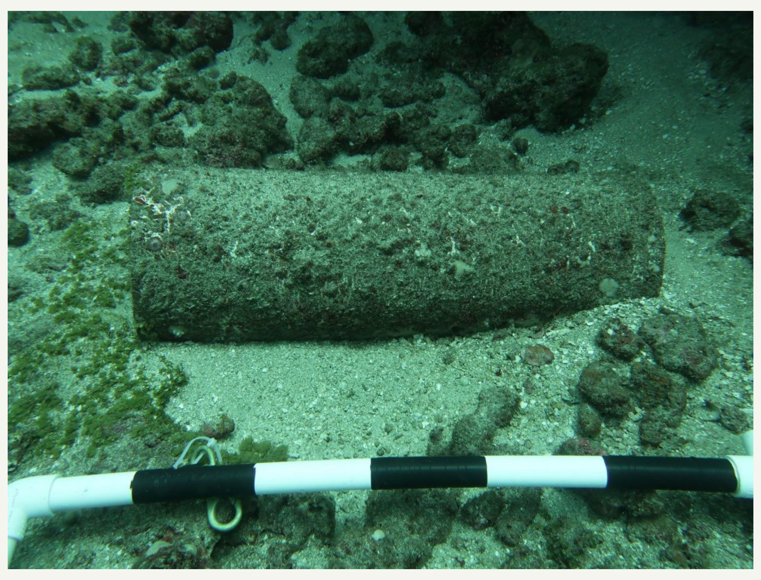


Figure 2: Possible partially buried UXO off Lanaʻi's south shore (Hawai) [1]

3. Fundamental goal

Is the target a mine/UXO or a man-made object?

Ambitious goals

- If the detected object is a mine/UXO, what are its **physical characteristics** (dimensions, thicknesses, elastic properties, etc.)?
- What **type of mine/UXO** is it?

Challenges

- Low frequency SONAR offers **less resolution** (details) of detected objects.
- Modeling **backscatter interaction** between the buried object and different **types of sediments.**
- Integrate a **Physics Informed Learning** approach with the **acoustic model.**

Motivations

This kind of system would accelerate and improve the **mine/UXO detection process**, positively impacting the **military and civil sectors.**

Novelty

This technique uses low frequencies to distinguish different types of targets that are **partially or completely buried** in various **sediment layers**, taking advantage of currently unused **resonances** of the objects.

4. Methodology

It is proposed to develop a model of the **target scattering response** for **elastic targets** of **different geometries** (such as spheres and cylinders), **various external and internal materials** (such as water, TNT or cement), at **different burial depths** (on the sediment, partially buried, flush buried and buried at a certain depth), in **various layers of fluid or elastic sediments** (fine sand, coarse sand, mud, rocks), and taking into account the **phenomena due to the interaction** between the object and the sediment or between the different layers of sediment and water.

For the **detection and classification of targets** it is proposed to analyze an approach based on **Physics Informed Machine Learning (PIML)**. This approach effectively combines observational data with physical-mathematical models. Among the different ways to integrate physical models into machine learning models, there are, for example, **Convolutional Neural Networks (CNN)**, which are the most efficient representative of the PIML, or **Physics-Informed Neural Networks (PINNs)**, which integrate partial differential equations in the loss function of a neural network.

In addition, data augmentation will be used to meet the requirements of diversity and quantity in training data.

In the short term it is expected to obtain a 2D model of a solid cylinder in a free field and also to be able to differentiate natural elements such as a rock from man-made objects. The final objective is to have a 3D model of an object in the shape of a truncated cone with some internal filler (such as TNT or cement) buried 50%, and also to be able to differentiate between various types of mine/UXOs.

5. Acoustic wave equation model

The acoustic model of the target scattering response is based on the **wave equation** , which in 2D can take the following continuous form:

$$\ddot{p}(x,z,t) \;=\; c(x,z)^2(\partial_x^2 p(x,z,t) + \partial_z^2 p(x,z,t)) \;+ s(x,z,t)$$

where $\boldsymbol{p}$ is the pressure field, $\boldsymbol{x}$ and $\boldsymbol{z}$ represent the length and depth of the space domain, $\boldsymbol{t}$ is time, $\boldsymbol{s}$ is the acoustic source, $\boldsymbol{c}$ is the velocity field and $\ddot{p}$, $\partial_x^2 p$ and $\partial_z^2 p$ are the second derivatives of the pressure field $\boldsymbol{p}$ with respect to $\boldsymbol{t}$**,** $\boldsymbol{x}$ and $\boldsymbol{z}$ respectively.

We can solve the wave equation for the pressure field $\boldsymbol{p}$ using the **Finite-Difference Method**, getting the following:

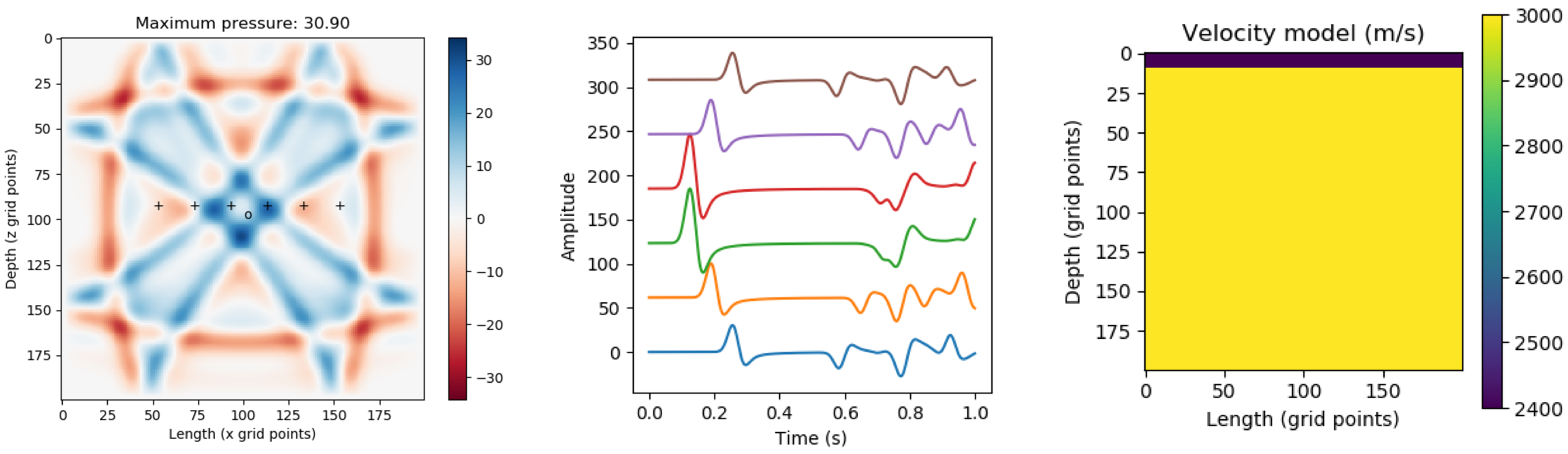
$$p_{j,k}^{n+1} \;=\; c_j^2\, \mathrm{d}t^2 \left[\partial_x^2 p + \partial_z^2 p\right] + 2p_{j,k}^n - p_{j,k}^{n-1} + \mathrm{d}t^2 s_{j,k}^n \quad (1)$$

where $\boldsymbol{dt}$ is the time step, the upper index $\boldsymbol{n}$ represents discretized time, the lower indices $\boldsymbol{j}$ and $\boldsymbol{k}$ represent discretized space in $\boldsymbol{x}$ and $\boldsymbol{z}$ respectively, and the space derivatives are determined by:

$$\partial_x^2 p \;=\; \frac{p_{j+1,k}^n - 2p_{j,k}^n + p_{j-1,k}^n}{\mathrm{d}x^2}$$

$$\partial_z^2 p \;=\; \frac{p_{j,k+1}^n - 2p_{j,k}^n + p_{j,k-1}^n}{\mathrm{d}z^2}$$

In Figure 3 there are three images that show: **a)** the wave propagation through the spatial domain of a heterogenous medium of 200 x 200 grid points with perfect reflective boundaries. The acoustic transmitter is in the center of the domain and 6 receivers are at 5 grid points above it registering the intensity of the pressure (color bar on the right). The maximum pressure at each time step is shown at the top; **b)** The pressure signal recorded by each of the receivers; **c)** the velocity model corresponding to $\boldsymbol{c}$ in equation (1). The velocity model is represented by a matrix that define the sound speed at each point of the grid. Adapted from [2]



a. Propagation of the wave after bouncing off perfectly reflective boundaries

b. Pressure signals recorded by the 6 receivers during 1 second

c. Velocity model type: surface low velocity zone

Figure 3: Simulation of the acoustic wave propagation using the Finite-Difference Method for a heterogeneous medium

References

[1] "Department of Land and Natural Resources. (2021, April 7). 04/07/21-UNEXPLODED ORDNANCE OFF LANAʻI IS INVESTIGATED. Retrieved from [https://dlnr.hawaii.gov/blog/2021/04/07/nr21-067/]".
[2] Igel, H. Computers, Waves, Simulations: A Practical Introduction to Numerical Methods using Python. Online course. Ludwig-Maximilians-Universität München (LMU)

Acknowlegment

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