ANTARTIC BLUE WHALE LOCALIZATION WITH OCEAN BOTTOM SEISMOMETERS IN SOUTHERN INDIAN OCEAN

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Abstract: *While visual survey of whales requires substantial means for limited areas, passive acoustic monitoring (PAM) offers larger scale coverage for long periods and less costs. It usually provides information about species behavior, e.g. seasonal movements, but tools are needed to detail the individuals' behavior.*
From October 2012 to November 2013 as part of the German-French "RHUM-RUM" (Réunion Hotspot and Upper Mantle - Réunion Unterer Mantel) seismic experiment, a 70km by 40km array of 8 Ocean Bottom Seismometers (OBS) was deployed in Southern Indian Ocean in a mountainous area, with depths from 2500 to 5500 meters. The [0-50] Hz-frequency band covered by the OBS's hydrophone provides observations about whales. Each source-OBS path has its own acoustic propagation. Indeed, closest OBS can be reached by direct rays, while remote OBS can only be reached by multi-reflected rays. Therefore, the localization problem cannot be solved directly using a classical Time Difference Of Arrival (TDOA) algorithm.
In this work, the TDOA problem is solved in the case of long range detection, even with mountainous relief, enabling localization and tracking of whales. For each point of the spatial matrix representing the area, Times Of Arrival (TOA) of signal on the OBS are computed with a ray tracing algorithm (BELLHOP), taking into account the bottom profile. The theoretical corresponding TDOA are then compared to measured ones using a loss function.
The obtained results, using L1, L2, cross-correlation cost functions, show the effectiveness of the proposed strategy to track whales on their calls. For example, an Antarctic blue whale is tracked during 10 hours from 40 kilometers south of the array center to 40 kilometers north where the mean speed is close to 10 km/h on a straight trajectory

Keywords: *Antarctic blue whale, TDOA, ray tracing*

1. INTRODUCTION

The golden age of commercial whaling in the early 20th century led to a dramatic decreasing of several whales species populations. Many studies aim to understand their behavior, their seasonal route and population number. Individuals count by visual survey requires huge and expensive means for very low ratings. However, Passive Acoustic Monitoring (PAM) is a very efficient and relatively low cost tool to detect whales. The characteristics of Antarctic Blue Whale (ABW) Z-calls, i.e. high source level and low frequency, are ideal for long range detection.

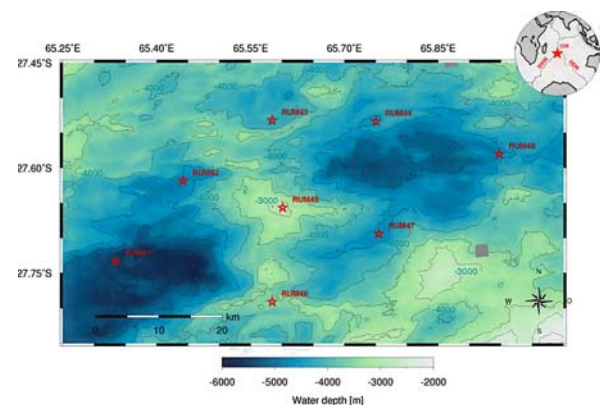
In this study, we propose to make use of a part of the RHUM-RUM [1,2] (Réunion Hotspot and Upper Mantle Réunion's Unterer Mantel) network, deployed in the Southern Indian Ocean from October 2012 to November 2013. The SWIR (South-West Indian Ridge) array (Fig.1) consists of 8 Ocean Bottom Seismometers in a 70 km by 40 km area, with depth varying from 2600 m to 5600 m. Each OBS has a three component seismic sensor and a hydrophone.

Previous studies have shown that whale vocalizations can be detected on OBS's hydrophone [3]. Due to several factors (distance, marine environment characteristics, mountainous bottom profile), the signal waveform can be drastically degraded by the propagation (Fig.4), and the classical TDOA resolution cannot be directly applied. The aim of this study is to propose a long range tracking method using an OBS array in order to understand the ABW local behavior.

2. EXPERIMENTAL DATA DESCRIPTION

2.1. Sensors and array description

Data were recorded by both hydrophone and three-component seismometer of the SWIR array OBS (Fig.1). The 100 Hz sample frequency (fs) is well appropriate for Z-call detection (16-27 Hz). Moreover, the dimensions of the array (70 km wide by 40 km height) and the 25 km mean distance between OBS are ideal for multi-sensors observation of the Z-call signal.



OBS	*Lat.*	*Long.*	*Depth* [m]	*Fs* [Hz]
RR41	-27.7330	65.3344	5430	100
RR42	-27.6192	65.4376	4776	50
RR43	-27.5338	65.5826	4264	100
RR44	-27.5324	65.7480	4548	100
RR45	-27.6581	65.6019	2822	100
RR46	-27.7909	65.5835	3640	100
RR47	-27.6958	65.7553	4582	100
RR48	-27.5792	65.9430	4830	100

Fig.1: SWIR antenna in the eastern Indian Ocean (red star, inset) and OBS informations.

2.2. Environment characteristics

The local sound speed profile (Fig.2) is typical of Indian Ocean, and composed of a thermocline with the minimum at 1800 m, followed by an isotherm layer. The SWIR array area is very mountainous with basaltic ocean floor, separated in two parts from north to south, by a 3000 m high submarine volcano (Fig.1).

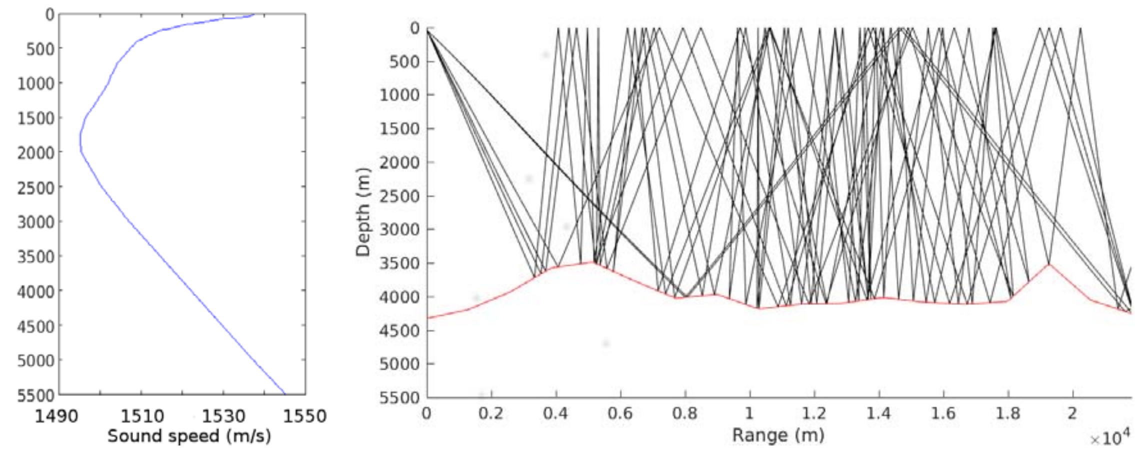


Fig.2: Sound speed profile-typical of Indian Ocean (left). OBS RR43: example of eigenrays tracing (right). Direct ray does not reach the OBS due to bottom profile, only reflected paths are possible.

2.3. Z-call description

ABW Z-call (Fig.3) has a very recognizable pattern composed of three units [4]:
- unit A: 8 seconds-long tone, between 25 and 27 Hz,
- unit B: 2 seconds-long down sweep from unit A to C,
- unit C: 8 seconds-long tone, between 16 and 20 Hz.

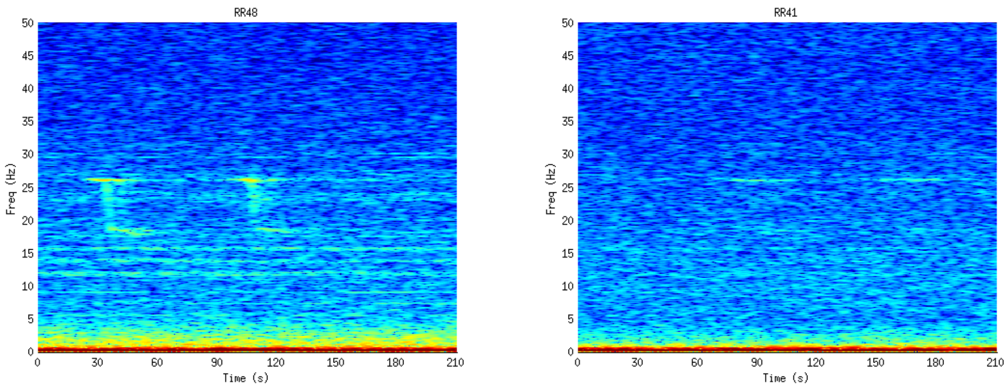


Fig.3: Spectrograms of two Zcalls observed by two different sensors: RR48 (left) and RR41 (right). FFT size: 1024 - Overlap: 97%.

The high source level (estimated at 179±5 dB ref.1µPa@1m [5]) provides very long range propagation. The shape of the observed Z-call can be highly modified by the distance due to the multipath propagation.

3. LOCALIZATION ALGORITHM

The estimation assumptions of a source position by TDOA measurements are a direct path and a constant sound-speed between the source and the different sensors. In this study, both long range detection and region topography are incompatible with those conditions (Fig.2). The method (Fig. 4) is divided into two steps. First, a pre-processing step estimates, for a set of theoretical sources (S_{th}), the theoretical TDOA ($TDOA_{th}$) between OBS. Then, $TDOA_{th}$ are compared to measured ones ($TDOA_m$) in order to build a probability of presence map of the source.

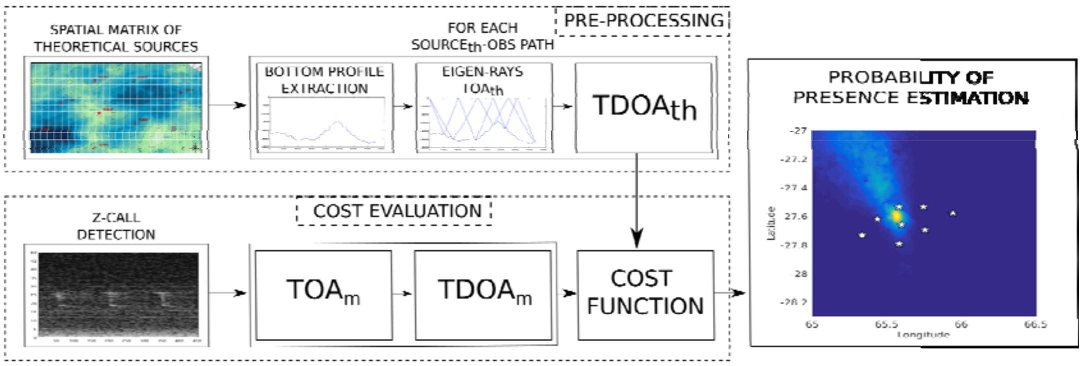


Fig.4: Description of the method. A pre-processing step calculates $TDOA_{th}$. Then a cost function estimates the similarity between $TDOA_{th}$ and $TDOA_m$ to provide the probability of presence map.

3.1. Pre-processing step

This pre-processing step consists in calculating Times Of Arrival (TOA) of eigenrays on OBS for a set of S_{th} regularly located over the area. This spatial matrix is sampled at 0.01 degree from North to South and from West to East. The covered area corresponds to 131 values in latitude axis, and 151 values in longitude axis. The total number of Sth is then close to 20000. The source depth is 40 m [6].

For efficient estimation of eigenrays TOA on every sensor, the bottom profile is considered. It is extracted from a xyz matrix in the S_{th}-OBS axis, and given as input parameter to the ray tracing software BELLHOP.

Due to multiple reflections and long range propagation, the shape of the signal is so modified that it is not possible to distinguish the different rays. Moreover, in the case of long distances, only unit A subsists. The only measurable time is the beginning of the first ray. Hence, the first arriving eigenray is considered and retained for the theoretical TDOA calculation.

3.2. Cost evaluation

The Z-call TOA_m is measured manually on each OBS spectrogram, or automatically by an adapted method [7]. The received pattern, composed of multiple reflected rays, can stretch over more than one minute, leading to a difficult identification of the appropriate ray to measure. Hence, the best way to guaranty a measure that fit with BELLHOP estimation is to consider the beginning of the received pattern.

Once TOA_m are correctly measured on each OBS, $TDOA_m$ are calculated. The similarity between $TDOA_{th}$ and $TDOA_m$ is evaluated by a cost function to generate a map of probability of presence. Three cost functions have been tested with similar results (L1-norm, L2-norm, Corr). The whale localization is selected at the maximum of this map.

4. RESULTS

The following example corresponds to an ABW passing through the array on May 31st 2013. RR45 and RR46 ran out off battery, so the whale is tracked using RR41, RR43, RR44, RR47, RR48.

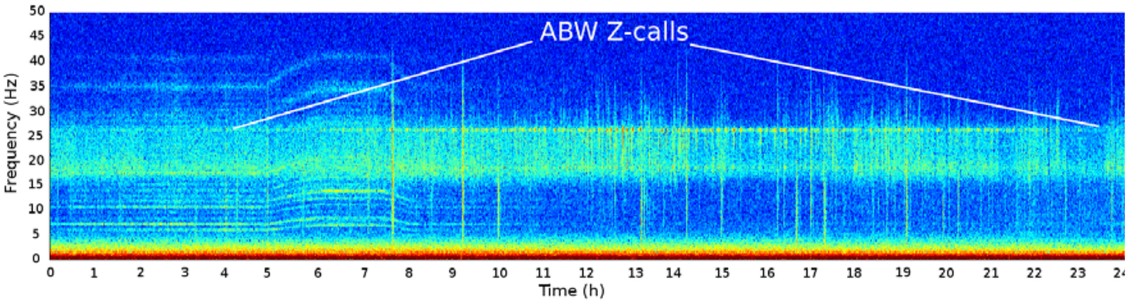


Fig.5: Spectrogram of May 31st. The ABW vocalizations are recorded continuously over about 20 hours. FFT size: 1024 - Overlap: 85%

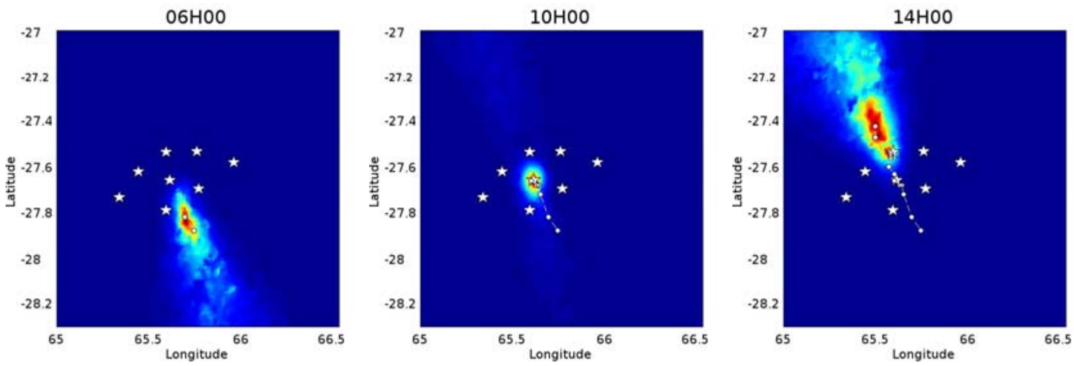


Fig.6: Blue whale tracking obtained by the TDOA based method. Localization precision is optimal for an inside array source.

Unlike hydrophone located in the SOFAR channel, OBS monitoring provides a continuous detection (Fig.5), due to the bottom-surface multiple reflections. The observation radius of ABW is estimated at about 100 km. Fig.7 shows the result of the 8 hours continuous tracking from 06h00 to 14h00. The ABW progresses in a straight direction with a mean speed of about 10 km/h. The localization accuracy is clearly better when the source is in the array than outside.

5. CONCLUSION AND PERSPECVTIVES

It has been shown that due to multiple bottom-surface reflections, whale observation is possible continuously on OBS records over several hours. The corresponding detection range on a simple spectrogram is close to 100 km. The proposed method, based on TDOA-algorithm including propagation characteristics, allows ABW tracking for 8 hours across 80 km.

Thanks to the OBS sampling frequency, it is also possible to extend the process to Madagascar Pygmy Blue Whales, and Fin Whales. This will improve the knowledge about their population density and about how species interact.

The continuous observation provided by OBS is a great benefit for whales PAM. A comparison with SOFAR located hydrophone could give useful information on the ideal array dimension and composition.

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