REMOTE BLUE WHALE CALL DETECTION USING A PASSIVE VERSION OF THE STOCHASTIC MATCHED FILTER PAPER

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Abstract: *More than 30 years after the institution of the moratorium on commercial whaling by the International Whaling Commission, one of the biggest challenges in whale monitoring, e.g. Antarctic Blue Whales (ABW), is assessing populations to evaluate their recovery from persecution by mankind. To do this, passive acoustic monitoring is widely used all around the globe focusing on call detection of vocalizing whales. It has been demonstrated that ultra low frequency Ocean Bottom Seismometer hydrophones (OBSh) provide high quality data for whale monitoring, especially because of their large covering areas. Due to high energy seismic noise, previously developed autonomous methods based on signal cross-correlation are not suitable for this kind of approach. As a first step to ABW monitoring, a new method is used, based on a passive application of the Stochastic Matched Filter (SMF). This is an extension of the matched filter for degraded signals in colored noise. The SMF has been adjusted to perform ABW Z-call detection in noisy environments (seismic broadband noise, boat direct tonal spectrum, other whale calls…). In addition, its properties allow degraded calls (frequency dependent attenuation, multi-path distortion) to be detected, covering large ranges. This new method is applied on a representative dataset -in terms of noise environment and signal variety- recorded by an OBSh in the [0-50]Hz frequency band, deployed at 4000 m depth on a mid-ocean ridge in the South West Indian ocean (RHUM-RUM project). The SMF's robustness against noise is compared to the classical Matched Filter: the output's SNR is maximized and the false alarm drastically decreases. It can then be arranged to provide call time of arrival as an input to a localization algorithm, even for remote calls.*

Keywords: *Call detection, Stochastic Matched Filter, Antarctic Blue Whale monitoring*

1. INTRODUCTION

Because of historic industrial whaling, blue whales have been considered endangered and protected internationally since 1965 [1]. Passive acoustic monitoring (PAM) seems to be a very efficient tool to understand their social behavior and interactions, follow their displacements and finally evaluate their population size.

For example automatic Antarctic Blue Whale call (Z-calls) detection algorithms have been developed [2] to facilitate large data analysis and monitor the specie in vast areas. They are mostly based on signal cross-correlation theory. However, those methods do not perform well at low Signal to Noise Ratio (SNR), whether it is due to distant call detection or high background noise environment (e.g. high intensity vocalizing period).

Because of numerous noise sources e.g. high energy broad-band noises due to seismic activity, boats spectrum etc., data analysis in the Z-call frequency band is quite challenging. To overcome fore-mentioned method's limitations a new approach based on the Stochastic Matched Filter (SMF) is proposed.

2. ANTARCTIC BLUE WHALE CALL

2.1. Call Description

The Antarctic blue whale (*Balaenoptera musculus intermedia*) repertoire has a highly recognizable intense and repetitive low-frequency vocalization with a Z-shaped time-frequency pattern Fig.1 (a). It is described in 3 short units from 27 to 17 Hz, composing the whole Z-call:

• **unit A**, the highest tonal part of the call with frequency between 25.5 and 27 Hz, lasting about 8 s,
• **unit B**, a ~2s-long down-sweep from unit A to C and,
• **unit C**, a slightly modulated 8 s-long tone between 17 and 20 Hz.

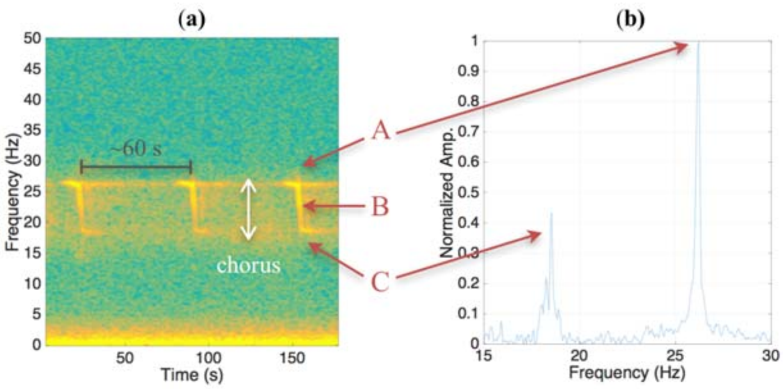


Fig.1: (a) Spectrogram of three successive Z-calls. (b) Spectrum of unit A and C.

Z-calls are usually repeated in ~60-s-apart series to form a phrase as illustrated in Fig.1 (a). Those phrases can occur from few minutes to several hours. Their simple shape and their repeatability allow Z-calls simulation, for example using parametric models [2].

2.2. Whale calls vs oceanic environment

Antarctic blue whale call levels have recently been evaluated for the [17−30] Hz frequency band at 179 ± 5 dB ref.1µPa@1m. According to Fig.1 (b), unit A carries more energy than the rest of the call. This is why it is the remaining unit of remote Z-calls (Fig.3 (a)).

Multi-path propagation might have several impacts (see Fig.1 (a)). First, differed arrival of acoustic paths generates a persisting ‘‘trail” of unit A and to a lesser extent C. Although, it appears that remote calls (from ABW and/or other species) create a diffuse field noise in the Z-call frequency band, a ‘‘hubbub’’ called chorus [2]. In this noisy context, the distinction between real Z-calls and chorus becomes tricky.

3. DETECTION USING THE STOCHASTIC MATCH FILTER (SMF)

3.1. Classical SMF

The SMF has been introduced, as an extension of the Matched Filter (MF) for random signals in colored noise. Initially used as active sonar processing, the method’s most informative concept representation has been reported in [3], as a time-varying linear filter. In addition, recent work [4] dealt with impulsive noise detection e.g. killer whale clicks, that can be seen as a roof of concept to a passive approach.

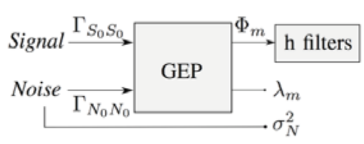
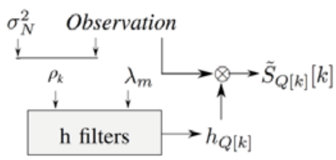
	Off-line	Online
Aim	Compute the linear filter bank h	Maximization of the output SNR
Block-diagram		
Inputs	• Signal reference • Noise reference	• Observation • Noise power σ_N^2
Action	Resolution of a Generalized Eigenvalue Problem (GEP) connecting the signal’s $\Gamma_{S_0S_0}$ and noise’s $\Gamma_{N_0N_0}$covariance matrices	Filtering of the k-current observation by the summation of the $Q[k]$-first filters. $Q[k]$ is the number of product between the time dependent input SNR ρ_k and the eigenvalues that satisfies: $Q[k] = \lambda_k\rho_k > 1$
Outputs	• Filter bank h • Eigenvalues λ_m • Noise power σ_N^2	Reconstructed observation $\tilde{S}_{Q[k]}[k]$

Table 1: Classical SMF principle.

The interest for the SMF comes from its ability to achieve both detection and classification at once. As for the MF, it searches through time for spectral similarities between an observation and the (more or less) degraded version of a reference signal, contained in the linear filter bank *h*. It aims to maximize the output SNR. The SMF off-line and online stages are presented in Table 1.

The classical SMF noise estimation rests on the strong assumption that a portion of the observation can be signal free. It cannot be satisfied in a passive context. In consequence, to use the SMF as a passive detection tool and fulfill its requirements, the adjustments are required [5].

3.2. Improved SMF for Z-call passive detection

The SMF, has been introduced in [5] as an innovative tool for Antarctic blue whale detection in a passive context. The necessary improvements regarding the method's transposition to a passive context concerns the signal and noise references and ρ_k estimation. The encountered issues and their responses are summed up in Table 2.

		Passive context issue	Method's improvements
SMF inputs	Signal's reference	Unknown emitted signal	Simulated for Z-call physical characteristics
	Background noise's reference	Useful signal can occur at any time. It is impossible to determine signal-free portion of the observation	Estimated by median filtering of the observation's time-frequency representation
	Time-dependent SNR estimation	Classical estimation non-adapted to passive noisy detection	Calculated by time-frequency analysis

Table 2: Improvements to a passive version of the SMF.

Through these improvements, it is then possible to compute off-line the ideal linear filter bank for Z-call detection. The first filter is a short-band filter centered on the call's unit A (~ 26.3 Hz), containing most of the energy of the Z-call. Its role is to maximize the output SNR. It cancels the noise when the estimation of ρ_k indicates the absence of signal. The superposition of the maximum number of filters is applied when the estimated input ρ_k is high enough. The filter's pattern is then close to the signal reference's spectrum. When applied, it bandpass filters the observation in the exact signal range.

4. APPLICATION TO REMOTE CALL DETECTION

The passive SMF is tested on a 30-min-long observation recorded on May 31st 2013 by two sea-floor OBSh (RR43 and RR48) of the South West Indian Region (SWIR) array deployed for the RHUM-RUM project [6][7]. Fig.2 shows the vocalizing whale location, close to RR43 station, using the method presented in [8]. The two stations are 37 km apart, corresponding to a 45 dB loss when considering cylindrical geometric divergence. Acoustic data are sampled at f_S = 100 Hz.

Fig.3 synthesizes obtained results. Different events occur (phrases, single call, earthquakes) that are annotated on the spectrogram (a) for both records. Due to the whale's location (Fig.2), events are shifted in time between RR43 and RR48. Z-calls are manually red-marked on (b) to (d).

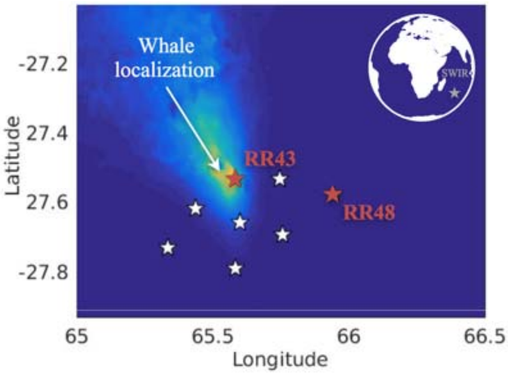


Fig.2: Whale location in the SWIR array [8].

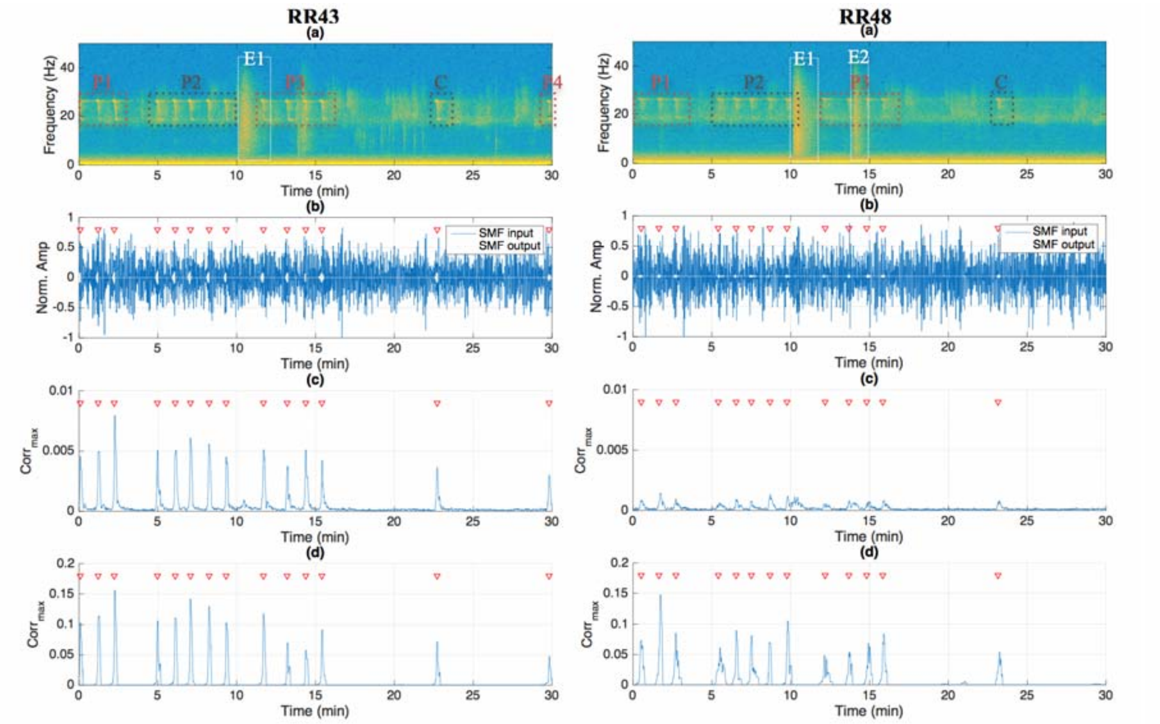


Fig.3: SMF application on recorded data from OBSh RR43 (left) and RR48 (right). (a) Annotated spectrogram. P for phrase, C for single call, E for earthquake. (b) Input and output of the SMF, normalized by the maximum amplitude of the input observation. Correlation maximum of the MF between the [observation (c) - SMF output (d) (SMF + MF)] and the reference signal.

Fig.3 (b) allows waveform comparison between the input and the output of the SMF. In both locations, it drastically improves the output SNR, even if amplitudes are reduced. It is important to notice that there is no signal due to E1 nor E2 after the filtering operation.

Considering station RR43, MF (c) and SMF + MF (d) detect both all calls but there is a potential False Alarm (FA) on E1 (c), depending on the threshold setting. Maximum correlation amplitudes are 10 times greater for the SMF + MF than for the MF. When considering OBSh RR48, observed remote Z-calls are attenuated by the propagation. It strongly impacts the MF amplitudes (c) that are lower than in RR43 and FA occurs due to E1 and E2. *A contrario*, there is no FA using SMF + MF (d) and amplitudes are in the same range than for RR43. What stands out of this example is the benefits of the SMF, in terms of SNR maximization, especially when dealing with remote calls detection. It reduces false alarm and provides greater correlation amplitudes with the reference signal.

5. CONCLUSIONS

This study has identified the SMF as a great asset for remote call detection. By maximizing the SNR, it generates less false alarm and can be used to improve call detection range. Combined with the MF, it provides accurate estimations of calls time of arrival, to be used at a localization algorithm input.

Further work has to be conducted on the assessment of the passive SMF performances, to get a better understanding on the method's limitations. However, this challenge is at the crossroad of biology, underwater acoustics and signal processing. To satisfy every expectation about algorithm performance assessments, one needs to find a great balance between comparison to an expert-marked database 'ground truth' and performance estimation on controlled environment like simulations.

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