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Definition Of The Antarctic And Pygmy Blue Whale Call Templates. Application To Fast Automatic Detection

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ABSTRACT

This paper deals with the automatic detection of low-frequency Antarctic (*Balaenptera musculus intermedia*) and Pygmy (*B. m. brevicauda*) blue whale sounds produced in the Southwestern Indian Ocean. A new detection method based on a matched filter is introduced. Four original match templates are presented and tested against original blue whale subspecies calls. The mathematical formulas of these templates, defined by Gaussian curve models, are provided. The detection threshold is based on the correlation coefficients. The threshold was set to reduce false detections obtained on simulated signals at various signal-to-noise ratios. We focus our work on the true detections of whale calls. Moreover, to obtain a real-time system, we decrease the computational time by decimating the recorded signal (Fs=250Hz). We show that this new method enables us to effectively detect both subspecies in various ambient noises, in the Southern Ocean.

RESUME

Dans ce papier, les sons de basses fréquences émis par les baleines bleues Antarctique (*Balaenoptera musculus intermedia*) et pygmées (*B. m. brevicauda*) dans le secteur sud – ouest de l'Océan Indien ont été détecté automatiquement à partir d'une technique de filtrage adapté. Pour ce faire, des signaux synthétiques ont été créés à partir de signaux originaux en modélisant leurs équations mathématiques à partir de courbes gaussiennes. La détection se fait alors par la corrélation entre le signal entrant et le modèle calculé (template). Le seuil de détection a été choisi au préalable en simulant une série de signaux dans des rapports signal sur bruit différents. Au final, un seuil de détection élevé a été choisi pour minimiser les fausses alarmes au risque d'augmenter les détections manquées. Pour diminuer le temps de calcul, le signal original (Fe=250Hz) a été décimé. Cette méthode originale c'est révélée très efficace pour détecter les sons émis par ces deux sous espèces de baleines bleues dans des niveaux de bruit ambiant très variés comme c'est le cas dans cette partie de l'Océan Indien.

1. INTRODUCTION

Knowledge of marine mammal sounds, and in particular baleen whale sounds, has been largely enhanced thanks to new acoustic data available from a wide variety of instruments that were originally designed to monitor the seismicity of the earth or for defence purposes. Instruments designed to monitor low frequency earthquakes (Watkins, 1981; Nishimura & Colon, 1994; Nieukirk et al., 2004), record seismic-acoustic signals and underwater seismicity (Stafford et al., 2004; Rebull et al., 2006), and listen to Soviet submarines during the cold war via the Navy SOSUS arrays (Costa, 1993; Gagnon & Clark, 1993; Clark & Mellinger, 1994; Mellinger & Clark, 2003) recorded a great variety of calls in the lower frequency range. These calls included Blue (Balaenoptera musculus), Fin (B. physalus), and Humpback (Megaptera novaeanglia) whales over long periods. Recordings of baleen whale calls document the seasonal distributions, the relative abundance, and the acoustic behaviour of particular species. Moreover, they have also been useful in tracking animals in their natural habitat (Mellinger & Clark, 2003; Stafford et al., 2001, 2003, 2004; Širović et al., 2004; McDonald et al., 2006).

The hydroacoustic stations of the International Monitoring System (IMS) were primarily designed to continuously record natural and artificial sounds in the oceans, particularly sounds generated by man-made explosions in support of the Comprehensive Nuclear-Test-Ban Treaty (CTBT) (Roueff et al., 2004). Between May 2003 and April 2004 six IMS stations, provided by the Commissariat à l'Énergie Atomique (CEA) were deployed off the coast of Possession Island (Crozet archipelagos in the French Indian Ocean Territory). The low frequency hydrophones (1-100 Hz) have enabled recordings of a large variety of signals: time-variant ambient underwater noise, biological signals including large baleen whales calls, and anthropogenic sounds.

Our aim is to detect the Antarctic blue whale calls (B. m. intermedia) and the Pygmy blue whale calls "Madagascar-type" (*B. m. brevicauda*) in the CEA dataset. Using spectrograms, our first analysis identifies the presence of 2 subspecies calls in the approximately 40,000 hour-long dataset. These calls contain some uniform patterns with one or more units, high acoustic intensity (above 180 dB re 1µPa at

1m), very low frequency range ([28-35 Hz]) and are repetitive (Clark, 1990; Ljungblad et al., 1998; Mellinger & Clark, 2003; Širović et al., 2004, 2007; Stafford et al., 2004; Rankin et al., 2005; McDonald et al., 2006).

Manually detecting each specific blue whale call among a large amount of data would require many hours of effort to scan the spectrograms visually and to listen to the recordings (Stafford et al., 2007). In this context, automatic processes to identify the location, the characteristics, and the abundance of the calls in the dataset are necessary. Moreover, automated detection methods provide objective criteria to detect and count a known sound in a year-long dataset within hours or days. An automated, fast, real-time detection method for blue whale calls was used to analyze the dataset obtained from permanent acoustic stations.

Recently, a variety of methods have been developed and used for automatic recognition of marine mammal sounds. The classical technique is based on the spectrogram matched filter, i.e. the cross-correlation between the spectrograms of the signal of reference (template) and the recorded signal. This cost minimisation matching technique constitutes the basis of the dynamic time-warping (DTW) developed in human speech recognition (Silverman & Morgan, 1990). In this case, the recorded signal could be compressed or dilated before being compared to the template. A variant of this approach, called crosswords reference templates (CWRTs), consists of comparing the recorded signal with a great variety of templates (Abdulla, 2003). Another approach is based on the use of templates defined in the frequency domain. The cross-correlation templates are obtained from the shapes of the known recorded signal spectrograms (Mellinger & Clark, 2000); this method has been used successfully to classifying right whale calls (Eubalaena japonica) (Munger et al., 2005). An edge detector has also been tried directly on the spectrogram (Gillepsie, 2004). The choice of referent spectrograms from real recordings determines the performance of the detector. Moreover, the performance may depend on the dataset, in which case it is difficult to generalize the results to other datasets. The referent call contains features of a single individual. If these features are not close to those of other individuals (of the same subspecies) referent spectrograms become non exhaustive. Recently, new methods were proposed including Hidden Markov Modeling (HMM) associated with Artificial Neural Networks (ANN) techniques (Trentin & Gori, 2003), and methods based on time-frequency or time-scale representation such as wavelets. The main disadvantage of these methods is their computational complexity as compared to the matched filter.

The signal conditioner and template definition are key to the successful implementation of the matched filter. To optimize performance detection, we have not chosen to extract one call randomly from the dataset and to use it as the referent signal. It is also important to spend time on the signal pre-treatment, especially the filtering process. This step contributes to improving performance of the detector. In our application, the signal-to-noise ratio varies with each hydrophone for the duration of the dataset. The use of multiple templates improves detector performance due to variation and distortion among blue whale calls (Munger et al., 2005; Mellinger, 2004).

In this paper, we provide details on the pre-processing of the signal and we describe the mathematical formulas of the different synthetic waveforms used for the detection of both blue whale subspecies calls. Our work is based on the analysis of the CEA dataset and on the knowledge of the blue whale calls (Stafford et al., 2004, 2005; Rankin et al., 2005; Širović et al., 2004, 2007; Mc Donald et al., 2006). The results obtained for different cross-correlation thresholds and different signal-to-noise ratios (SNR) are presented. It should be noted that our work was aimed at minimizing computational complexity. Before concluding, we present results of true and false detections on real signals.

2. MATERIALS AND METHODS

2.1 Dataset and blue whale calls

This IMS dataset has been made available for the analysis of South Indian Ocean biological signals. In May 2003, six autonomous stations were moored on the northern (H04N1, H04N2, and H04N3) and southern coasts (H04S1, H04S2, H04S3) of Possession Island (Crozet archipelagos in the French Indian Ocean Territory) in the Indian Ocean between 46°09'S-46°51'S and 51°48'E-51°53'E. Each station consisted of an anchor, a buoy and a hydrophone, called an Underwater Monitoring Unit (UMU).

The optical fiber cable and the converter transmitter constitute the digital communication link, once the analog-to-digital conversion (performed in the UMU) has been carried out. The digital acquisition and storage system perform data format changes without affecting the sampling rate and sample values. The data are dated by a 1ms precision absolute clock synchronized by GPS. Data are transmitted in real time via satellite link to the International Data Center to be analysed at the CEA / DIF / DASE - Bruyères-le-Châtel FRANCE. These instruments are moored to the seafloor between 1100 and 1500 meter depths. Sensors are suspended near the sound channel axis (SOFAR) at a depth of approximately 300m. They were deployed in a triangular configuration (triad) far from the northern and southern coasts of the island with approximately 2 km spacing between moorings and 60 km between two triads. Acoustic data for H04N2, H04N3, H04S1 and H04S3 were available for the entire recording period; data for H04S2 were available from May 2003 to December 2003; and no data were available for H04N1 due to instrument failures.

The UMU contains the sensor, the analog signal conditioning circuits, and the analog-to-digital converter. These instruments monitored sound continuously, at a sampling rate of 250 Hz, coded by 24 bits (S/N: 126.5 dB), and a flat (±3 dB) frequency response of 1.2-102.5 Hz. Note that the ambient underwater noise is time-variant for the duration of the dataset. For example, during a given month (March 2004), the mean acoustic pressures recording by the hydrophones

are different between the northern network (92.6±2.5 dBrms) and the southern network (109.5±6.4 dBrms) (Table 1).
In our preliminary study, we focus on two types of easily recognizable calls: the Antarctic blue whale call (BMi) and the Pygmy blue whale call (BMb) “Madagascar type” (bandwith [15-35 Hz]).

Antarctic blue whale calls

Spectrograms of the first category of detected calls are similar to those of typical Antarctic blue whale calls (Ljungblad et al., 1998; Širović et al., 2004; Stafford et al., 2004; Rankin et al., 2005). These calls consist of three tonal units repeated in patterned sequences every 40-50 seconds over a period of a few minutes or hours (Figure 1).

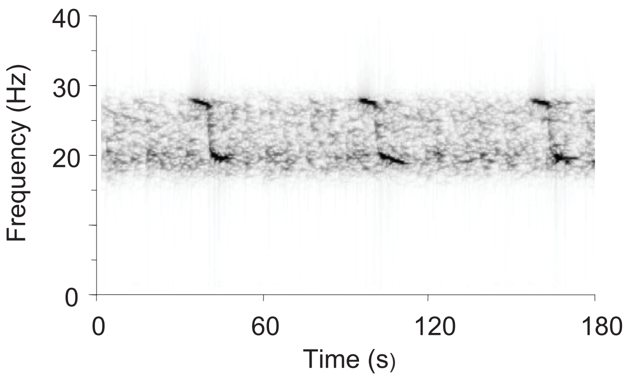

Figure 1: Spectrogram of Antarctic blue whale calls recorded off Crozet Island (Spectrogram parameters: 1024 points FFT length, 90% overlap, 250 Hz sample rate, Hanning, for a filter bandpass between 18 and 28 Hz)

The first component is a constant frequency tone centered at 28 Hz followed by a short frequency-modulated (FM) down-sweep from 28 Hz to 20 Hz ending with the third component, a slightly modulated tone (20-18 Hz). This call lasts approximately 26 seconds but sometimes only the first one or two components are present. This degree of variability in the presence of the three individual components was previously reported (Stafford et al., 2004; Rankin et al., 2005). In the dataset, the calls have variable amplitudes (from 84.3 to 117.8 dB re 1µPa at 1m) depending on the distance of the whales to the hydrophones and the original amplitude of their sounds (Table 1).

Pygmy blue whale calls

Since the first pygmy blue whale call description established by Ljungblad (1998), information regarding the content of these calls has been scarce. These low frequency calls were often present in the dataset. Like Antarctic blue whale calls, these signals occur in patterned sequences of long tonal calls every 90-100 seconds over the course of a few minutes or hours (Figure 2).

Each sequence is composed of two long units that repeat themselves. The first component is primarily a constant frequency tone at 35 Hz lasting 15-20 seconds. A silence

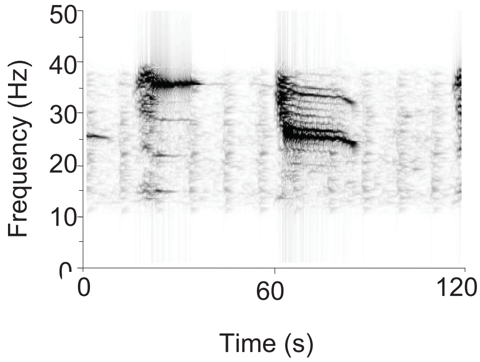

Figure 2: Spectrogram of pygmy blue whale calls “Madagascar type” recorded off Crozet Island (Spectrogram parameters: 1024 points FFT length, 90% overlap, 250 Hz sample rate, Hanning, for a filter bandpass between 12 and 40 Hz).

(approximately 20 sec) separates the two-part phrase. The second component starts with a 1-2 second 15-28 Hz FM down-sweep that ends with a long (20 sec) slightly modulated tone. Each component has strong associated harmonics. In the dataset, the signal-to-noise ratio is time-variant and could have a negative value.

2.2 Automatic detection methods

We present the specific synthetic waveforms, the process for the matched filter and our approach for choosing the detection threshold.

Definition of the templates

In both cases (BMi and BMb), we follow the approach described in Figure 3. The first step is to condition the original signal. As previously mentioned, the sample frequency is 250 Hz. We applied first a high-pass filter then a low-pass filter on the dataset. We used Butterworth filters which present a frequency maximally flat response. Since the frequency bandwidths vary for the 2 subspecies whale calls, different filters for the BMi and the BMb whales are necessary. For the BMi (resp. BMb), the order of the filter is 10 (resp. 12) and the cut-off frequencies are 13 Hz (resp. 17 Hz) and 30 Hz (resp. 50 Hz). The signal is decimated by 2.

The second step allows the extraction of the common features of the parts of the signal with high energy in this bandwidth. This first detection method is based on the energy with non-overlapping sliding windows of 24.6 sec. The noise is reduced when using the average method. Our first choice is to use the recordings with the higher signal-to-noise ratio but we obtain similar results with the complete dataset (Table 2).

The objective of the third step is to synchronize each part of the signal that contains the call. To that effect, we calculate the cross-correlation between the dataset and the averaged signal obtained at the end of Step 2. The averaged signal is used to define the model of the template. Finally both subspecies calls are modelled using Gaussian curves to obtain the equations of the templates. Step 4 will be described in the following section.

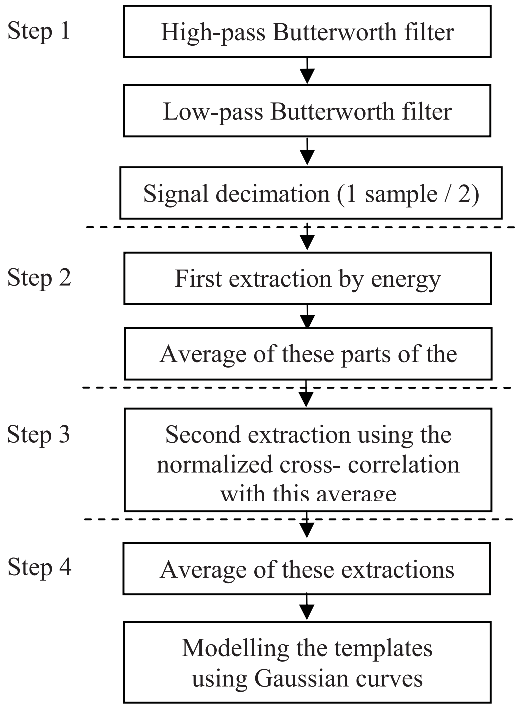

Figure 3: Algorithm for the definition of the call templates. This algorithm is applied first to the BMi calls and after to the BMb calls.
Step 1: Conditioning the original recorded signal.
Step 2: Search for common features
Step 3: Time-synchronization of each part of the original signal
Step 4: Template obtained with the Gaussian model

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Definition of the Antarctic blue whale calls template

For the Antarctic blue whale (BMi) the equation of the synchronized averaged signals is modelled in 2 different parts. For part 1 of the signal, the main frequency is 28 Hz and the spectrum amplitude is modelled using a single Gaussian curve. For the second part, the main frequency is 19 Hz and the spectrum amplitude is modelled using 4 Gaussian curves (Figure 4).

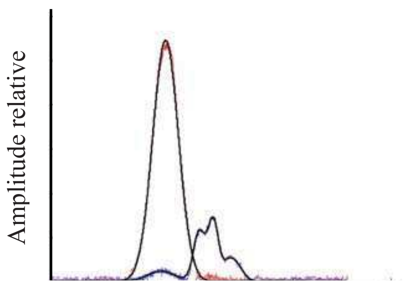

Figure 4: Modelling the spectrum with Gaussian curves

The mathematical formula for the BMi call template is:

$$tpl_{BMi}[k] = \underbrace{a_0^{BMi1} \times e^{-\left(\frac{k-b_1^{BMi1}}{c_0^{BMi1}}\right)^2} \times \sin\left(2\pi f_0^{BMi1} k\right)}_{PART\ 1} + \underbrace{\left(\sum_{j=0}^{3} a_j^{BMi2} \times e^{-\left(\frac{k-b_j^{BMi2}}{c_j^{BMi2}}\right)^2}\right) \times \sin\left(2\pi f_0^{BMi2} k\right)}_{PART\ 2} \qquad (1)$$

with k=1…3000 and

$f_0^{BMi1} = 27.53\text{Hz}$, $f_0^{BMi2} = 19.36\text{Hz}$.

The parameters are:

Part 1:

$a_0^{BMi1} = 10.9$, $b_0^{BMi1} = 2378$, $c_0^{BMi1} = 372.4$

Part 2:

$a_0^{BMi2} = 0.4648$, $b_0^{BMi2} = 2288$, $c_0^{BMi2} = 420$

$a_1^{BMi2} = 2.659$, $b_1^{BMi2} = 3353$, $c_1^{BMi2} = 148.5$

$a_2^{BMi2} = 2.265$, $b_2^{BMi2} = 3070$, $c_2^{BMi2} = 169.4$

$a_3^{BMi2} = 1.081$, $b_3^{BMi2} = 3730$, $c_3^{BMi2} = 261.2$

Equation 1 allows for the reconstructing of the template sample by sample. The time representation of the BMi call template is shown in Figure 5. The duration of this template is 24 seconds. To validate our template, we apply the modelling process on the 1-hour length signal having the highest signal-to-noise ratio and on the complete dataset. We obtain two similar templates. The frequencies of the 2 parts of these templates are presented in Table 2. The correlation coefficients obtained between an unknown signal and these two templates are similar because of the similitude of the two templates.

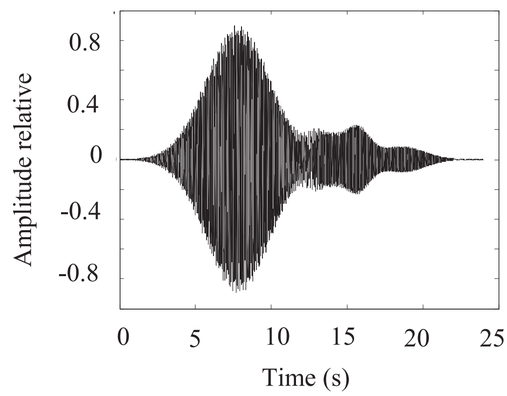

Figure 5: The template of BMi calls

Definition of the Pygmy blue whale calls template

For the Pygmy blue whale (BMb), the equation of the synchronized signals is more complex. We distinguish three parts. The durations of part 1, part 2 and part 3 are 22.3 seconds, 20 seconds and 26.7 seconds respectively. Note that we consider the second part as a silence between part 1 and part 3. Employing the same approach as described before, we obtain the model of the spectrum using Gaussian curves (Figure 6).

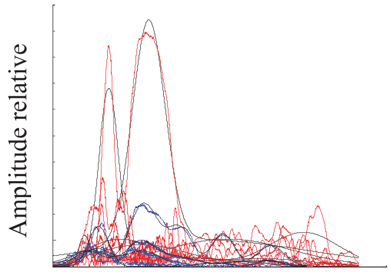

Figure 6: Modelling the spectrum using Gaussian curves

The equations of the 3 parts of the template are:

Part 1:

$$tpl_{BMb1}[k]=\sum_{i=0}^{3}\left(\left(\sum_{j=0}^{4} a_{ij}^{BMb1}\times e^{-\left(\frac{k_{ij}^{BMb1}-b_{ij}^{BMb1}}{c_{ij}^{BMb1}}\right)^2}\right)\sin\left(2\pi f_i^{BMb1}k\right)\right) \quad (2)$$

With k=1…2790 and the frequencies are

$f_0^{BMb1} = 35.03$ Hz , $f_1^{BMb1} = 14.13$ Hz ,
$f_2^{BMb1} = 21.11$ Hz , $f_3^{BMb1} = 22.72$ Hz .

The duration and the parameters of each Gaussian curve are respectively reported in Table 3 and Table 4.

Part 2:

$$tpl_{BMb2}[k]=0 \quad (3)$$

With k = 2791…5295;

Part 3:

$$tpl_{BMb3}[k]=\sum_{i=0}^{4}\left(\left(\sum_{j=0}^{1} a_{ij}^{BMb3}\times e^{-\left(\frac{k_{ij}^{BMb3}-b_{ij}^{BMb3}}{c_{ij}^{BMb3}}\right)^2}\right)\sin\left(2\pi f_i^{BMb3}k\right)\right) \quad (4)$$

With k = 5296…8639 and the frequencies are
$f_0^{BMb3} = 24.96$ Hz , $f_1^{BMb3} = 26.05$ Hz ,
$f_2^{BMb3} = 23.96$ Hz , $f_3^{BMb3} = 27.15$ Hz , $f_4^{BMb3} = 33.0$ Hz

The parameters of the Gaussian curves are reported in Table 5 and Table 6. The time-representation of the complete template is given in Figure 7.

Presentation of our detector based on the matched filter

Our preliminary analysis of the CEA dataset regularly shows incomplete calls for the 2 subspecies of blue whales. For the Antarctic blue whale, this observation is well documented

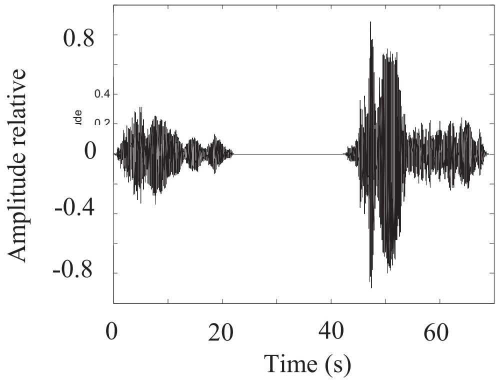

Figure 7: The template of BMb calls

(Stafford et al., 2004; Rankin et al., 2005). However, for the sounds emitted by the Pygmy blue whale, there are few references available. To our knowledge, no study has reported such incomplete calls. We define 2 new templates corresponding to these incomplete calls. These templates are deduced from the previous templates: each new template is composed of the first part of the calls only. We respectively note that BMie and BMbe are the incomplete calls for BMi and BMb.

$$tpl_{BMie}[k]=tpl_{BMi1}[k] \quad (5)$$

$$tpl_{BMbe}[k]=tpl_{BMb1}[k] \quad (6)$$

The algorithm is based on the cross-correlation of the dataset and these 4 templates (Figure 8):

$$R_{xy}=\frac{TF^{-1}\left(X\times Y^{*}\right)}{\sqrt{\sum x^2\times\sum y^2}} \quad (7)$$

where X is the dataset spectrum and Y the template spectrum. Note that spectrums for the 4 templates are calculated before starting the detection process to reduce the computation time. The results list the occurrence of the calls for the 2 blue whale subspecies and some features are saved, like the name of the station, the time of the beginning and the end of the call (year, month, day, hour, minute and second), the signal intensity (Peak and RMS), and the value of the correlation coefficient.

3 RESULTS AND COMMENTS

3.1 Selected threshold for the cross-correlation

The objective of the signal detection method is to validate one of these 2 hypotheses (Harvey, 1992):

$$\begin{cases} H_0 : x = n \\ H_1 : x = s + n \end{cases} \quad (8)$$

with x, s, n respectively the observation, the signal that we have to detect, and the noise.

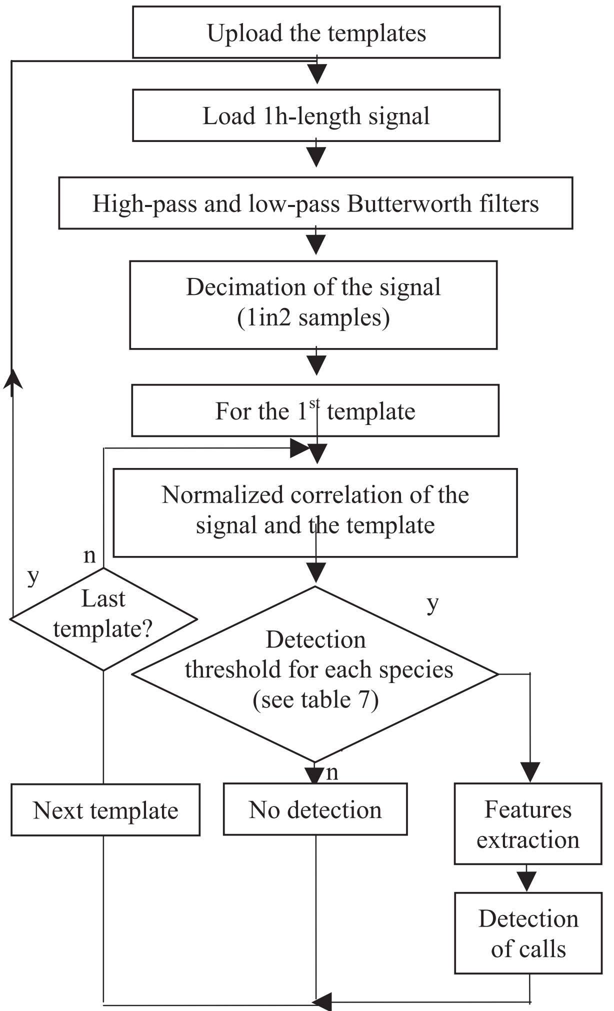

Figure 8: The automatic detection method

Whatever the detector, a threshold can be used to distinguish both hypotheses. The performance of the detector is based on the choice of the threshold. We have selected the value of the threshold from the analysis of simulated signals. These synthetic signals are composed of 100 BMi templates corrupted with a white Gaussian noise. We can assume that the white Gaussian noise properties are close to those of the underwater noise on the specific narrow bandwidth of our application ([20-40Hz]). The distribution of the templates is coherent with a real recorded blue whale signal (same rhythm). We change the signal-to-noise ratio from -30 to 25 dB (range 5 dB). The goal is to assess the value of the threshold for the efficiency of the detection method. Results of the total number of detections, correct detections and false alarms are shown in Table 7. Note that we consider the detection correct when the call is localized at ±1 sec.

First, the number of the total detections decreases with the SNR and increases when the threshold value decreases. For Gaussian white noise only, no call was detected. Second, the rate of the correct detections is 100% for SNR higher than -15 dB, showing the resistance of this approach to noise. This rate decreases dramatically when the SNR is less than -20 dB. The number of false alarms increases significantly when the threshold decreases. For example, when the SNR is 25 dB, the false alarm rate varies from 0 to 66 when the threshold value varies from 0.19 to 0.1. On the other hand, the false alarm rate increases proportionally as the SNR decreases and reaches a maximum value for SNR=-30 dB. Table 7 shows that when the threshold is superior to 0.17, the number of total detections and the correct detection are 100%, except when the SNR<-15 dB.

The same method was applied for BMie, BMb, and BMbe in choosing the threshold. The selected thresholds were respectively 0.17 and 0.15 for the complete and incomplete Antarctic blue whale calls. For both pygmy blue whale calls, the threshold is 0.14. Nevertheless, our margin for error allowed for an occasional missed call because the calls are produced very regularly and the main objective in this process is to decipher whether calls are present or not, and not to determine the exact number of calls. Figure 9 is plotted from data of table 7. The ROC curves are calculated with 6 different SNRs from -25 to 25 (range 10 dB). We deduce the threshold for BMi (0.17 in bold in Fig.9). Note that the signal-to-noise ratios are different in the northern and southern acoustic stations involving more false alarms in the south.

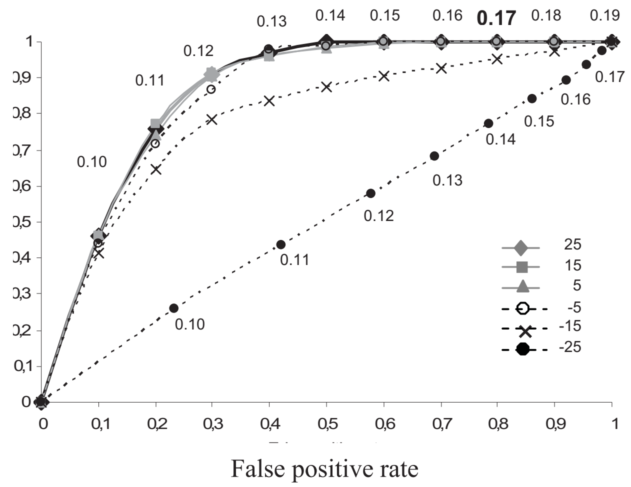

Figure 9: ROC curves from Table 7 value for BMi threshold.

3.2 Performance comparison for matched filter between templates and real referent calls

To validate the templates, we compare the results obtained from the matched filter using our templates and the matched filter using real blue whale calls. We used 4 different calls, 2 by subspecies. For each subspecies, we first extract from the dataset the call with the best shape and with a high signal-to-noise ratio. Second, we choose another call with a low signal-to-noise ratio. The correlation coefficient between the real calls with high (low) SNR and our templates gives 0.58 (0.17) for BMi and 0.35 (0.14) for BMb. For matched filters we use these 4 calls as templates and we apply the same detection thresholds. The results are given in Table 8.

The matched filter using high SNR correctly detects 47% (15%) of BMi (BMb) calls for the northern network dataset. These results decrease dramatically (to reach just less than 1%) for matched filters based on low SNR real calls. The performance is comparable for the southern network. These results show the benefit of using the templates in the matched filter.

The synthetic signals are not representative of a single individual but rather contain features common to calls of other individuals. We note too, a better resistance to the presence of the non-stationary underwater noise.

3.3 Detection of real blue whale calls

The number of calls detected for each blue whale subspecies reflects the appearance of the species, i.e. the vocal activity or the migration pattern of both subspecies (Širović et al., 2004; Stafford et al., 2004; McDonald et al. 2006). The number of blue whale calls detected in a given month (March 2004) is shown in Table 9. We choose March 2004 because the 2 subspecies are present during this month of the year and, secondly, the dataset is almost complete (98% on the 744 hours of the month).

The variation in the number of calls depends on the localization of the calling whales relative to each network and to the signal-to-noise ratio (recording conditions, ambient noise in the recording area). The correlation coefficients are proportional to the quality of the blue whale signals received at the hydrophones. Correlation coefficients vary between 0.17 and 0.72 for BMi calls and between 0.14 and 0.55 for BMb calls (Table 9). Note that the minimum values correspond to our thresholds (see §3.1).

For both whale subspecies, the number of detected calls is higher for the northern network dataset compared to the southern network dataset. This could be justified if the whales were constantly present in the north. This is true for BMb whales. But catches of Antarctic whales show that BMi whales were localized south of Crozet Island (Branch et al., 2007). The reason is that the noise level is higher on the hydrophones in the southern stations (Table 1). As seen in the previous section, our method detects fewer calls when the signal-to-noise ratio is less than -15 dB.

This presupposes that the detected calls are reliable blue whale calls. This result is reinforced by the correlation coefficient means superior to 0.2 for each whale and each network (Table 7).

3.4 Computation time

One of our objectives is to develop a method for real-time application. We attach great importance to computation time. Taking this constraint into account, we do not consider methods based on time-frequency representation. Moreover, we reduce the computation time by decimating the original signal by 2 and implementing the matched filter in the time domain. The algorithm code (Figure 8) is developed with Mathworks Matlab 7.04 and processed on Dell Pentium 4 CPU 2.4 GHz (1 Go RAM). Note that we take into account the load of the recorded signal and the saved results. For the 2 subspecies and the 4 types of calls, the computation time is 3382.04 seconds for analysis of the entire March 2004 dataset. The ratio is approximately 1/1000.

This result allows us to consider real-time application. Computation time could be decreased by using machine code in place of Matlab. Moreover, most of the time is dedicated to the uploading and the conversion of the dataset. This is a drawback of post-processing analysis. This step is avoided for real-time application.

4 CONCLUSION

In this paper, we investigated the performance of matched filters dedicated to the automatic detection of the calls of 2 blue whale subspecies in long-term acoustic recordings in the Southwestern Indian Ocean. We presented the definition of 4 templates corresponding to the complete and incomplete calls of these whales. We provided the mathematical formulas for Antarctic blue whale and pygmy blue whale call templates. Our automatic detection is based on the cross-correlation method; we optimized the process to be time-efficient in analysing such long recordings.

This automated detection method was useful in detecting blue whale calls in the whole dataset. The limited range of variability in the Antarctic blue whale and pygmy blue whale calls allowed us to create the synthetic waveforms for both calls. Four templates were used for the matched filter. The choice of the detection threshold was based on minimizing the false alarms.

Compared to alternative automated detection methods where the perfomance can be modified by the length of the dataset, the acoustic characteristics of the call, the behaviour of the calling whale, the properties of the water, and the physical environment of the recording location, the pattern chosen here is efficient in detecting all Antarctic and pygmy blue whale calls present in a given recording. It is also human and dataset independent. Moreover, this automated detection method could evolve by completing the current library with other baleen whale calls.

We intend to test the method on another training set of blue whale calls recorded in the northern and eastern parts of the Indian Ocean. Our first perspective is to use certain specific features, in particular, rhythm of the whale calls, for increasing detection reliability. As an end goal, we will use this detector for extracting the time of arrival of calls on each hydrophone to localize the whales.

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	Northern network			Southern network		
	Ambient noise level	BMi	BMb	Ambient noise level	BMi	BMb
Min	85.9(97.7)	84.3(94.6)	89.3(101.5)	100.1(113.8)	99.8(111.6)	104.4(116.6)
Max	106.2(121.0)	107.1(132.0)	119.4(133.2)	133.4(145.3)	117.8(137.6)	120.0(139.9)
Mean	92.6(104.5)	91.1(103.9)	97.2(111.3)	109.5(120.7)	103.9(115.4)	109.3(122.9)
SD	2.5(3.2)	3.2(4.2)	3.4(4.0)	6.4(6.6)	1.3(1.9)	3.2(3.9)

Table 1: Acoustic intensities (rms (peak) re 1µPa at 1m) (calculated on 1 month)

	One hour recording	All dataset
1st frequency (Hz)	27.57	27.53
2nd frequency (Hz)	19.35	19.36

Table 2: Difference between the templates modelling from 1-hour recordings and from the whole dataset.

	k_{ij}^{BMb1}			
	i=0	i=1	i=2	i=3
j=0	1…679	1…691	1…679	1…2790
j=1	68…1572	692…1686	680…1464	0
j=2	1573…2035	692…1686	1465…1989	0
J=3	1573…2035	1687…2790	1990…2790	0
j=4	2036…2790	0	0	0

Table 3: Duration of each Gaussian curve (0 for $k \neq k_{ij}^{BMb1}$) for the part1

	a_{ij}^{BMb1}				b_{ij}^{BMb1}				c_{ij}^{BMb1}			
	i=0	i=1	i=2	i=3	I=0	i=1	i=2	i=3	i=0	i=1	i=2	i=3
j=0	2.944	3.153	3.309	7.63	385.2	398.8	464.2	484.8	211.6	270.7	198.9	147.8
j=1	12.02	4.215	3.001	0	956.8	920.9	946	0	210.5	189.7	268.8	0
j=2	7.359	2.08	0.7191	0	1335	1251	1706	0	189.3	324	218.3	0
j=3	6.306	1.148	1.262	0	1790	2135	2272	0	203.1	404.6	169	0
j=4	3.97	0	0	0	2295	0	0	0	203.1	0	0	0

Table 4: Parameters of the Gaussian curves for the BMb call part 1

	k_{ij}^{BMb3}				
	i=0	i=1	i=2	i=3	i=4
j=0	5296…8639	5296…6173	5296…7090	5296…6692	5296…5745
j=1	5296…8639	6174…8639	7091…8639	6693…8639	5746…8639

Table 5: Duration of each Gaussian curve (0 for $k \neq k_{ij}^{BMb3}$) for the part 3

	a_{ij}^{BMb3}					b_{ij}^{BMb3}					c_{ij}^{BMb3}				
	i=0	i=1	i=2	i=3	i=4	i=0	i=1	i=2	i=3	i=4	i=0	i=1	i=2	i=3	i=4
j=0	5.15	33.1	4.2	5.21	5.24	1537	590	940.9	714	338.3	1591	144.7	694.7	527.3	78.5
j=1	42.5	5.25	6.54	1.53	1.76	1010	1840	2640	2189	1289	242.8	949	516.2	757.9	917.1

Table 6: Parameters of the Gaussians for the BMb call part 3

	0.10	0.11	0.12	0.13	0.14
25	166(*100*,**66**)	143(*100*,**43**)	121(*100*,**21**)	110(*100*,**10**)	103(*100*,**3**)
20	167(*100*,**67**)	135(*100*,**35**)	121(*100*,**21**)	108(*100*,**8**)	101(*100*,**1**)
15	171(*100*,**71**)	148(*100*,**48**)	122(*100*,**22**)	107(*100*,**7**)	104(*100*,**4**)
10	169(*100*,**69**)	144(*100*,**44**)	121(*100*,**21**)	110(*100*,**10**)	104(*100*,**4**)
5	179(*100*,**79**)	146(*100*,**46**)	128(*100*,**28**)	109(*100*,**9**)	104(*100*,**4**)
0	167(*100*,**67**)	137(*100*,**37**)	122(*100*,**22**)	110(*100*,**10**)	105(*100*,**5**)
-5	156(*100*,**56**)	135(*100*,**35**)	119(*100*,**19**)	109(*100*,**9**)	105(*100*,**5**)
-10	175(*100*,**75**)	145(*100*,**45**)	127(*100*,**27**)	109(*100*,**9**)	105(*100*,**5**)
-15	165(*96*,**69**)	135(*96*,**39**)	119(*96*,**23**)	105(*96*,**9**)	102(*96*,**6**)
-20	170(*87*,**83**)	146(*87*,**59**)	128(*87*,**41**)	117(*87*,**30**)	112(*87*,**25**)
-25	157(*72*,**85**)	131(*72*,**59**)	117(*70*,**47**)	102(*68*,**34**)	96(*65*,**31**)
-30	155(*27*,**133**)	119(*22*,**97**)	81(*18*,**63**)	50(*13*,**37**)	30(*11*,**19**)

(a)

	0.15	0.16	0.17	0.18	0.19
25	101(*100*,**1**)	101(*100*,**1**)	100(*100*,**0**)	100(*100*,**0**)	100(*100*,**0**)
20	101(*100*,**1**)	101(*100*,**1**)	100(*100*,**0**)	100(*100*,**0**)	100(*100*,**0**)
15	102(*100*,**2**)	100(*100*,**0**)	100(*100*,**0**)	100(*100*,**0**)	100(*100*,**0**)
10	103(*100*,**3**)	101(*100*,**1**)	101(*100*,**1**)	100(*100*,**0**)	100(*100*,**0**)
5	102(*100*,**2**)	101(*100*,**1**)	100(*100*,**0**)	100(*100*,**0**)	100(*100*,**0**)
0	102(*100*,**2**)	100(*100*,**0**)	100(*100*,**0**)	100(*100*,**0**)	100(*100*,**0**)
-5	103(*100*,**3**)	100(*100*,**0**)	100(*100*,**0**)	100(*100*,**0**)	100(*100*,**0**)
-10	101(*100*,**1**)	101(*100*,**1**)	100(*100*,**0**)	100(*100*,**0**)	100(*100*,**0**)
-15	101(*96*,**5**)	100(*96*,**4**)	100(*96*,**4**)	100(*96*,**4**)	100(*96*,**4**)
-20	105(*87*,**18**)	101(*87*,**14**)	101(*87*,**14**)	100(*87*,**13**)	99(*86*,**13**)
-25	84(*62*,**22**)	67(*50*,**17**)	50(*35*,**15**)	38(*25*,**13**)	25(*17*,**8**)
-30	15(*9*,**6**)	11(*7*,**4**)	5(*4*,**1**)	3(*3*,**0**)	2(*2*,**0**)

(b)

Table 7: Evaluation of the detection threshold value (lines show the threshold values and columns show SNR (dB)). Number of total detections (*correct detections*, false alarms)

	Northern network		Southern network	
Matched filter used	BMi	BMb	BMi	BMb
Template	6313	7 495	2856	717
Real call with high SNR	2971	1116	2082	93
Real call with low SNR	148	130	461	28

Table 8: Number of calls detected by using template and real call in various SNR for matched filter (calculated on 1 month)

	Northern network		Southern network	
	BMi	BMb	BMi	BMb
Number of calls detected	6313	7 495	2856	717
Min	0.17	0.14	0.17	0.14
Max	0.72	0.55	0.49	0.45
Mean	0.23	0.23	0.19	0.20
SD	0.07	0.07	0.02	0.06

Table 9: Number of calls detected and correlation coefficient (calculated on 1 month)