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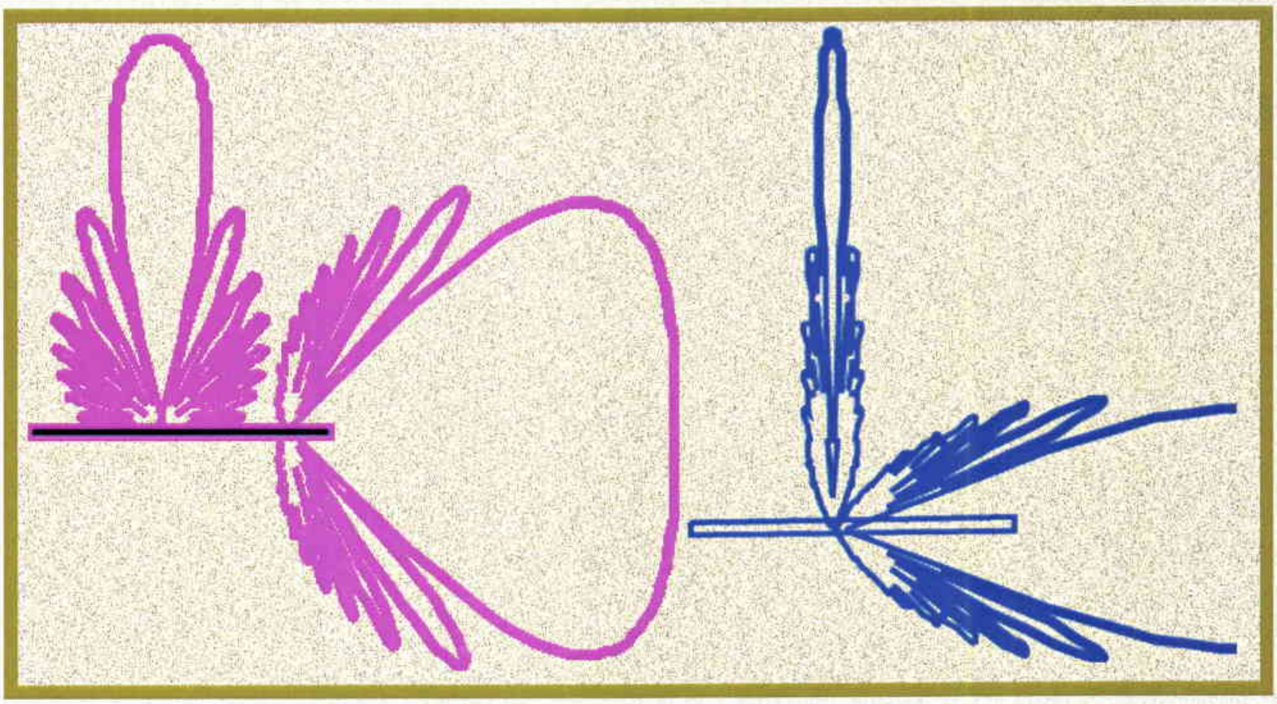
SACLANT UNDERSEA
RESEARCH CENTRE
REPORT

Passive acoustic detection of marine mammals



Douglas A. Abraham

April 2000

NORTH ATLANTIC TREATY ORGANIZATION ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD

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Passive Acoustic Detection of Marine Mammals

D. A. Abraham

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Jan L. Spoelstra
Director

Report no. changed (Mar 2006): SM-351-UU

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Report no. changed (Mar 2006): SM-351-UU

Passive Acoustic Detection of Marine Mammals

D. A. Abraham

Executive Summary: This memorandum presents a passive acoustic analysis of data recorded during the SACLANTCEN SWAC4 sea-trial in Kyparissiakos Gulf during May 1996. Specifically, the automatic detection algorithm used to find marine mammal acoustic emissions is described and the results of the analysis presented. The algorithm detected sounds that were classified by experts to be sperm whale click trains and generic dolphin click bursts. The results of localization through triangulation are also presented for two sets of sperm whale click trains.

Report no. changed (Mar 2006): SM-351-UU

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Passive Acoustic Detection of Marine Mammals

D. A. Abraham

Abstract: A passive acoustic analysis of data recorded during the SACLANTCEN SWAC4 sea-trial in Kyparissiakos Gulf during May 1996 was performed with the specific objectives of detecting, localizing, and classifying marine mammal sounds. Detection and localization (bearing only) was performed using a passive sonar system in a playback mode and by an automatic detection algorithm for specific runs or run segments. The results of the automatic detection processing allow association over time and bearing, creating 'events' that may then be classified by experts. This memorandum describes the preprocessing of the SWAC4 sea-trial data and the algorithm used to perform the automatic detection processing. The results of the automatic detection processing are then displayed in time-beam number plots and used to perform rough localization of detected events through triangulation.

Keywords: detection ∘ marine mammal sounds ∘ Page test ∘ power-law

Report no. changed (Mar 2006): SM-351-UU

Contents

1 Introduction

Detection of the presence of marine mammals is crucial in the vicinity of a research vessel carrying out operations involving projecting acoustic energy into the local ocean environment. This memorandum details an analysis of passive acoustic data garnered from data recorded during the SACLANTCEN SWAC4 sea-trial in Kyparissiakos Gulf during May, 1996. Specifically, the preprocessing of the recorded sonar data (filtering and beamforming) and the automatic detection processing will be described. The results of the automatic processing are displayed and then used to localize detected marine mammal sounds through triangulation.

The detection, localization, and classification objectives could have been met by either passive listening or active ranging. The latter is desirable because it provides range and bearing information as opposed to bearing-only information from passive listening. However, the difficulties in detection, clutter rejection, and classification in active ranging systems forced the use of passive techniques for this situation. Passive analysis was further supported in that experts were available to perform aural classification for many types of marine mammals.

Figure 1 contains a flow diagram of the processing applied to the recorded hydrophone data. The filtering was required to obtain passive data as reverberation from active sonar transmissions occupied the frequency bands 450–700 Hz and 2.8–3.3 kHz. The beamforming is required to increase the signal-to-noise ratio (SNR) by reducing the effect of interfering noises (e.g., surface vessels) arriving from different directions. Array data were available from the Centre's low-frequency (LF) and mid-frequency (MF) arrays. A description of the filtering and beamforming along with a justification for choosing the frequency band 750–1500 Hz is found in Section 2. The automatic detection algorithm and the results of its application to the SWAC4 data (detected events and localization) are found in Section 3.

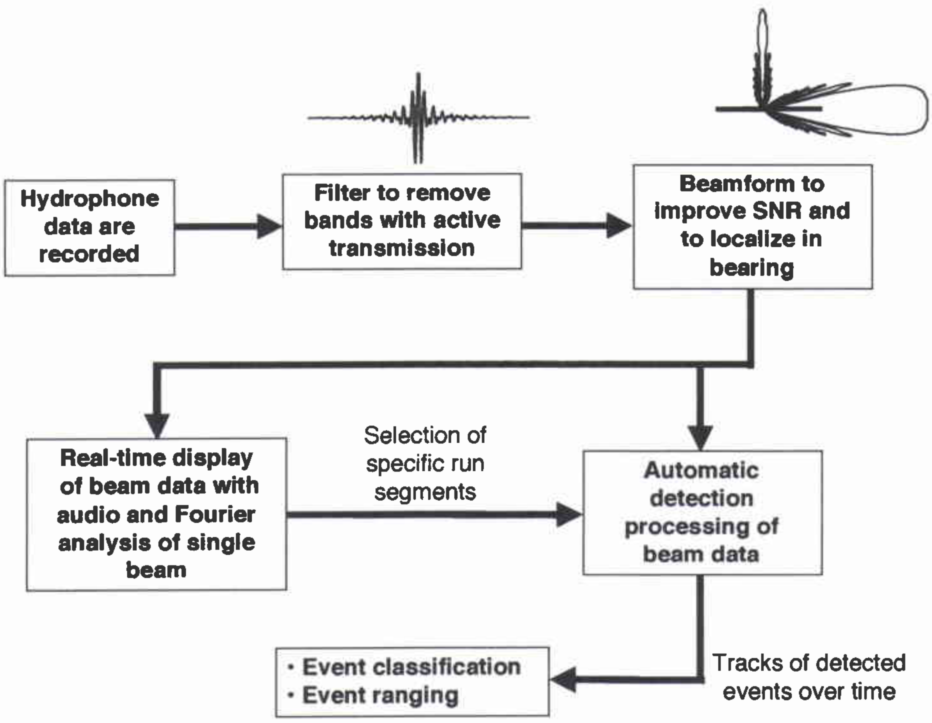


Figure 1 *Flow diagram of signal processing.*

2
Passive sonar data processing

Acoustic data were available from the Centre's MF and LF arrays, providing a 32 element aperture at 4166 Hz (MF) and 128 element apertures at 375, 750 and 1500 Hz (LF). The MF array hydrophone data were bandpass filtered to the band 1–3.8 kHz and sampled at 12 kHz prior to recording. The LF array hydrophone data were bandpass filtered to the band 200–1860 Hz in conjunction with an equalization filter with −3 dB point at 360 Hz (resulting in roughly 8 dB of attenuation at 200 Hz) and sampled at 6 kHz. Time did not allow analysis of all array apertures. Under the constraints of the data acquisition and assumptions about the frequency bands of marine mammal acoustic emissions, one frequency band was chosen for immediate analysis. The following sections detail the reasoning behind the choice and the processing performed to provide the best data possible for detection analysis.

2.1 Beamforming

The 2 metre spaced LF array (375 Hz design frequency) was not considered as having a frequency band viable for analysis for the following reasons:

- the equalization and low-pass filtering prior to recording
- higher levels of ambient noise at lower frequencies
- limited available bandwidth

The 1 metre spaced LF array (750 Hz design frequency) was mostly corrupted by reverberation from the active transmissions (from 450–700 Hz) and therefore not viable for passive analysis. This leaves the 0.5 metre spaced LF array (1500 Hz design frequency) and the MF array. The directivity index[1] of these arrays for beams pointing to broadside and endfire is shown in Fig. 2. Here it is seen that the largest bandwidth available for processing is from the MF array from 1–2.8 kHz, less transition bands for filtering out the active transmission. However, owing to the smaller number of hydrophones in the MF array and the fact that this band

[1]Directivity index is the gain achieved against isotropic noise by beamforming an array of hydrophones.

is well below its design frequency (4166 Hz), the directivity index of the 0.5 metre spaced LF array (1500 Hz design frequency) is roughly 9 dB higher and therefore more appealing for analysis.

To further illustrate the effectiveness of the 1500 Hz LF aperture over the MF array, beampatterns for the LF and MF arrays are found, respectively, in Figs. 3 and 4. Here it is seen that the beams for the LF array at 750 Hz (worst case) are narrower than the MF array at both 2 and 4 kHz (best case). This is also quantified by the 3 dB beamwidths found in Table 1. These figures also illustrate the decreasing effectiveness of the beamforming as frequency is decreased with fixed hydrophone spacing. The beampatterns are wider at lower frequencies as a result of a reduced effective aperture (array size in wavelengths). This effect also exhibits itself as the look direction of the beamformer changes from broadside to endfire: at endfire there is a smaller effective aperture which results in broader beampatterns.

Thus, based on a trade-off between available bandwidth and directivity index, the frequency band 750–1500 Hz from the 0.5 metre spaced LF array was chosen for passive analysis. Conventional time-delay and sum beamforming was performed with uniform shading of the hydrophone data. A total of 120 beams were formed, equally spaced in wavenumber. Note that this does not provide 3 dB overlap at 1500 Hz (which would require 128 beams), but does for most of the lower frequencies.

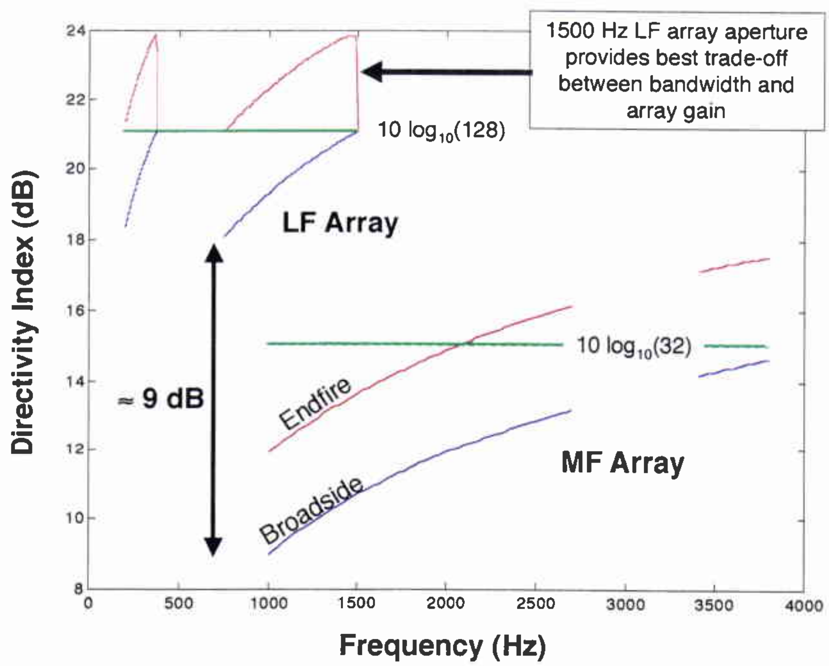
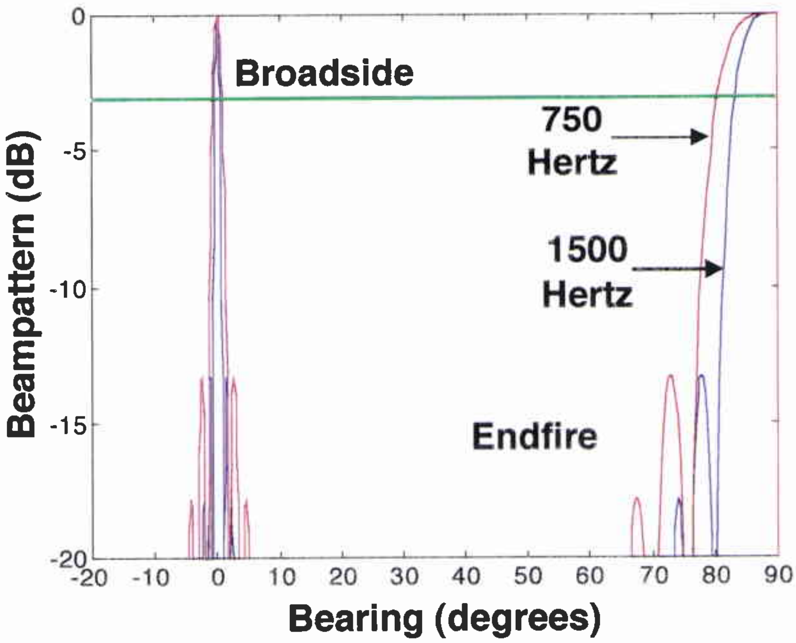


Figure 2 *Directivity index vs. frequency for different array apertures.*



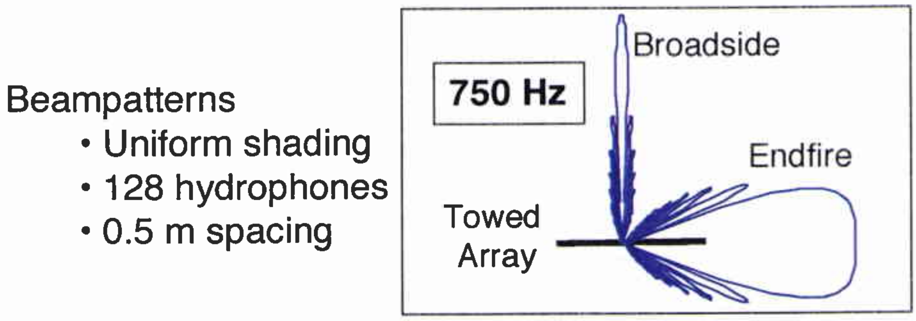


Figure 3 *Beampatterns for LF array.*

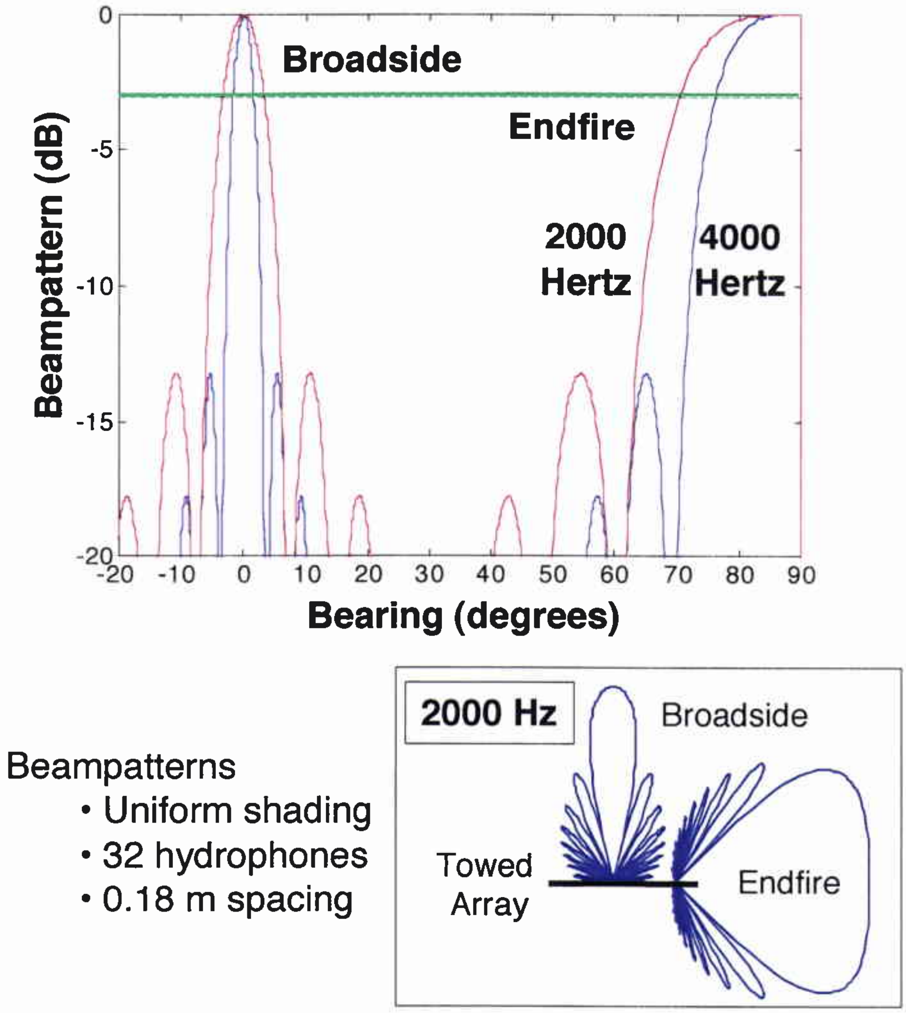


Figure 4 *Beampatterns for MF array.*

Table 1 3 *dB beamwidth in degrees for* 1500 *Hz aperture LF array and MF array at various frequencies.*

LF Array		
	750 Hz	**1500 Hz**
Broadside	1.6°	0.8°
Endfire	19.1°	13.5°

MF Array		
	2000 Hz	**4000 Hz**
Broadside	6.5°	3.3°
Endfire	39.1°	27.6°

2.2 Filtering

Data were only recorded during and following active sonar transmissions. This corrupts the data from the perspective of passive analysis in two ways. First, during the transmission and for some period immediately following, the hydrophones are overloaded by the high levels of acoustic energy from the direct blast (i.e., the active sonar transmission) and some of the immediately following reverberation. As this overloading causes a non-linear response in the hydrophones, these data are not viable for analysis. Second, the frequency bands of the active sonar transmission, plus guard bands to allow for Doppler shifts, are corrupted by reverberation for nearly the complete time of each ping cycle (the time between transmissions, which was one minute). In order to obtain valid passive data for analysis, an FIR bandpass filter was applied with magnitude and phase response as shown in Fig. 6, rejecting out-of-band signals with 60 dB attenuation. The vertical lines on the plots represent 750 and 1500 Hz. The impulse response of the filter is found in Fig. 7. Note that the output of the filter would look like the impulse response if the input were nearly flat with linear phase over the passband (e.g., a sperm whale click). An example of the filtered and beamformed data is shown in Fig. 5 where the active transmission, extremely loud reverberation spilling into the pass band, and some sperm whale clicks are clearly visible.

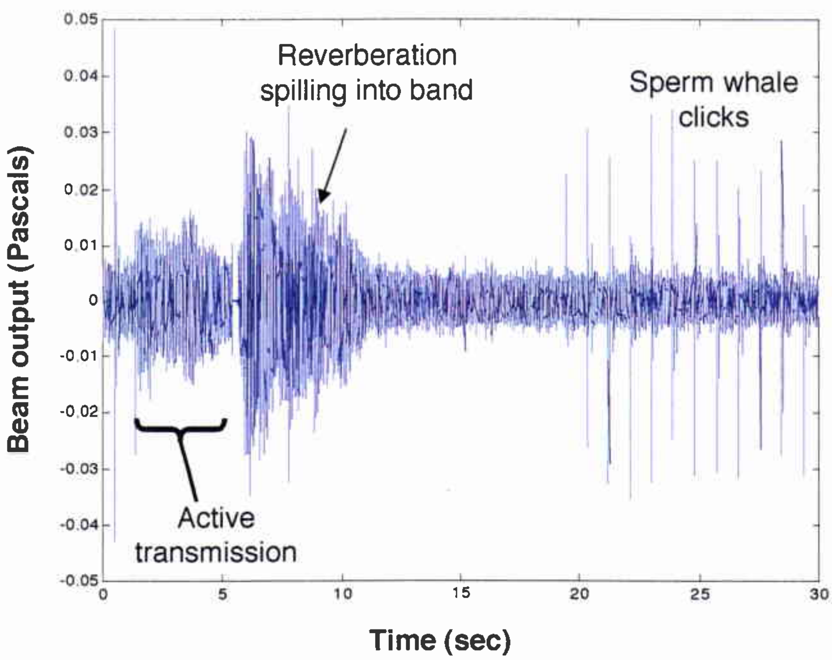


Figure 5 *Example of filtered and beamformed data with sperm whale click train.*

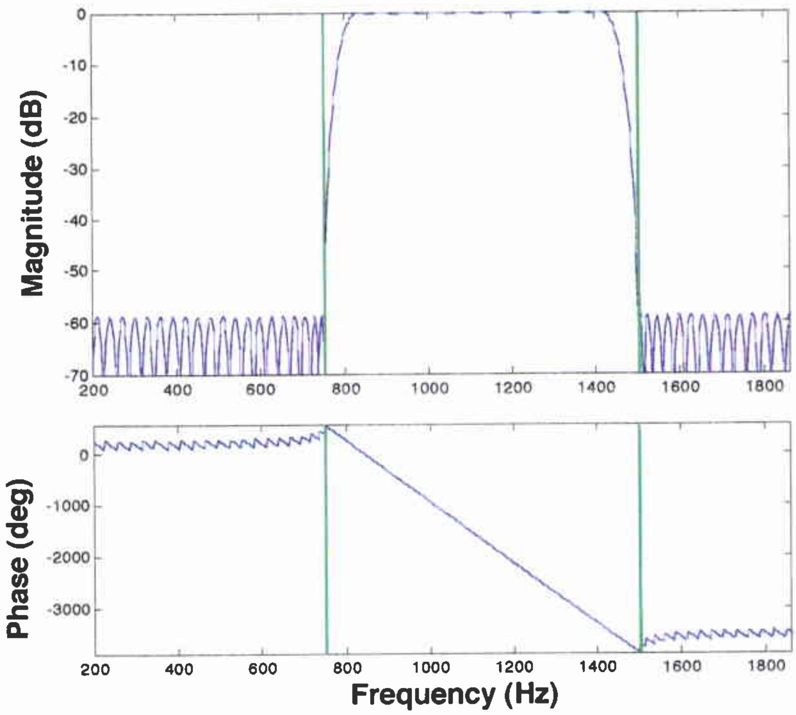


Figure 6 *Filter magnitude and phase response.*

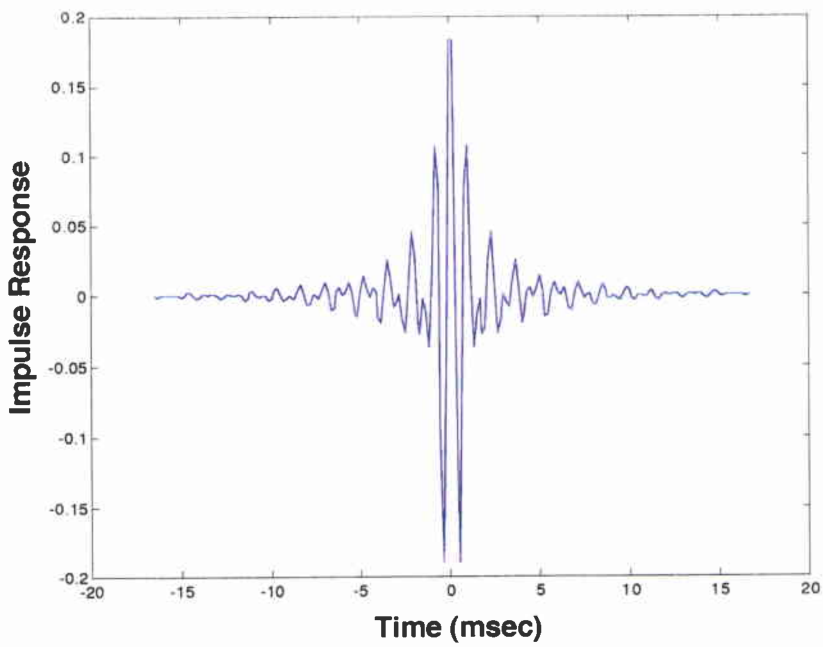


Figure 7 *Filter impulse response.*

3

Detection Processing

The automatic detection of marine mammal acoustic emissions is a difficult task. The wide variety of frequencies, bandwidths, and time characteristics of emissions from different species makes the design of one detector a daunting task. Take, for example, the sperm whale clicks shown in Fig. 5. Expanding a few of these clicks along with a time-frequency analysis (spectrogram) it is seen that the spectrum is not necessarily flat and the time series exhibits the effects of multipath propagation, spreading the signal energy in time. As other types of waveforms are expected (e.g., whistles or sweeps) a detector is desired that is flexible both in the time duration of the waveform and its frequency content. The following sections describe such an algorithm and illustrate its application to data from the SWAC4 sea-trial.

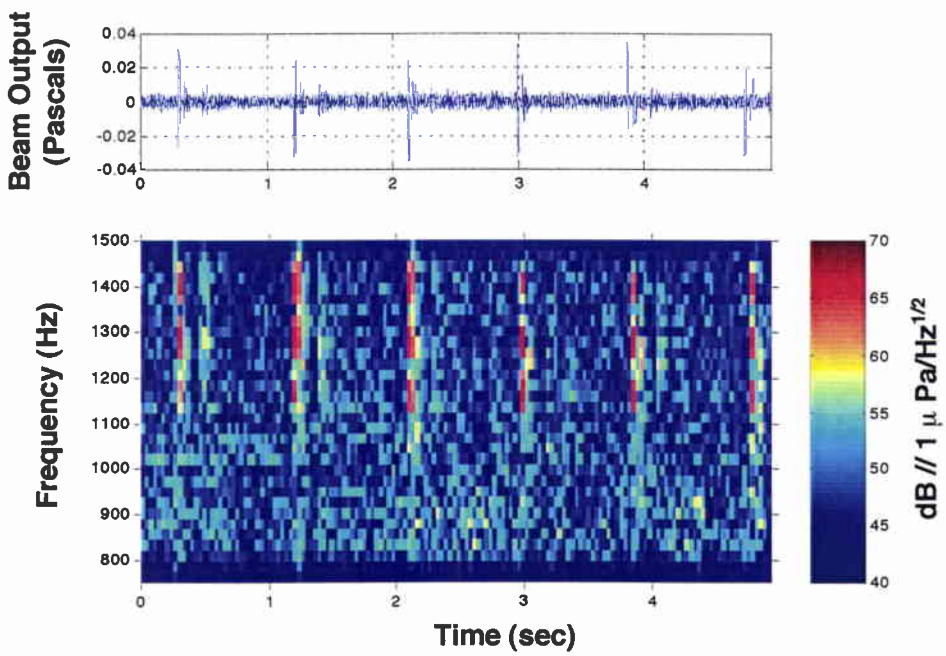


Figure 8 *Time series and frequency spectrum of sperm whale click train.*

3.1 Algorithm

A detector requires some method for distinguishing the signal to be detected from the background noise and any interferences. As this situation calls for a very general detector, not tuned to any specific characteristics of individual marine mammal emissions, the only distinction from the background or interferences is time duration. Thus, a detector is desired that finds short duration signals that are not similar to the (more slowly changing) background or interferences. Additionally, the detector should be robust to varying signal duration and frequency content. A detector with these characteristics was proposed by Abraham and Stahl [1] by combining the power-law processor of Nuttall [2] for the combination of discrete Fourier transform (DFT) bin outputs with a Page test [3]. The power-law aspect of the detector provides robustness against varying signal bandwidth. The Page test configuration provides robustness to an unknown signal duration. As both the start and end times of the signal are desired, the alternating-hypothesis form of the Page test [4, 5] must be implemented. In this configuration, the start and end times of a detected event are denoted by the most recent reset of the Page test to its null state as described in [6]. A block diagram of the detector structure is shown in Fig. 9.

Necessary to the implementation of the detector is the estimation of the background noise and interference power at the output of each DFT bin. As these may be considered 'nuisance' parameters (i.e., parameters that need to be estimated but are not used to describe the signal), the scheme proposed in [7] exploits the structure of the Page test to isolate data believed to be signal-free and therefore appropriate for estimation of the background noise and interference power. As this requires some feedback of information from the detector, there may not be a straightforward implementation in the Centre's real-time system. The detector structure of [7] uses data prior to the most recent reset of the Page test to estimate the nuisance parameters, in this case the background noise and interference power at the output of each DFT bin. The form of the background estimator may be of a sliding block or exponentially averaged type. In this case, the latter has been chosen because it is (marginally) easier to implement. Each time the Page test has a reset to zero, the background estimate is updated using all the non-signal data between the previous reset to zero and the current reset to zero (i.e., if a signal was detected in between, those data would not be included).

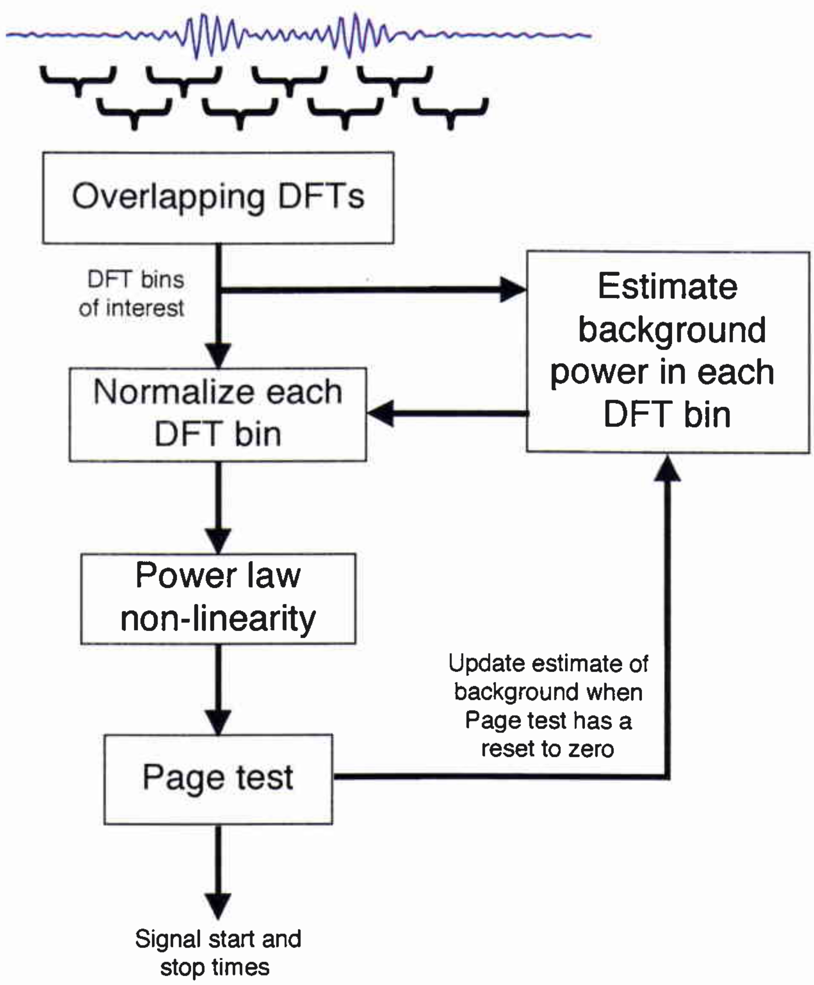


Figure 9 *Block diagram of detection scheme.*

3.1.1 Algorithm specifics

As the detector was to be applied to 120 beams for large amounts of data, the 6 kHz sampled data were decimated by a factor of 4 without any filtering beyond that described in Section 2.2. The effect of this is to alias the 750–1500 Hz band into the region between zero and 750 Hz. This is not simply a shift in frequency as 1500 Hz aliases to zero and 750 Hz aliases to −750 Hz.

In order to describe the detector algorithmically, some preliminary defintions are required. Let the magnitude squared output of the bins of interest from the k^{th} DFT be $\{X_{k,1}, X_{k,2}, \ldots, X_{k,m}\}$. In this case, all DFT bins representing the band 750–1500 Hz are of interest. Because of the decimation to 1500 Hz sampling rate, the DFT bins of interest are between zero and 750 Hz. Let the current estimators of the background power for the DFT bins be $\{\lambda_1, \lambda_2, \ldots, \lambda_m\}$. These should be initialized with a fixed block method or an exponential averager that has been running for a short time. Following are definitions of some of the variables used to implement the detector and the values for those that require setting, which were obtained through trial and error.

Description of variables

p - power law ($p \geq 1$, $p = 1$ was used)

h_0 - threshold for signal onset detection ($h_0 = 12$)

b_0 - Page test bias for signal onset detection ($b_0 = 2.5$)

h_1 - threshold for signal termination detection ($h_1 = 10$)

b_1 - Page test bias for signal termination detection ($b_1 = 5$)

α - time constant for exponential averager ($0 < \alpha < 1$, $\alpha = 0.95$ was used)

N_{fft} - size of DFT block ($N_{fft} = 128$)

N_{off} - offset from one DFT block to next ($N_{off} = 32$)

W - Page test statistic

i_0 - index to most recent reset to zero

i_0' - index for updating background power estimates

i_1 - index to most recent reset to $h_1 + h_0$ (signal present state)

The algorithm is described in pseudocode on the following page. It should be noted that the indices for the starting and stopping times are in terms of DFT blocks and must be converted to time samples based on the DFT size and amount of overlap.

Detection Algorithm

(1) Initialization

- Set $W = 0$, $k = 1$, $i_0 = 1$, $i_0' = 1$
- Form initial estimate of $\{\lambda_1, \lambda_2, \ldots, \lambda_m\}$

(2) Normalization and power-law

- Form normalized DFT bin outputs $Y_j = \frac{X_{k,j}}{\lambda_i}$ for $j = 1, \ldots, m$
- Apply power-law to normalized data $Z = \left[\frac{1}{m}\sum_{j=1}^{m} Y_j^p\right]^{\frac{1}{p}}$

(3) If $W < h_0$,

- Set $W = \max\{0, W + Z - b_0\}$
- If $W \geq h_0$,
  - The leading edge of a signal has been detected
  - An estimate of the starting time index is i_0
  - Set $W = h_0 + h_1$ and $i_1 = k$
- Else if $W = 0$,
  - A reset to zero has occurred, update background estimate

    for $i = i_0'$ to k and $j = 1, \ldots, m$

    $\lambda_j = \alpha\lambda_j + (1 - \alpha)\, X_{i,j}$

    end
  - Set $i_0 = k$ and $i_0' = k$

(4) If $W \geq h_0$,

- Set $W = \min\{h_0 + h_1, W + Z - b_1\}$
- If $W \leq h_0$,
  - The lagging edge of a signal has been detected
  - An estimate of the stopping time index is i_1
  - Set $W = 0$, $i_0 = k$, and $i_0' = i_1$
- If $W = h_0 + h_1$, set $i_1 = k$

(5) Set $k = k + 1$ and goto **(2)**

3.1.2 Alternative algorithm

The algorithm described on the previous page was found to perform well in detecting sperm whale clicks, most likely because they were strong and slightly spread in time owing to multipath. When faced with shorter and weaker dolphin click bursts, a modification was required. The DFT processing and normalization of each bin is necessary when the background noise and interference power is not constant with frequency. Assuming that the background noise and interference power is constant with frequency, or accepting the inherent loss when it isn't, the detector may be simplified by not performing a DFT and simply using the squared time series data. This simple modification fits into the framework of the algorithm described in Section 3.1.1 if $N_{fft} = 1$, $m = 1$, and $p = 1$. Then the squared time series data (decimated to a 1500 Hz sampling rate) are normalized and submitted to the Page test (effectively without a power-law non-linearity). This, however, proved to be too time consuming to process the data at hand. Therefore, a further compression of the data was performed by summing the square of every $L = 8$ samples to create a sequence with a sampling rate of 187.5 Hz,

$$X_k = \sum_{i=1}^{L} \left(V_{(k-1)L+i} \right)^2 \tag{1}$$

where V_i are the 1500 Hz sampling rate beam data. The sequence $\{X_k\}$ was then submitted to the algorithm of Section 3.1.1, as described above, with $h_0 = h_1 = 8$, $b_0 = b_1 = 4$ and $\alpha = 0.99$.

3.2 Detection results

The bandpass filtered and beamformed data were displayed on a passive sonar system developed by W. Zimmer, with audio and spectral analysis available for a single beam. All of the runs from the Kyparissiakos Gulf portion of SWAC4 were analyzed in this manner [8], selecting Run 9 and the first hour of Run 11 for further analysis by an automatic detection algorithm. The algorithm of Section 3.1.1 was applied to Run 9 data and the alternative algorithm described in Section 3.1.2 was applied to the Run 11 data. To avoid the problem of the direct blast and reverberation spilling into the processing band, the first 12 seconds of each ping were not processed. From the start and stop times of each detected event in the latter 48 seconds of each ping, the total signal energy was estimated and tabulated along with the current averge noise power estimate (here it is assumed that the detected signal is an energy signal and that the background noise is a power signal). Additionally, an estimate of the noise background after removal of the detected signals was formulated every 12 seconds. These data may be displayed as a signal energy-to-noise power ratio (ENR), as shown in Fig. 10 for the nearly three hour Run 9. The display in Fig. 10

Report no. changed (Mar 2006): SM-351-UU

shows the total ENR over 6 second intervals for the latter 48 seconds of each ping. Additionally, any detections spanning more than 10 beams were removed, cleaning the display of data glitches.

The detection results are then grouped into events by association over beam and time, as indicated by the numbers in Fig. 10. Event time series are then formed by choosing the beam containing the largest ENR over each 12 second period. These time series were then submitted to Prof. G. Pavan of the University of Pavia for classification. Those shown in Fig. 10 were all classified as sperm whale click trains. The detector also found many signals associated with surface vessels, particularly those from the RV Alliance in the forward beams, and a plethora of isolated detections that could be marine mammal, fish, man-made or false alarms. It is possible to associate some of the detections with surface vessels by overlaying the detection results on the estimated background noise, as shown in Fig. 11 for the first 20 minutes of Run 9. The surface vessels are clearly visible and detections overlaying them in beam and time are most likely originating there as well. The sperm whale click trains (events 1, 2 and 3) arrive on quiet beams, additionally supporting their classification as marine mammal. Event 21 was eventually classified as acoustic emissions from fish of unknown type. It may also be surmised that of the two sperm whales detected during the first several minutes that event 1 is nearer than event 2, assuming they both produced approximately the same source levels and suffered similar transmission loss. As the LF towed array was completing a turn previously carried out by the RV Alliance, localization of these two events was possible, including resolution of the left/right ambiguity. This will be discussed in Section 3.3.

The alternative algorithm described in Section 3.1.2 was applied to the first 52 pings of Run 11 as shorter click bursts were observed on the passive sonar system. The ENR of detected events is found in Fig. 12 where, of the events submitted to Prof. G. Pavan of the University of Pavia, many were classified as sperm whale or generic dolphin. The latter classification category can not be made more specific owing to the limited bandwidth available for analysis. As indicated by the display, there were many false alarms, indicating that the thresholds may need to be increased to limit the cluttering of the display, accepting the associated reduction in detection performance. Noteworthy in this figure is that ENR scale differs from that of Fig. 10 — the detections here are, for the most part, weaker than those of Run 9.

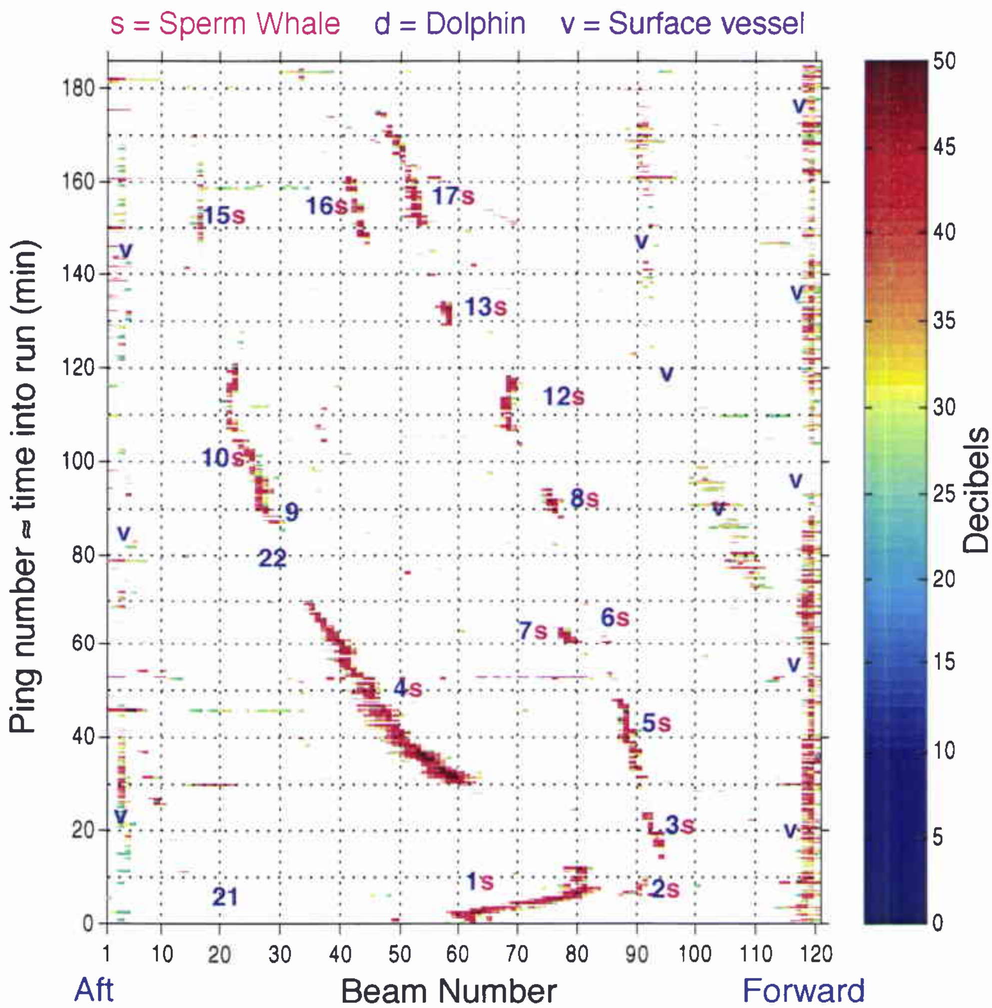


Figure 10 *Signal energy-to-noise power ratio (ENR) of detected events from Run 9, combined over every 6 seconds.*

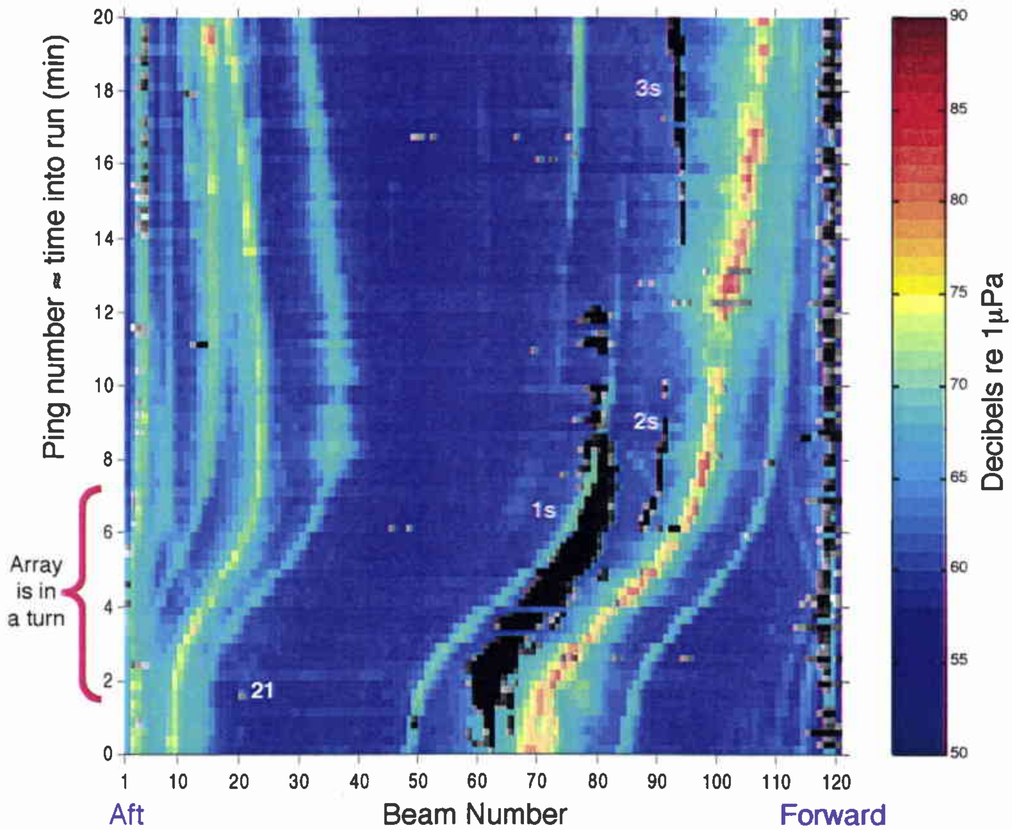


Figure 11 *ENR of detected events from first 20 minutes of Run 9 (gray scale) overlayed on background noise and interference power (color scale).*

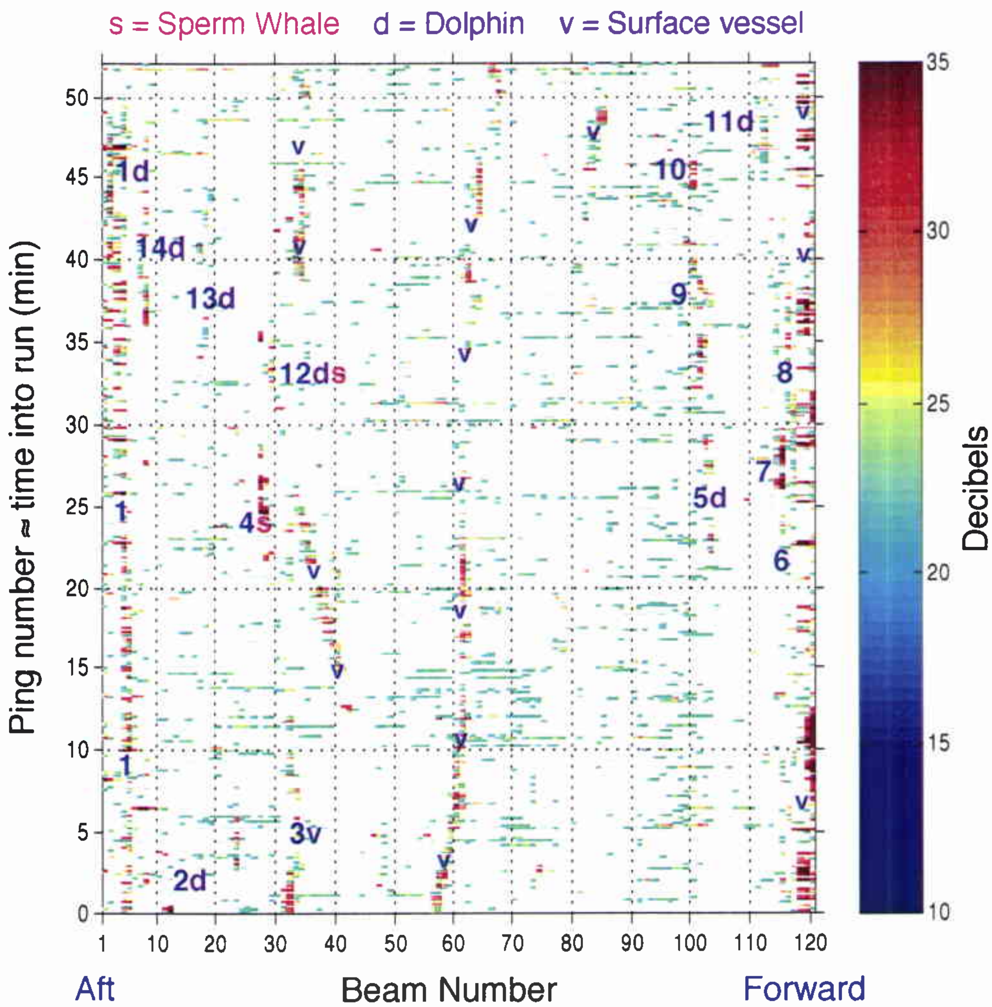


Figure 12 *Signal energy-to-noise power ratio (ENR) of detected events from the first 52 minutes of Run 11, combined over every 6 seconds.*

Report no. changed (Mar 2006): SM-351-UU

3.3 Localization

Passive listening of acoustic emissions inherently only provides bearing information, and owing to the line array nature of the acquisition, there exists a cone of ambiguity; that is, the sound arriving at the array sounds the same if it arrives from anywhere on a cone axially aligned with the towed line array. All of the runs analyzed were such that the tow ship (RV Alliance) was on a constant bearing. Thus, triangulating detections observed over extended periods of time still results in an ambiguity to the left or right side of the array. However, during the first 10 minutes of Run 9, the array was still completing a turn the tow-ship had made prior to commencing the run. From the array heading information (which is quite noisy) it was then possible to localize the two sperm whale click trains detected as shown in Figs. 13 and 14. Lines along the bearing of the detected events from the position of the RV Alliance are shown for events 1, 4, 10 and 15 of Run 9 in Fig. 13. Each line is 15 nautical miles long and when taken in conjunction with the others form a locus where the sperm whale might have been, effectively localizing the whale in range, bearing and resolving the left/right ambiguity. The lines from event 1 (the red ones) illustrate how assuming the wrong side for the left/right ambiguity results in diverging lines. It should be noted that there is no proof that the events shown are the vocalizations of the same animal. Figure 14 contains the localization of events 2, 3, 5, 6, 8, 12, 13 and 17 of Run 9. The ranging information garnered from Figs. 13 and 14, that event 2 is further away than event 1, is corroborated by the ENR levels observed in Fig. 10 where event 2 is weaker than event 1.

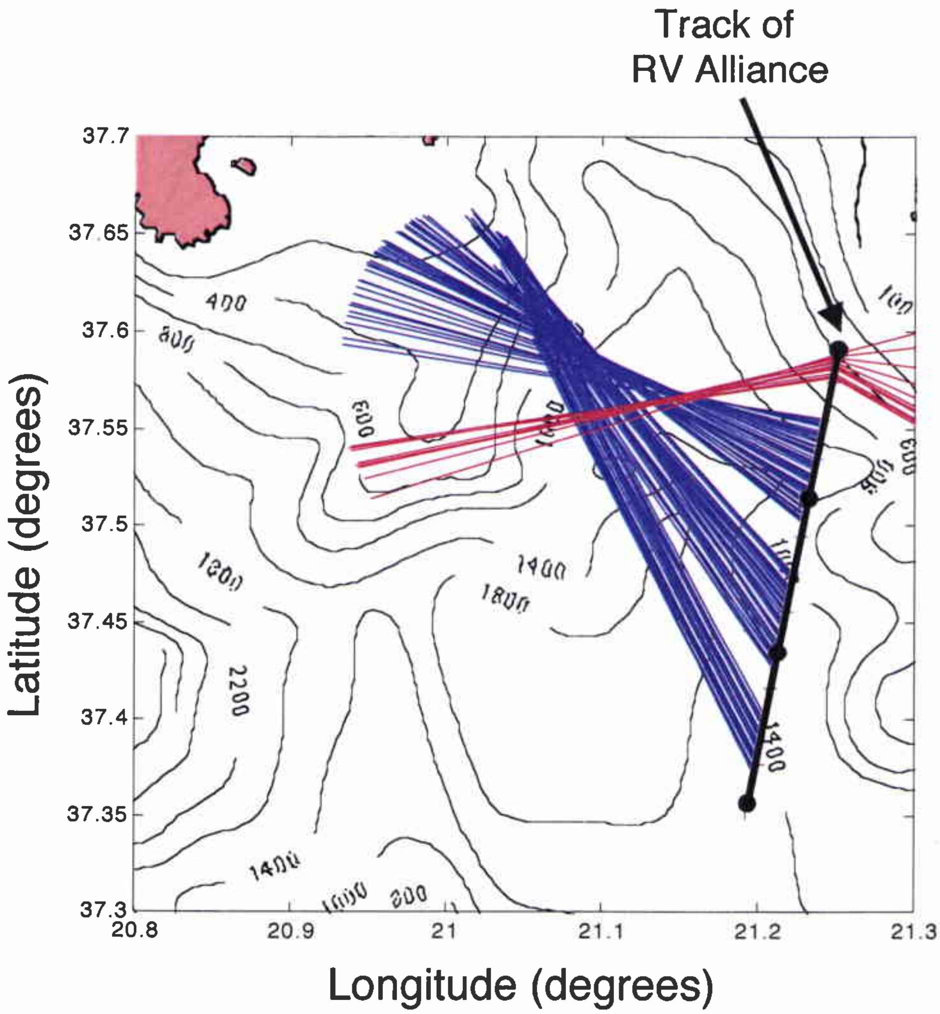


Figure 13 *Lines along bearings of detections for events 1, 4, 10 and 15 of Run 9. Each line is 15 nautical miles in length. Red lines are from event 1 and illustrate localization of a sperm whale to west side of the track of RV Alliance.*

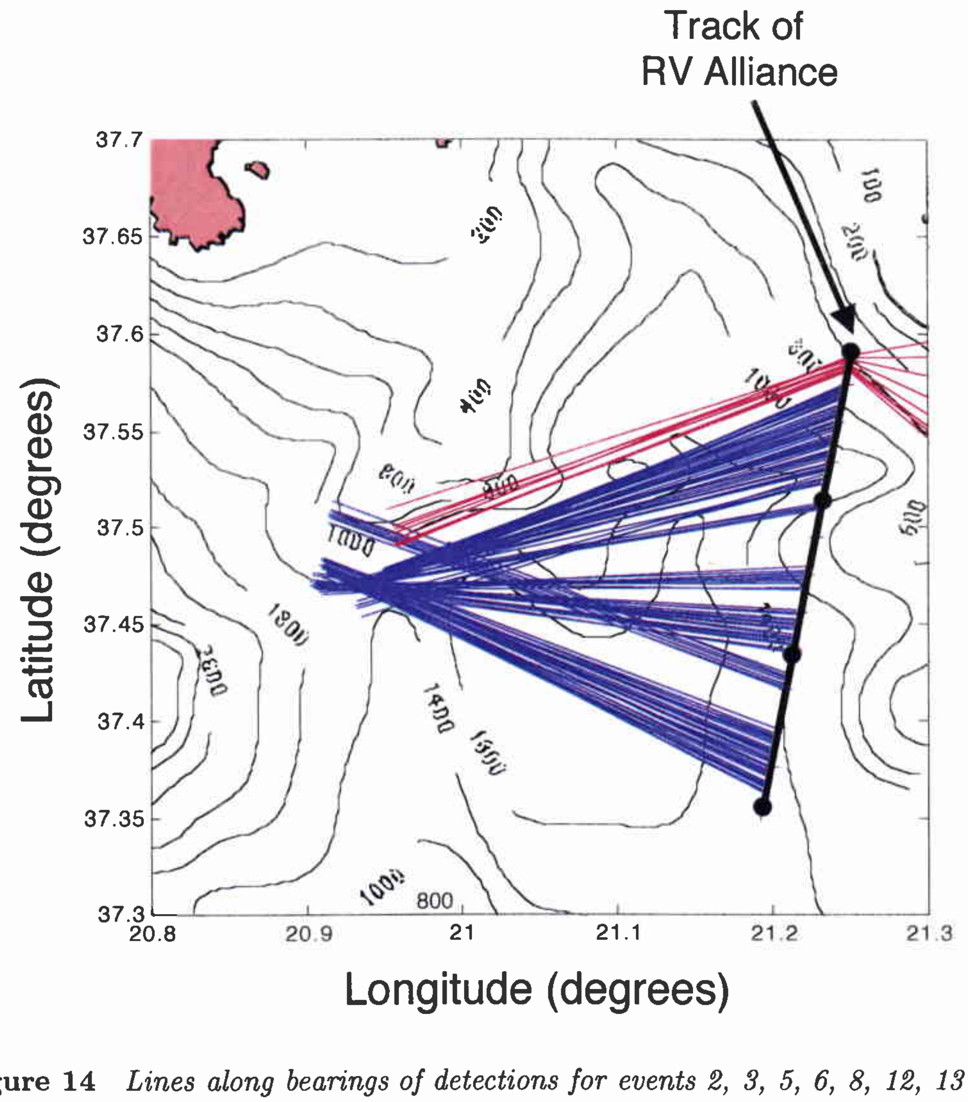


Figure 14 *Lines along bearings of detections for events 2, 3, 5, 6, 8, 12, 13 and 17 of Run 9. Each line is 15 nautical miles in length. Red lines are from event 2 and illustrate localization of a sperm whale to west side of the track of RV Alliance.*

4
Conclusions

A passive analysis of acoustic data (from the Centre's SWAC4 sea-trial) for the detection and localization of marine mammals has been described, detailing the signal processing and analysis choices made and the reasons behind them. An automatic algorithm for the detection of marine mammal acoustic emissions was presented, along with the results of its application to data from the SWAC4 trial. The algorithm was effective in estimating the background noise and interference power and then detecting departures from that norm. Sperm whale and dolphin sounds were detected within the data analyzed, along with numerous other detections not analyzed owing to limited time. Localization of some of the sperm whale sounds was possible through triangulation, with resolution of the left/right ambiguity of the line array data obtainable from a turn of the array at the beginning of Run 9.

5

Acknowledgements

Without the efforts of Walter Zimmer, this work would not have been possible. He designed and implemented a passive sonar system on the Centre's real-time system, enabling the analysis of large amounts of data and provided the filtered and beamformed data for the automatic detection processing. The author would also like to acknowledge the efforts of Angela D'Amico and Ettore Capriulo who both contributed to the work presented in this memorandum.

Report no. changed (Mar 2006): SM-351-UU

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Title

Passive acoustic detection of marine mammals.

Abstract

A passive acoustic analysis of data recorded during the SACLANTCEN SWAC4 sea-trial in Kyparissiakos Gulf during May 1996 was performed with the specific objectives of detecting, localizing, and classifying marine mammal sounds. Detection and localization (bearing only) was performed using a passive sonar system in a playback mode and by an automatic detection algorithm for specific runs or run segments. The results of the automatic detection processing allow association over time and bearing, creating 'events' that may then be classified by experts. This memorandum describes the preprocessing of the SWAC4 sea-trial data and the algorithm used to perform the automatic detection processing. The results of the automatic detection processing are then displayed in time-beam number plots and used to perform rough localization of detected events through triangulation.

Keywords

Detection – marine mammal sounds – Page test – power-law

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