Detection and localization of blue whale calls recorded on a seafloor hydrophone array near the East Pacific Rise

Olga Hernandez

March - August 2006

Blue whale - Baleanoptera Musculus

Long internship, First year of Master in Earth Science (Ecole Normale Superieure de Paris)
Performed at the SOEST - University of Hawaii.
Supervised by Neil Frazer and Robert Dunn.
## Contents

**Acknowledgements**  
2

**Abstract**  
3

**Resumé**  
3

1 **Introduction**  
4

2 **Data**  
6  
2.1 Study site and Instrumentation  
6  
2.2 Airgun source  
7  
2.3 Data Processing  
8  
2.3.1 PSD  
8  
2.3.2 Spectrograms  
8  
2.3.3 Filtering  
9  
2.4 Recorded sounds  
9

3 **Methods**  
11  
3.1 Tracking Methods - location algorithm  
11  
3.2 Arrival Times  
11  
3.3 Inverse Problem theory - Grid search method  
12  
3.4 Sources of error for acoustic location  
16  
3.4.1 Input variables  
16  
3.4.1.1 Arrival times measurement  
16  
3.4.1.2 Sound velocity  
17  
3.4.1.3 Receiver position coordinates  
17  
3.4.1.4 Conversion between spherical earth and cartesian grid  
17  
3.4.2 Source array geometry - Bathymetry  
17  
3.5 Ellipse error: simplification of the probability surface  
19

4 **Results**  
21  
4.1 Blue whale call characteristics  
21  
4.2 Whale localization  
26  
4.3 Whale velocity  
30  
4.4 Sound levels. Comparison between sound levels of air-guns, local earthquakes and blue whale calls  
31

5 **Discussion**  
33  
5.1 Blue whales call  
33  
5.2 Localization  
34  
5.3 Effects of the noise on the blue whales  
35

6 **Conclusion**  
37

**References**  
38
Acknowledgements

I would like first to thank Neil Frazer for having given me the wonderful opportunity to do this internship and to work in this subject I wanted to study since my childhood. Thanks for allowing me to learn about the whale’s world and marine acoustics domain. Thanks to Robert Dunn and Eva Nosal for their helpful presence during my internship. Thanks to the people from Coconut Island who gave me the opportunity to see their fieldwork in acoustics with the dolphins.

A huge thank to all the people who made me enjoy these five months and a half in Hawaii, especially Quentin for having discovered a bit of Hawaii with me, and my mother, cousins and Jacopo for the great time we had when they visited me. Eventually, I would like to address a special thank to Basile, Mélanie and Eric, for having spent such a good time in Hawaii together, for their companies, for our great weekends, diving and hiking around these so beautiful hawaiian islands.
Abstract

Low frequency calls produced by blue whales were recorded near the northern East Pacific Rise on a seafloor hydrophone array moored in the area. Data from the hydrophones were examined and during 3 of 20 days of recording, blue whale calls were found on 11 hydrophones. We studied the characteristics of the blue whales’ calls and their different patterns and add additional information about Blue whale calls to the small body literature on the subject. More than 3 whales were recorded during these 3 days and 2 or 3 different whales were tracked using a grid search algorithm that is based on inverse theory. We determined that these whales were of the Northeastern Pacific Blue population. We detected call types known as A, B, C, and D in various patterns. Over the course of a day, the whales moved approximately west to east at about 4.5 km/hr. During 2 of the 3 days that we tracked the whales, a seismic ship, the R/V Ewing, carried out an active-source seismic experiment using an air-gun source. We examined the whale calls and locations with respect to the times of air-gun activity and we did not find any correlation between the whales’ behaviour and the air-gun activity. Nevertheless, this result in itself is significant and indicates that for whales located at 30 km or more from a 139 liter, 20-gun air-gun source, there is little or no detectable behavioural response.

Resumé

Des sons basse fréquence produits par des baleines bleues ont été enregistrés près de la ride Nord-est Pacifique grâce à une série de d’hydrophones amarrés sur le fond marin de ce secteur. Pendant les 3 des 20 jours d’enregistrements, des sons de baleine bleue ont été détectés sur les signaux de 11 hydrophones. Nous avons étudié les caractéristiques de leurs différents chants, ce qui a permis de compléter la faible littérature existante sur le sujet. Plus de 3 baleines ont été enregistrées pendant ces 3 jours, dont 2 ou 3 ont été localisées en utilisant un algorithme de recherche sur une maille issu de la théorie du problème inverse. Nous avons identifié ces baleines comme faisant partie de la population du Nord Est du Pacifique. Nous avons détecté des types de vocalisation connus sous le nom de sons A, B, C, et D dans divers types de chants. Pendant la journée, les baleines se sont déplacées d’Ouest en Est à une vitesse d’environ 4.5 km/h.

Un bateau sismique, le R/V Ewing, effectuait une expérience sismique utilisant des canons à air basse fréquence pendant les 2 des 3 jours où nous avons localisé les baleines. Nous avons recherché des corrélations entre les chants des baleines, leur localisation, et les signaux envoyés par les canons à air, mais nous n’en avons pu en mettre en évidence. Ce résultat est tout de même significatif et indique que, pour des baleines situées à 30 kilomètres d’une source sonore composée de 20 canons à air (V=139 litres), la réponse comportementale est faible ou non détectable.
1 Introduction

Acoustic detection and tracking of marine mammals is of interest to biologists who study whale behavior. The ability to understand the behavior and location of different populations is also vital to work in fisheries, seismic experimentation, tourism, and military activities because the legal protections for marine mammals can restrict or alter the way these activities are undertaken.

During the last century, the population of some species of whales has been decreasing at an alarming rate due to modern whaling [1]. Recently, despite passing protective legislation against whalers, current populations are still scarce and some populations continue to decline. Other sources of harm and disruption to whale populations still persist such as ship collision, disturbance by vessels, entrapment and entanglement in fishing gear, habitat degradation, military operations and especially noise produced through such activities [1]. How does the noise affect cetaceans?

The ocean is far from being the world of silence described by Jacques Cousteau [2]. Earthquakes and volcanoes, wind and waves, rain, biological noise (shrimps, cetaceans, etc.) and sea ice noise create a complex source of natural sound. But in this last century, humans have increased the sound level in the ocean with vessel traffic, the use of marine seismic surveys, drilling activity, fisheries, military activity, aircraft overflights and industrial activity. The combination of the natural and anthropogenic noise has lead to a spectacular increase in noise in the sea [3]. The effect of high levels of man made noise on whales is not well understood. Some studies have focused on how the noise disturbs whales behaviour and whale migration and showed that it might affect hearing sensitivity [3].

Collisions with vessels and strandings have been linked to the use of low frequency sonar. In fact, low frequency waves, because they can travel long distances, are probably the most damaging. For example, in 2002, 14 beaked whales were stranded on a beach in the Canary Islands following NATO military exercises [4]. In 2005 between 70 and 110 rough toothed dolphins were stranded in southern Florida. Twenty hours before, a US navy submarine was in the area but they refuse to confirm whether or not they used a low frequency sonar. Air-guns used in seismic exploration, much less powerful than military sonars, also represent a significant man made noise, and restrictions have been placed on their use in some waters (US, Canada waters). But for now, the knowledge of how their sound affects whale populations is poor and most of these rules are based on only a few studies. Therefore, further studies are needed to properly define how to protect marine mammals.

To study in more detail how human activities affect whales behaviour we attempted to track blue whales during a seismic experiment using records from a seafloor hydrophone array moored in Northeast Pacific during a research cruise in November 1997 near the East Pacific Rise.

The blue whale is the largest known mammal ever to inhabit the Earth (length of more than 33m and weight of around 190 tons) and the second loudest animal after the sperm whale. Classified as endangered species in 1966 and protected by the International Whaling Commission, the worldwide population is hard to evaluate and is estimated between 4000 and 12 000 individuals in 2002, 1750 of them living in the North East Pacific [5]. Between 1898 and 1976, 365 870 blue whales were killed worldwide, and less than 9000 were killed in the North Pacific Ocean.

There are 3 subspecies of blue whales; only the Baleanoptera Musculus Musculus was recorded in our data, the two others living only in the southern hemisphere and in Antartic waters. Common to all blue whales is the production of high intensity, low frequency, long duration acoustic calls that are produced in repetitive patterns or songs, and most likely used for communication [6]. Different populations with specific vocalization can be identified. Indeed, blue whale vocalization recorded in the Atlantic Ocean, Indian Ocean, off Southern Chile, Northeast Pacific and Northwest Pacific are distinctly different and allow identification of different populations from their calls. In
the data analyzed here the blue whales are identified as belonging to the Northeast Pacific blue whale population.

In the first part of this work we study the characteristics of the Northeastern Pacific blue whale’s calls. Mysticete (baleen whale) vocalizations with fundamental below 100 Hz are evident in low frequency record. Most commonly recorded are blue and fin whales, which vocalize between 10 Hz and 400 Hz. Comparisons of the calls in our data with those of other studies reveals that our data is of blue whale calls (references [7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18]). Acoustic methods for studying whales are very useful because in an environment where visibility is limited and individuals are often dispersed, it provides an opportunity to study the presence and movements of a species within a given area. Studies of whale vocalization allow us to distinguish whale populations, to determine the characteristics of their vocal behaviour, and to determine their swimming speed. We document here the characteristics of blue whale calls in our data and compare them to previous work.

In the second part, we track the whales from their calls using a localization algorithm based on inverse theory and we attempt to detect some anomalous behaviour in the whales during times of nearby air-gun activity.
2 Data

2.1 Study site and Instrumentation

From November 6 1997 to December 6 1997 an array of ocean bottom seismometers and hydrophone were moored near the East Pacific Rise (Long: -105°00’ -103°3’ Lat: 8°20’ 10°10’) to record active-source seismic data generated by air-guns (cruise EW97-08 aboard the R/V Ewing). These data were collected to seismically image the structure of the crust and uppermost mantle with the objective to study the nature of magma transport from the uppermost mantle to the crust beneath this active mid-ocean ridge.

Figure 1: The observation site was located along a segment of the East Pacific Rise near 9°N latitude. This segment is bounded by the Clipperton Transform to the north and the Siqueiros Transform to the south and it is approximately 210 km long.

Figure 2: Location of 11 hydrophones moored in the Eastern tropical Pacific used for this study - Bathymetry of the study site
Seismic data were collected on 37 ocean bottom receivers from the Woods Hole Oceanographic Institution. Twenty of these were Office of Naval Research, three-component seismometers (OBSs: ocean bottom seismometers) equipped with 1-Hz geophones and a hydrophone; the remaining units were ocean bottom hydrophones (OBHs: ocean bottom hydrophones and ORBs: ocean reflex in a ball). For our study we use the hydrophone channel of each instrument. Recordings were made with a sampling rate of 200 Hz for the OBH and ORB and 128 Hz for the OBS. The placement depth for the hydrophones was 2880-3100 m.

Hydrophones are a transducer that converts sound pressure into electricity (V). For a plane wave of sound, the pressure \( p \) is related to the velocity of the fluid particles \( u \) by \( p = \rho c u \) where \( \rho \) = fluid density, \( c \) = propagation velocity of wave, \( \rho c \) = specific acoustic resistance of the fluid, for the seawater = \( 1.5 \times 10^7 \text{g cm}^{-2} \text{ms}^{-1} \).

There exists a proportionality factor, called the “response” of the hydrophone, that relates the recorded voltage to the acoustic pressure of the sound field [19]. Unfortunately, in our study we did not have access to response. We only knew that the instrument responses were different between the hydrophones channels of the OBH, ORB and OBS. Effectively, figure 3 shows how the noise levels are different with the two types of hydrophone: in the OBH the highest sound are recorded between 40-80 Hz and for the OBS hydrophone the interval is 3-30 Hz. Because we do not have access to the instrument responses, and it is not possible to know the acoustic intensity, all the plots, spectrums and spectrograms are in relative, not absolute, units.

![Figure 3: At left, one example of spectrogram for the OBH, at right one for the OBR (3-63 Hz). A filter passband 3-95 Hz was applied.](image)

### 2.2 Airgun source

The seismic source was the now retired R/V Ewing’s 20-gun, 8500-cubic-inch (139 litre), air gun array. The array was towed behind the ship and was fired at intervals of 210 s (shot spacing of 500 m). The air-guns are designed to focus energy downward rather than to the sides. Furthermore, fore and aft energy transmission is greater than in the transverse directions.

In a study of the air-guns sound output [20] it was found that for deep water, and at distances of about 0.5-1 km, near surface sound levels are about 180 dB in the 5-100 Hz range. Sound levels decrease to around 140 dB when the ship is at 10 km from the receiver (figure 4). Sound levels at greater distance are less known, but expected to be less than 140 dB in any case.
2.3 Data Processing

2.3.1 PSD

We use the function pwelch in Matlab to estimate the power spectral density (PSD) of the signal (PSD=square of fourier transform module). This calculates the FFT (Fast Fourier Transform) using Welch’s method (averaged periodogram with overlapping). The sound spectra depict the distribution of sound power as a function of frequency using the Fourier Transform, although does not show the non stationary character of the signal. It does not give information over time that the events of frequencies occur.

2.3.2 Spectrograms

To study the characteristics of non stationary signals such as animal sounds, we used the spectrogram (also called a sonogram) that represents the spectrum over time. The spectrogram is computed by the function called Short Time Fourier Transform (STFT). Figure 5 shows this principle. The signal is divided into small intervals that are overlapped and windowed with a Hamming window. The purpose of the windows is to extract a portion of the signal that is approximately stationary. For each small interval of time, the discrete Fourier transform is calculated. This spectrum is then represented in one time that corresponds to the middle of the window. We made all the spectrograms with Matlab using the spectrogram function: 

\[ \text{SPECGRAM} \left( \text{Signal}, \text{nfft}, \text{Fs}, \text{window}, \text{numoverlap} \right) \]

where Nfft specifies the number of frequency points used to calculate the discrete fourier transforms, we use a nfft as a power of 2 because the execution is faster, Fs the sampling frequency, numoverlap specifies the number of samples the sections of signal overlap, and window is the length of the window applied.

There is a compromise between frequency resolution and the resolution of details in the time domain. If we use a higher NFFT, we will have better frequency resolution and poorer temporal resolution, and vice versa if we use a smaller NFFT. To have better resolution in the time domain we can use larger overlaps, but the computation is much longer. In this study, a Hamming window with length between 1.28s and 5.12s with 50-99 % overlap was used to calculate the spectrogram and to provide a good resolution.
2.3.3 Filtering

To separate the blue whale calls from other noise that is not in the same frequency band, we applied a 3rd order Chebyshev band pass filters to the data (Figure 6).

![Figure 5: Principle of the spectrogram](image)

![Figure 6: Example of low pass Chebyshev filter I](image)

2.4 Recorded sounds

Twenty days of recordings were study and analyzed and several signals were found in the data. The most common signals are from seismic sources such as earthquakes (fig 7) and air-guns (fig 8), and from anthropogenic noise sources (instruments, ships - figure 8). During 3 days it was possible to record signals from biological sources. These sounds were compared with the literature and were identified as blue whale calls (based on literature comparison of blue whales spectrogram). Blue whale data was recorded throughout the days of 23-24-25-26 November on about 11 hydrophones. But for the days 24-25 the records are poor because air-gun shots are present every 210s and obscure many of the records. In general, whale calls are masked by underwater noise that propagates at similar frequencies. Underwater earthquakes, volcanoes, air-guns, sonars, wind, waves and rain produce low frequency sounds that mask whale calls in general.
Figure 7: 1.- Principle of P, S, T waves propagation: underwater earthquakes generate P and S waves inside the earth. At the interface with the ocean (X) P waves are transformed to T waves (tertiary wave). This acoustic wave is propagated at $1500 \text{m/s}$ in the water and is usually trapped in the low velocity oceanic water called the Sofar channel (Sound Fixing And Ranging). In this channel, 500-1500 m deep, the waves are more often trapped by the reflection and refraction mechanisms and travel very long distance with little attenuation. 2.- Earthquake recorded by the hydrophone obh20 hour 22 - P wave and T phase are visible in this record. The multiples of the P wave are also visible. These are generated by the reflection of the P wave in the surface and the seafloor.

Figure 8: Waveform, Spectrogram, Spectrum for records of ambient noise (A), air-guns (B) and ship noise (C). In C, the ship is at less than 1km from the station that recorded this signal. The ship noise appears as parallel bands of energy in the spectrogram.
3 Methods

3.1 Tracking Methods - location algorithm

Largely developed within the earth sciences community, inverse theory is arguably the most rigorous method of using data to make inferences about physical systems. The inverse problem is used in many branches of science and mathematics like medical imaging, remote sensing, ocean acoustic tomography, etc., but it was essentially developed in geophysics [22]. Since the calls of marine mammals can be detected at long distances, this facilitates their use for acoustic localization of the animals via inverse theory. The whale localization problem is similar to the earthquake location problem, with the principal difference that the whale repeats its call and moves in time. As with the earthquake location problem, we record and measure the times when the signal (the acoustic energy of the call) arrives, we know the positions of the receivers, and we have a theoretical model for the propagation of the acoustic energy. Together, these pieces of information allow us to solve for a whales location.

3.2 Arrival Times

Measurement of the arrival times of whale calls on instruments can be made by several different methods and is a critical step in any localization problem. Usually cross correlation is the standard method for automatically determining differences in arrivals times between pairs of stations. This technique provides a correlation function between two waveforms. This can be done in the time domain or the frequency domain. We tried cross correlating the waveforms, the envelopes of the waveforms, the phase, and spectrograms. The presence of air guns and noise at the same frequency as the whales made this step difficult with our data. Thus, we picked the arrivals times manually. For picking, we filtered the signal with a 14-20 Hz band pass filter (in this band the calls are the most visible) and picked the arrivals times in the waveform. We could pick the spectrogram instead but computation time limited this procedure. We picked one or two calls each hour, and we picked only the onset of the B call because the onset is cleaner than for the A calls. (A and B call are the two most common calls for the blue whale). Figure (9) shows the signals on 11 hydrophones, we picked only the calls that are the clearest. For each manual pick, 1-sigma uncertainties were assigned that ranged from 0.1s to 4 s.

Figure 9: Record of A-B calls in 11 hydrophones on November 23 at hour 7. At left, figure of signal before filtering, at right after filtering
3.3 Inverse Problem theory - Grid search method

A common technique for passive acoustic localization of whales is the hyperbolic method [23], [24]. This approach provides one location estimate and an estimate of its corresponding error. However, there are strong implicit assumptions build into this method and better methods have since been developed in the seismic literature for earthquake location. Based on the work by Tarantola and Vallette [25], [22] our approach is to provide a complete representation of the probability of a whale's location. The most general procedure, which we employ, is to use a brute-force grid search method that compares arrival time measurements with predicted arrival times for all grid locations and computes a probability density over this grid based on a measure of the misfit surface between the observed and calculated data. Then we can choose the maximum likelihood position for a whale and examine the probability distribution of the whale's location [25]. Because the calculations can be very long, this method has been seldom used in the past. However, with the advent of faster and faster computers, this method is sure to become a standard tool for localization procedures in the near future.

Our method consists of defining a grid over the "model space", which is the area of the ocean for which we might find the whale. The model space could be the entire ocean, but because of transmission loss and detectability thresholds, any recorded whale will be within \( \sim 100 \) km of the nearest station. Choosing a smaller area greatly reduces the computation time of the algorithm, but one must be careful at a true location does not fall outside of the grid. In general, the unknowns in the problem are the spatial-temporal coordinates of the whales, \( m=(X,Y,Z,T) \) where \( X \) is the longitude and \( Y \) is the latitude, \( Z \) is the depth and \( T \) is the origin time of the whale call. We neglect the depth of the whale, since it is small compared to the distances to the stations and will have little affect on our solutions; in addition, all hydrophone are bottom moored and depth estimates will be poorly constrained. As described below, for simplicity we also remove the origin time of the whale call from the problem. After localizing the whale a simple back calculation can be made to get a rough estimate of the call origin time if needed. We did not consider that the origin time was of importance to our study, but other researchers may wish to solve directly for this parameter. Finally, our unknown model parameters is reduced to \( m= m(X,Y,T) \).

Additional information includes the coordinates of the hydrophones \( (x^i, y^i, z^i) \), the acoustic velocity model of the ocean \( c \), and the observed arrival times \( t_{\text{obs}} \), and uncertainties of the observed times \( \sigma_t \).

For a given \( (X,Y) \), the arrival time of the calls at the \( i^{th} \) hydrophone can be computed using:

\[
t^i_{\text{calc}} = g^i(X, Y, T) = \sqrt{\left(\frac{x^i - X}{c}\right)^2 + \left(\frac{y^i - Y}{c}\right)^2 + \frac{z^i}{c}^2} + t_{\text{origin}}
\]
To calculate the travel time for acoustic energy between a point on the grid and a hydrophone we make the following assumptions:

- **Constant water velocity.** We use the mean velocity over the depth range of 0-3000m, as measured at sea during the seismic cruise.

- **Flat Earth:** we assume a 2-D grid for the whale location (whale is assumed to be at/near the surface). On the other hand travel times are calculated from the deeply moored hydrophone positions to the grid at the surface with 3-D rays.

- **Straight-line paths for energy propagation.** Since the water velocity is taken as a constant, the ray paths are straight lines. This assumption is made to shorten the computation time. Another method, not employed here, would be to use a velocity model that changes with depth, \( c = c(Z) \), and precompute the travel times a function of distance for each hydrophone. Then, the travel time to any grid location can be simply looked up in (or interpolated from) this precomputed table of values.

- **Short distance conversion factors to map between lat/long and \((x,y)\) distance on a grid (in km).** For additional simplicity and speed in the grid calculations, we map all lat/lon values to a local cartesian grid defined in kilometers. Because the overall area is small and the experiment is located near the equator, the distortion resulting from this mapping is inconsequential.

- **Not assuming a prior model information.** For each call and computation of the whale’s location, we assume that we have no a priori information about the whale location other than that it is close enough to be heard and so it is on our grid somewhere. A future modification would be to use the previous known location of the whale and its speed and heading as a priori information for the next location calculation. The addition of such information would reduce the overall uncertainty in a whale’s location, but it is not clear that the maximum likelihood location of the whale would be greatly altered.

Later, we will examine the impact that these simplifications have on the certainty of a whale’s location.

The relationship between the data and the parameters, between the arrival times and the spatiotemporal coordinates of the whale, are given by

\[
t = g(X, Y, T) = g(m)
\]

with \( g \) representing a nonlinear operator from the model space into the data space. In other words, given a position \( X, Y \) on the grid and origin time \( T \), then \( t \) is the arrival time calculated at a station.
The general solution for the inverse problem is given by [22]:

$$\sigma(m) = \int \frac{\rho(d,m) * \theta(d,m)}{\mu(d,m)} d \theta$$

where $\sigma(m)$ is the probability density function of the solution, $\theta(d,m)$, the theoretical probability density representing the theoretical relationships between data and parameters, $\mu(d,m)$ representing the state of uniform information on the system, and $\rho(d,m)$ the prior probability density, representing both the results of measurements and all a priori information on parameters.

This equation can be simplified by the model parameters assuming that the a priori information of the data $d$ is independent from the a priori information of the model $m$ (then $\rho(d,m) = \rho_d(d) * \rho_m(m)$), and by assuming that $\theta(d,m) = \theta(d|m) * \mu(m)$. Thus,

$$\sigma_m(m) = \rho_m(m) * \int \frac{\rho_d(d) * \theta(d|m)}{\mu(d)} d \mu$$

where $\rho_m(m)$ is the prior density information in our parameters, $\rho_d(d)$ the prior density information in our data, $\theta(d|m)$ the conditional probability density representing for given values of the model parameters $m$ a probability density over $d$ and $\mu(d)$ the state of uniform information for the data.

We assume that the uniform information function $\mu(d)$ is constant and need not be considered, so $\mu(d) = 1$. We assume that the whale has equal probability of being anywhere on the grid, each grid point has the same a priori probability, nevertheless we could say that the position whale in time could be closer that in the time $i-1$ and not assume a uniform information function.

In our problem we didn’t considerate a priori density information in our parameters, then $\rho_m(m) = 1$. We assume that the data and the parameters are independent and there aren’t a theoretical relation ship between these, so $\theta(d|m) = 1$.

After this simplification, we obtain that the probability density function is equal to the a priori density information of our data. Then:

$$\sigma(m) = \rho(d)$$

$$\sigma_{X,Y,T}(m) = \rho(X,Y,T)$$

The measured data always have errors. These errors may have any distribution, since there are several sources of errors, the combined error is likely to give rise to a Gaussian distribution [22]. Assuming this our data possess a Gaussian structure,

$$\rho(t) = exp(-\frac{1}{2} * (t - t_{obs})^T * C_T^{-1} * (t - t_{obs}))$$

with $C_T$ the covariance matrix of the observed time.

If we assume that we have a Gaussian model, and assume that $t^i = t^{i,calc}$, the probability density function is given by:

$$\sigma(X,Y,T)^i = exp(-\frac{1}{2} * t_{obs} - t^{i,calc})^2$$

$$\sigma(X,Y,T) = exp(-\frac{1}{2} * (t_{obs} - t)^T * P * (t_{obs} - t))$$

with $P = (C_t + C_T)^{-1}$, with $C_t$ the modelization error covariance matrix, and $C_T$ the observational error covariance matrix.

The probability density function $\sigma(X,Y,T)$ gives the general solution for the problem of spatiotemporal whale location in the case of Gaussian data. Because we are interested in the spatial location data and not in the temporal location, we calculate the probability density function $\sigma(X,Y)$.
\[ \sigma(X, Y) = \int \sigma(X, Y, T) dt \]

After integration and some matrix manipulations [22], the equation can be simplified by:

\[ \sigma(X, Y)^i = \exp\left(\frac{-1}{2} \cdot \frac{(t_{\text{obs}}^i - t_{\text{calc}}^i)^2}{\sigma^2}\right) \]

or

\[ \sigma(m) = \sigma(X, Y) = \exp\left(\frac{-1}{2} \cdot (t_{\text{obs}} - t_{\text{calc}})^{\text{T}} P (t_{\text{obs}} - t_{\text{calc}})\right) \]

where \( t_{\text{obs}} \) is the observed arrival time minus the weighted mean of observed arrival times, and \( t_{\text{calc}} \) is the computed travel time minus the weighted mean of computed arrival time.

\[ t_{\text{calc}}^i = t_{\text{calc}}^i - \frac{\sum_{j} (p_j \cdot t_{\text{calc}}^j)}{\sum_{j} (p_j)} \]

\[ t_{\text{obs}}^i = t_{\text{obs}}^i - \frac{\sum_{j} (p_j \cdot t_{\text{obs}}^j)}{\sum_{j} (p_j)} \]

with \( p_i = \sum_j P_{ij} \) and \( P = (C_t + C_T)^{-1} \)

We used these equations in the Matlab scripts of our localization algorithm.

The probability density \( \sigma \) describes all the a posteriori information we have on the whales coordinates. Having this result, the simplest way for study this information is to plot the values of \( \sigma(X, Y) \) directly in the region of the study (see figure 11).

![Figure 11](image)

Figure 11: Results of the inverse problem for the whale’s location. Gaussian distribution appears as a series of constant color contour ellipse: Probability density surface.

With an array of \( N \) receivers one can measure \( N-1 \) independent arrivals time. This is the reason that to obtain a good location, we need a minimum at 3 stations. For a 3D localization, 4 hydrophones are needed.

The measured data and the parameters have errors and associated uncertainties. In our algorithm we incorporate known sources of errors, and we define two covariance matrices \( C_t \) and \( C_T \).
$C_t$ is the covariance matrix which contains estimates of errors made when we calculate the theoretical arrival time at the hydrophone from a source $(X,Y)$. $C_T$ contains the error in the observed time which is described by the variance $\sigma_t^2$ and is assumed to have a Gaussian distribution. Each arrival time has its own uncertainty.

The total error is defined by the matrix covariance $C$

$$C = C_t + C_T = C_t + \sigma_t^2$$

In the Gaussian assumption, observational error and model errors simply combine by addition of the respective covariance operators, even when the forward problem is non-linear.

By assuming $C_t = 0$, one assumes that all the errors from the path, the model velocity and the instrument location are negligible. But in our case, we assume an error of $C_t = 1$. This error is made by the sum of the straight line path errors, the error in the instruments and the model velocity. We assume that error in the model velocity is less than 0.4s, and the error induced by assuming straight line paths is less than 1s: therefore,

$$C_t = \sqrt{\sigma_{velocity}^2 + \sigma_{linepath}^2} = \sqrt{(0.4^2 + 1^2)} \approx 1$$

We can assume that data and parameters are independent each with each other, and therefore the covariance matrix $C_t$ is diagonal.

To find the reliability of our algorithm and then the reliability of our location, we compare the calculated travel time with the observed travel time (see figure 3.3).

![Figure 12: Comparison of observed and calculated travel time data for one vocalization of a whale recorded by 6 hydrophones](image)

### 3.4 Sources of error for acoustic location

#### 3.4.1 Input variables

##### 3.4.1.1 Arrival times measurement

For the travel time picks the 1-sigma error in the arrival times is estimated to be between 0.1 s - 2s, varying from pick to pick and is largely dependent upon the noise levels on the instruments and the emergent versus sharp onset of whales call - the sharper the onset, the lower the uncertainty. The root-mean-square error of all of the arrival times is around 1s. Larger errors overall tend to spread out the probability density of the whales location and thus reduce the certainty of the whales location. Relative differences in the errors from pick to pick weight their respective arrival time measurements. Thus, a pick with large error has less weight towards affecting the solution than picks with small errors.
3.4.1.2 Sound velocity

In the ocean, pressure, temperature and salinity modify the acoustic sound speed, and thus sound speed varies both horizontally and vertically, with the vertical variation being much stronger. Figure 13 shows a measurement of the sound velocity profile (SVP) in the study area. The measured SVP decreased from 1540m/s at the surface to 1485m at the depth of 1000m. From this depth, the velocity increases to 1520m/s at 4000m. Between 2880m and 3100m the SVP increase from 1504m/s to 1507m/s. After linear interpolation of the data into a uniform depth grid, we calculated the sound velocity average from the surface to 2800m and from the surface to 3100m. This calculation gives velocities of 1493.5m/s and 1494.5m/s, respectively. For our localization algorithm, we used a constant velocity \( c = 1494 \text{m/s} \pm 5 \text{m/s} \). A 5 m/s error in the sound speed makes an error in the arrival time of less than 0.4s.

![Average Sound Velocity Profile (SVP) in the study area](image)

3.4.1.3 Receiver position coordinates

The receiver positions coordinates on the seafloor were determined from the air-gun shot positions (using a GPS antenna) and water wave travel times to the instruments using an inverse problem algorithm. Because the shots occurred along a single lines that passed over the instruments many of the instruments positions are poorly constrained along one of the two horizontal axes. The error ellipses are \(< 0.16 \text{ km for the major axes and 0.005 km for the minor axes. Based on this relocation algorithm, the standard deviation of the instrument depths was assumed to be 50m.}

3.4.1.4 Conversion between spherical earth and cartesian grid

We calculated a conversion factor for longitudinal directions of \( x_{\text{lnkm}} = 111.19 \text{km/deg} \), and a conversion factor for the latitudinal directions of \( x_{\text{ltkm}} = 111.19 \times \cos(\text{latitude} \times \frac{\pi}{180}) \text{km/deg} \). Over our model space, this approximation is quite accurate, because we are fairly close to the equator. We can estimate the error induced by examining changes in the conversion factor across our grid. Assuming the minimum and maximum latitudes of interest are 9°N and 10°N, then the difference in the conversion factor is \( \delta_{\text{ltkm}} = 111.19 \times (\cos(9 \times \frac{\pi}{180}) - \cos(10 \times \frac{\pi}{180})) \text{km/deg} = 0.32 \text{km/deg} \). Such an error would give rise to a maximum travel time error of 1 s across the entire grid.

3.4.2 Source array geometry- Bathymetry

In our problem we assume that the acoustic signal travels along a straight line from the source to the receiver in three dimensions. But because the sound velocity changes with the depth, the path changes and in the reality the signal does not travel in along a straight line path. To evaluate the
associated error made by assuming a straight line path, we calculated rays and new travel times using the depth-varying velocity model and compared the new times with time for straight paths. The travel time difference between the straight line path and the more realistic ray is less than 1s for a distance less than 40 km. Figure 14 illustrate the differences between the straight and curved rays and figure 1 provides some time difference for various ranges. In general, we estimate that the maximum error is less than 2-3 seconds, with most errors less than 1 s, depending on the range between a whale and a hydrophone. This error is at the same order of the error for the observed time and location won’t be very affected by this error.

Figure 14: Ray trace of a sound source at the surface in a constant 3000 m water depth using the sound speed profile of figure 13. The figure at left shows the distance function of the depth, and at right the time function of the depth. In this model of ray tracing we didn't consider reflection. This model is very simplified but gives us an estimate of the error that we make using a straight line path.

<table>
<thead>
<tr>
<th>Distances (km)</th>
<th>Ray path</th>
<th>Straight Line Path</th>
<th>Difference times</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>7.05</td>
<td>6.99</td>
<td>0.06</td>
</tr>
<tr>
<td>19.47</td>
<td>12.68</td>
<td>13.18</td>
<td>0.5</td>
</tr>
<tr>
<td>30</td>
<td>19.53</td>
<td>20.18</td>
<td>0.65</td>
</tr>
<tr>
<td>43.7</td>
<td>28.31</td>
<td>29.36</td>
<td>1.05</td>
</tr>
</tbody>
</table>

Table 1: Difference times between the straight line path and the ray path function of the distance between the whale and the receiver.

Because we assume that the whale is at the surface, we should examine the error induced by this assumption. Studies of dive characteristic of blue whales off the central California coast [26] shows that the most part of the blue whale dives are between 0-16m and 97-152m. Dives < 16m represent primarily blow intervals during surface time between longer dives (75 %), 72 % were < 1 min of duration. Dives to 97-152m with an average at 105 ± 13m represent 15,2 % of all dives. Because the blue whale do not normally dive deeper than 150 m, the error is negligible when we consider that the depth of the receivers is 3000m.

We also note that if the whale is inside the area defined by the stations, its location can is usually well estimated, but if it is outside, the location is usually poorly constrained because good azimuthal data coverage on the whales location is missing.
3.5 Ellipse error: simplification of the probability surface

\( \sigma_m \), a full representation of the probability of a whale's location (figure 11), provides the maximum likelihood position of the whale's location, the point with highest probability, and a possibly complex probability surface indicating the range of possible locations. Another way to interpret the probability surface is that it provides an error map of the uncertainty of the whale's position. On the other hand, a simpler way to show the location of the whale and its region of probable location is to plot the maximum likelihood location and an \textit{“error ellipse”} for that location which is a simplification of the probability surface. However, since the error ellipse is gross simplification it doesn’t always provide an accurate description of this error, as illustrated in figure 15.

![Error ellipse](image)

Figure 15: At left, error ellipse for the probability density function. Location on November 25 at hour 14. At right, the probability density function shows two possibilities for the location of the whale on November 24 at hour 6. The location with the largest probability is chosen, but it is obvious that another location is almost as probable as the chosen location. A linearized inverse problem method would only find one or the other of these two possible locations, while our more general algorithm shows them both.

To study the ellipse confidence of our error model we calculate the matrix of covariance \( C_m \).

This is an estimator of the dispersion of the model. Indeed, errors in the data cause errors in the calculated position. The model covariance matrix depends on the covariance matrix of the data.

To calculate \( C_m \), we crop into little sections \( dm=di* dj \) all the misfit surfaces. We normalize the surface so there is a probability of 1 that the whale is within the grid.

\[
N = \int \int (\sigma(m) * dm) \simeq \sum_i \sum_j \sigma(i, j) * di * dj
\]

To obtain estimates of the dispersion we calculated the mean value. The most probable value in the probability function is given by:

\[
m_o = \frac{1}{N} \int \int \sigma(m) * dm \simeq \sum_i \sum_j \sigma(i, j) * di * dj
\]
The covariance matrix $C_m$ is then obtained by:

$$C_m = \int (m - m_o)^2 \cdot \sigma(m) \cdot dm$$

The uncertainties in the model parameter estimates are correlated because the off diagonal elements of the model covariance matrix $\sigma_m$ are non zero.

To plot the ellipse, we diagonalize the covariance matrix and we calculate the eigenvalues $\lambda^{(1)}$ and $\lambda^{(2)}$ and the associated eigenvectors $(x_1^{(1)}, x_2^{(1)})$ and $(x_1^{(2)}, x_2^{(2)})$. The uncertainty in the location is then given by an ellipse with semi majors axes and semi minor axes $\sqrt{\lambda^1}$ and $\sqrt{\lambda^2}$ oriented by a direction given by $tan^{-1}(\frac{x_1}{x_2})$.

This ellipse gives the 1 $\sigma$ and thus 68 % confidence level. Figure 15 shows that the simplified uncertainty can be a poor representation of the probability surface. It provides overall less information because the ellipse is symmetrical and gives only one approximation of the error. In reality, the errors are different in all the directions. Because the whale location problem is a nonlinear problem and also because uncertainties in the data, model parameters and modelization may not be Gaussian, the probability density surface is not in general ellipsoidal. However, for plotting and visualization purposes, it is much easier to use an approximation of the probability surface plotted as an ellipsoid at each location than the entire surface at each location.
4 Results

4.1 Blue whale call characteristics

A typical spectrogram of Northeastern blue whale calls is shown at figure 16. The difference between the Northeastern blue whale calls and Northwestern blue whale calls is showed at figure 17.

Northeastern blue whale calls were recorded before by [27], [11], [10], [7] and others. The waveform and the spectrogram shows two different calls labelled as “A” and “B”.

The A call is characterized by a train of amplitude modulated short pulse with a fundamental carrier frequency of 16 Hz and a strong fifth harmonic at 90 Hz. Since the sampling rate is 128Hz-200Hz, this last harmonic cannot be seen in our data.

The B call is characterized by a fundamental tone that begins at $17.05 \pm 0.36$ Hz and sweeps down in frequency to $15.03 \pm 0.32$ Hz. The second harmonic begins at $34.20 \pm 0.5$ Hz and sweeps down to $30.43 \pm 0.33$ Hz. The third harmonic is strong and begins at $51.86 \pm 0.65$ Hz and finish at $45.99 \pm 0.46$ Hz. The forth harmonic is between $67.98 \pm 1$ Hz - $61.68 \pm 0.5$ Hz. This average (n=15, with n the number of calls used) was made with the AB calls recorded in the hydrophone obh23 the 23 November between hours 7 and 8.

Figure 16: The spectrogram and waveform correspond of a record of a typical blue whale call. The call, divided in the portions “call A- call B” is successively repeated during hours. The duration of the B call is $20.85 \pm 1s$ (n=15), the duration of the A call is $23.18 \pm 1.5s$ (n=14). The duration between the A call and the B call is about $26.90s \pm 1.3s$ (n=14) and between two sequences A-B is about $66.75 s \pm 11$ (n=14); C call: Upsweep $11.42 \pm 0.36$ Hz to $9.51 \pm 0.47$Hz - precursor of the B call. This precursor is not always observed because it does not contain a significant amount of energy. Its duration is about $11.88s \pm 1s$ (n=13). The spectrogram was made using a filter bandpass 8-95Hz and using 1024-point FFT’s with 70 percent overlap. It was recorded with the hydrophone obh23 the 23 November at hour 7.

Figure 17: Figure showing the difference in the vocalization between a Northwestern blue whale and a Northeastern blue whale. By Stafford [14]
Before the B call, a 10-12 Hz upsweep precedes the 16 Hz portion of the call (figure 16). This low-frequency precursor has been noted before in the literature [10] and is called the C call [15]. There is also a high frequency precursor for the B call around 400 Hz [27, 10], but the Nyquist frequencies of our instruments were 64 -100 Hz and this precursor and the other components of the call sequence above 64 - 100 Hz were not recorded.

Figure 18: Power spectral density of the A call and the B call for the whale recorded the 23 November in the hydrophone obh23. This spectrum was made with 5.12s points FFT and 99 % overlap

The different calls are combined into structures forming that we can call “phrases”. The most common call pattern in the data is a sequence of A calls and B calls (figure 19). But it is also possible to see one A call followed by several B calls figure (22 and 20). In any case, we do not see consecutive A calls and each sequence starts with an A call. These patterns are repeated regularly for many minutes or even hours. The pattern ABB and ABAB can be combined as in the example shown in figure 22.
Figure 19: This spectrogram shows the most common pattern of the blue whales' call - The A calls is always followed by the B calls. This spectrogram was recorded on November 23 in the hydrophone obh 23, at hour 7.

Figure 20: The waveform (1) and spectrogram (2) correspond of a record of A call followed by more B calls. The numbers of B calls are variable during this 30 mins of recording. Recorded at the hydrophone orb3, on November 23 at hour 21. (3) Spectrum of this record - the cross show the presence of one other whale vocalizing at lower frequency, and then further away.

Besides the A, B, and C calls, there is one more type of blue whale call, labelled the "D call"
These vocalizations were described before by [7]: “an 80 to 30 Hz downswept typically 2 to 5 s in duration, often produced by multiple animals as counter-calls and not produced in combination with the other call types”. It was also described by [10]: “downswept calls of about 1-s duration ranging from 60 to 45 Hz, these being labeled as type D calls”. D calls do not appear very often and are highly variable [10]. Our downswept calls have 1 s duration ranging from 60 to 40 Hz. This call was only recorded on two hydrophones, orb03 and orb02, at different times. In the orb03, the D calls are present the November 25 when two other whales are in the same area around 16h and the November 23 around hour 21 when one or two whale were not very far away. In the orb02, the D calls are present the November 24 around the hour 21 when two whales are recorded at the same time. In general, D calls are rare and hard to find, and little is known about them, but they seem to be present when there is more than one whale in the area.

Figure 21: Record of type D calls. We can see their high variability. At left, the second call, lower in frequency precedes the first call in all four vocalization and is certainly a propagation artefact. Record by hydrophone orb03, these spectrograms were made using 2.56s points FFT, 98 % of overlap and a Hamming window. At right, we can see the presence of two other whales at the same time that the D calls appear.

Figure (22) illustrates the presence of two blue whales.
Figure 22: Two whales are recorded at the same time. This data was recorded on hydrophone orb3 on November 25 at hour 17. In the circles, it’s possible to see the difference between the A and B call for the whale 1 and for the whale 2. This spectrogram was made with 5.12s point FFT and 70% overlap.

The sound levels are similar for both of these whales, indicating either their close proximity to each other or equal distance from the hydrophone. However, D calls recorded during this time suggest that the two whales are probably in the same location or nearly so.

We can also see how whale 1 changes its vocalization pattern. Its call is at first ABAB and later changes to ABBB. This figure shows differences between the A calls, too. The A1 call is always followed by a fundamental tone with its harmonics, similar in structure to the B call. But the B1 call is also quite different that the B2 call. B1 seems to have some discontinuity (see 24).

If the frequencies are the same for all our blue whales record, the durations of the A call and B call are nevertheless quite different. Table 2 shows the duration of the calls that we think are different whales.

<table>
<thead>
<tr>
<th>Whale</th>
<th>Duration A call</th>
<th>Duration B call</th>
<th>Hydrophones</th>
</tr>
</thead>
<tbody>
<tr>
<td>November 23 hour 7</td>
<td>23.18 ± 1.5 n=14</td>
<td>20.85 ± 1 n=15</td>
<td>obh23</td>
</tr>
<tr>
<td>November 24 hour 20</td>
<td>22.86 ± 2.9 n=12</td>
<td>19 ± 0.9 n=11</td>
<td>orb02</td>
</tr>
<tr>
<td>November 23 hour 21</td>
<td>29.8 ± 3 n=4 (A call like figure 22)</td>
<td>21 ± 2 n=13</td>
<td>orb03</td>
</tr>
</tbody>
</table>

Table 2: Duration of the A and B calls at different times at different stations.

We can see in this table that the duration of the B call seems to be around 20 s ± 1 s of duration and doesn’t change between one whale and then other. The little differences in the times are certainly due to the errors in the measurement but they can also be due to the difference between the whales calls. Given the uncertainties that we have, it is not possible to determine if the call duration are different (statistically they are the same)

Detected A calls have two characteristics. One type of A call is about 22 s ± 2 s in duration, and the other are around 29 s or 26s in duration (figure 24).
Figure 23: Zoom of figure (22). The superposition of the A call and B call prove the presence of two whales. This spectrogram was made with 2.56 s points FFT and 99 % overlap.

No difference in call was found between night and day. Pattern ABAB or ABBB is present in all day but pattern ABBB is less common.

4.2 Whale localization

Using scripts written in Matlab we analyzed the signal at all the hydrophones concurrently and measured the arrivals times of the calls for each hydrophone. The study was made during 3 days, hour after hour (one or two calls per hour).

Having the arrival times of the calls and using our algorithm explained in the Methods, we localized all the calls. Each position were determined and an ellipse error about each location was estimated (figure 25).

Figure 25: Results of the inverse problem of location computation. The rightmost plot shows the positions of the 8 hydrophones used and the probability density function obtained for the whale’s coordinates on the 25th of November at hour 14. The maximum likelihood location of the whale: (256.194 deg. E, 9.270 deg. N).

During this, for each hour during the 3 days we obtain results shown in figure 26.
Figure 26. Location map showing the instrument positions, the ship track during shooting, and the whale positions. We recorded more than 3 whales but only 2 (perhaps 3) of these whales were tracked during the 23, 24 and 25th of November 1997.

Legend:
- Red: 23 November
- Blue: 24 November
- Green: 25 November
- Crossed: Localisation of the ship
- Station: Position of the ship when not shooting
- Direction: Direction of whale’s movement
Figure 26 shows the location of the whale and the ship during the November 23-25. It seems that only 2 whales are present and located but the data (figure 22) show that more than two whales are present during these localization.

From the hour 2 on November 23 until 1 hour on 24 November, we could track one whale and his movement are showed in figure 27. This whale comes from the north-west and traveled to the east. Nevertheless when only the hydrophones moored at the east of our study site were recording this whale on other hydrophone, the orb03, was recording another whale. And some hour later, when the whale who came from the north-west, was closer to the hydrophone orb03, different whales were recorded at the same time at the orb03(see figure 20). We will call this whale whale 1.

Figure 27: Whale position every each hour on day 23 and the first hour of November 24. The numbers indicate the hour of the day.

From November 24 at hour 2 until November 25 at hour 20, we tracked another whale (see figure 28) from the north-west of our study site. This whale first traveled to the south and afterward traveled to the east to a similar position as the whale 1. We didn’t know if the location of the whale corresponds to one or two different whales because the data are not very good. In the south of our study site, in the “blue circle”, two whales are recorded at the same time.
Orb2 recorded 2 whales from 24 November at hour 15 until 25 November at hour 2.

Orb3 recorded 2 whales at the same time from November 25 at hour 15 until November 26 at hour 13.

Figure 28: Whale position each hour on November 24 and 25. The numbers indicate the hour of the day.

The "blue circle" represents the zones where the two whales were recorded at the same time. We cannot determine if the whale tracked at the first hour of November 24 is the same whale tracked at the end of November 25. Orb02, moored at the south of our study area recorded two different whales from hour 15 on November 24 until hour 2 on November 25. On November 25 at hour 0, two whales were recorded on this hydrophone at similar sound level (see figure 29). Obh27 recorded two whales at hour 12 on November 24, but one whale is recorded with low sound level.
The third day the signal disappeared in the of the hydrophones. The whale locations are outside of the receivers array, and only recorded by one hydrophone orb03. After hour 21, the calls are only visible in orb03. Beginning the hour 15, two whales are recorded at the same time on orb3. The similar call intensity and the presence of D calls, lead us to think that the two whales were very close to each other.

We located the ship at the same time as the whale. In the solid line we located the ship when is shooting. The dashed line represents the ship’s travel when it is not shooting. During the first day, the whale goes from the north-east to the west and does not seem affected by the noise of the ship. During the second day, the whale travels from the East to the south-west, and the ship travels to the west faster. Perhaps the whale is affected by the air-guns and goes south before going west in the third day.

4.3 Whale velocity

Blue whales can accelerate to speeds of over 30km/h when being chased, but usually their speed is much slower [28]. Figure (30) shows the velocity average for the 3 days that the whale was located. The distance moved between any two calls is similar to the uncertainty of the location, so it is difficult accurately measure a whales velocity. The velocity average is around 4.51km/hour.
4.4 Sound levels. Comparison between sound levels of air-guns, local earthquakes and blue whale calls

Whale calls can be found during 4 days of the hydrophone data. For only 22 hours during these days are not the air guns active. During air-gun activity the whale continued to vocalize and we did not detect any difference in the vocalization, frequency, patterns, or amplitudes when the ship was shooting or not. Without detailed instrumentation response information, it is difficult to know what the sound levels of the whales and air-guns are at different distances and what sound levels the whales experience. On the basis of the work by Tolstoy and others [20], we can conclude that sound levels are less than 140 dB re 1uPa for all whales in our study, since they approached the ship to distances of no less than 30 km.

Nevertheless, we can see that the sound level of the air-guns seems to be important compared to the amplitude of the vocalization of the whale, even at distances as great as 90 km (figure 31 and 32). For example, given a single instrument, the sound level of the guns is < 140 dB at 60-90 km [20] but has the same recorded amplitude as a whale at 1.5 km from the station. From this we can speculate that the whale call sound level is not much more than 140 dB, although maximum call levels have been reported as high as 188 dB [27]. We also looked at recorded amplitudes (on the same instrument) the record of a very small earthquake located 63.5 km from the receiver. Sound amplitude are much less than for the whale or air-gun in this case. While many earthquakes of this size occur near mid-ocean ridges every day, earthquakes that are several orders of magnitude larger than the one shown here occur less frequently.

Figure 31: A-B call recorded on November 24 at hour 12 at less than 1.5 km from the receiver b: Air-gun recorded on November 24 at hour 4 at less than 1.1 km from the receiver c: Earthquake located on 23 November 23 at hour 7 at 63.51km of the receiver - Waveforms made with a filter passband 14-20Hz (up) and 3-63Hz (down) -Receiver: OBS 52 - The figures at the top are made using a bandpass filter 14-20Hz, frequency range where the sound level of the whale are higher. Down, the figures are made with a bandpass filter 3-63Hz.
Figure 32: Relative amplitude for the air-guns at less than 1.1 km (hour 04) of the receiver (a), at less than 66 km (hour 12) (b) and at 96.25km (hour 20) (c) - Waveforms made with a filter passband 3-63Hz -Receiver: OBS 52 - November 24

Figure 33: Recorded at hour 12 on November 24. The ship is at 63 km from the receiver. The whale is at less than 1.5 km from the receiver. The sound level is around the same in the frequency band of 14-20Hz (up) and is lower in the frequency band 3-63Hz (down)- In other words, the signal recorded in this hydrophone shows the air-guns sound relative level listened by the whale at 63km from the receiver.
5 Discussion

5.1 Blue whales call

Recorded blue whale calls are similar to those discussed in the literature but we see that the blue whales calls can vary and are possibly different for each individual. Figure22 shows little difference between the A calls and the B calls for different whales. Possibly reasons for these differences are more than one type of blue whale or different whales of different age or size. Is it possible to identify each whale by its call? Perhaps, but we do not have enough information to do so. Our study of the duration of the calls show that the duration can change and the records in the literature are also different. Is a 1-2 seconds difference in duration between calls significant? Is call duration a particularity of each whale? Table 3 shows a summary about the different calls in the literature.

<table>
<thead>
<tr>
<th>References</th>
<th>Duration A call</th>
<th>Duration B call</th>
<th>Study Site</th>
<th>Duration C call</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stafford2001 [14]</td>
<td>18.2s (± 2.5 n=16)</td>
<td>17.5s (± 1.5s n=19)</td>
<td>North Pacific</td>
<td>8.7s (±1.9 n=4)</td>
</tr>
<tr>
<td>Stafford1999 [15]</td>
<td>21s</td>
<td>18.7s</td>
<td>Vicinity of Costa Rica dome</td>
<td>7.7s</td>
</tr>
<tr>
<td>Stafford1998 [13]</td>
<td>20s</td>
<td>20s</td>
<td>Oregon</td>
<td>no data</td>
</tr>
<tr>
<td>Burthenshaw2004 [8]</td>
<td>20s</td>
<td>20s</td>
<td>In all the Northeast Pacific</td>
<td>no data</td>
</tr>
<tr>
<td>Tiemann2002 [18]</td>
<td>20s</td>
<td>20s</td>
<td>Southern California</td>
<td>no data</td>
</tr>
<tr>
<td>McDonald2001 [10]</td>
<td>17</td>
<td>17</td>
<td>California: west of San Nicolas Island</td>
<td>around 10s</td>
</tr>
<tr>
<td>Thompson1996 [17]</td>
<td>13.5 n=13</td>
<td>12.5 n=12.5</td>
<td>Gulf of California- Mexico</td>
<td>no data</td>
</tr>
<tr>
<td>Rivers97 [12]</td>
<td>3 whales: n=4 15.2 s ± 1.5 - n=8 14.9 s ± 0.87 - n=4 15.9s ± 0.87</td>
<td>3 whales 14.7s ± 1.86 - 12.3s ± 1.90 - 13.3s ± 1.69</td>
<td>Central California</td>
<td>no data</td>
</tr>
<tr>
<td>ME</td>
<td>3 whales: n=15 23.18 s ± 1.5 - n=12 22.86 s ± 2.9 - n=4 29.8 s ± 3</td>
<td>3 whales n=15 20.85s ± 1 - n=11 19s ± 0.9 - n=13 21 ± 2</td>
<td>North East Pacific Rise</td>
<td>11.88s ±1 n=13</td>
</tr>
</tbody>
</table>

Table 3: Synthesis of the durations of A, B, C calls recorded in the literature.

Comparing this table with table 2 we can see that our A call and C call are longer than found in
The different call patterns produced by blue whales are also poorly known. A whale can vocalize ABAB or ABBB or perform the D call. These different sequences seem to correspond with different behaviour. But to know more about that, we need to study the vocalization of the whale at the same time that a visual observation is made. Many aspects about the blue whale calls are unknown for the moment. What is the reason for this different vocalization? How do the different whale (different size) adjust their calls to the same frequency? What is the information transmitted by the calls? Do the different patterns ABAB or ABBB correspond at different behavior?

5.2 Localization

As many as 4 whales are recorded in the data, but only 2 or 3 whales were located. In most cases, only 2 hydrophones recorded the whales and a location could not made. But it’s important to understand that a group of whales where present only during 3 days total.

While our location algorithm location shows at least two distinct whales in the area there may be three localized whales. Because the data show that more than 2 whales recorded at some times, we can have two hypotheses about the computed locations for days 2 and 3 (Figure 34). Because a whale was recorded close to ORB02 on November 29 and we also detect a loud sound level of another whale on ORB27 at the same time, we suspect that a 3\textsuperscript{rd} whale comes from the south (3B) or the west (3A) during this time.

The 2 whales were travelling from the north-west to the east. If whale 2 on day 3 is actually a third whale, then whale two probably moved south-east out of the area, while whale 3 moved from the south into the area and passed out to the north-east.

We speculate that these whales were migrating to tropical waters near the coast of Mexico. Indeed, blue whales migrate seasonally ranging from the water off Central America to Gulf of Alaska [8]. They spend time to feed in the mid-to high latitudes, highly productive, in the summer and fall, and migrate to the tropical regions to give birth and mate in the winter and spring.
5.3 Effects of the noise on the blue whales

Studies of bowhead and gray whale behaviour in the presence of air-gun noise indicate avoidance at broadband levels of about 160 to 170 dB [3]. For blue whales little is known. One study [11] reported anomalous behaviour for the blue whales when an airgun was used. Cessation of vocalization during one hour, resumption of vocalizations and movement away from the source were observed.

Studing the relative amplitude of the air-guns, and comparing this with the calls (figure 33), we see that when the ship is around 65 km from the whale and that the sound level of the air-guns is similar to the calls. This cannot be understood by the fact that the blue call source levels is around 188 dB [27] and the air-guns source level at 60 km is around 140 dB [20]. The whale at this moment was at 1.5km from the receiver. In any case, we saw in the signal that the relative amplitude is larger for the calls than for the air-guns. How can explain we this results? The energy of the air-guns goes downward, and for the energy for the whales calls this goes in all directions but particularly forward. Then, the sound level for the calls received by the station at 3000m is will be less than 180 dB. This could explain how the record of the sound levels of the air-guns at 3000m is lower than the sound level of the whale at the same depth.

In our results at more than 30km from the ship, during the presence of the air-guns, the vocalization of the whales does not seem to be disturbed, and the characteristics of the vocalization with or without the air-guns are the same.
In our results a whale is never closer than 30km from the ship and during the presence of the air
guns the vocalization of the whales does not seem to be disturbed. In addition, the characteristics of
the vocalization with or without the air-guns are the same. Our results suggest that the presence of
the air-guns does not disturb the whale’s behaviour, as there is no obvious correlation between the
behaviour of the whale and the ship position. One observation is that although sound amplitudes
for the guns are large as compared to a whales vocalization, on day two a whale moves towards
the ship while the guns are active and passes aft of the ship.
6 Conclusion

Little is known about blue whales and acoustic method are one of the best ways to study these animals who live underwater. In this work, we have provided additional information about blue whale calls and call patterns to the small body of literature on the subject. We found blue whales call characteristics that are both similar and different to those presented in the literature to date. Even though this work did not detect any impact on the behaviour of blue whales by the presence air-guns, this result in itself is significant, and we should be heartened by the outcome presented here. It indicates that for whales located at 30 km or more from a 139 liter, 20-gun air-gun source, there is little or no behavioural response.

This work also presents a new method to the biological community for whale localization and we have shown the advantages of the grid search algorithm as compared to hyperbolic methods, because it shows all the probabilities in the location. Using a seafloor array designed for seismic exploration to track and monitor the calls of blue whales or other whales can have the disadvantage that the signal can be masked at times by the seismic exploration activity and seismic work may at time affect a whales behaviour, but it also allows us to monitor whales continuously for long periods of time and at lower cost (cost is born by the seismologists!) than for a whale survey. This method allows one to study and identify species of whales in the ocean, seasonal distribution, possible regions stocks, movements, etc. If there were more hydrophones in the ocean, we could track the migration of the whales with more precision and know more about these mammals. But with a seafloor array there are disadvantages too; the problem with acoustic surveys of the nature presented here, is that they are opportunistic and usually do not record at frequencies above 100 Hz. Whales species that can be tracked below this frequency are quite restricted.

Nevertheless tracking whales from a seafloor array during seismic exploration is important for understanding the behaviour of the whales during this experiment, and to obtain more information about the consequences of seismic noise on whales.

Future works deploying a long-term moored hydrophones in regions of the ocean frequented by whales will be a useful means of surveying cetaceans habitats, identifying species present, distribution, habitats, etc. Future works need to study the acoustic calls of the whales at the same time that a visual observation is made. This will provide better information on the behaviour and the meaning of the different patterns observed.
### References


