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Estimation of the source signal characteristics and variability of blue whale calls using a towed array

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THESIS

ESTIMATION OF THE SOURCE SIGNAL CHARACTERISTICS AND VARIABILITY OF BLUE WHALE CALLS USING A TOWED ARRAY

by

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June 1999

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A four-day experiment was conducted to study the feasibility of locating, tracking, and counting blue whales acoustically in the Monterey Bay National Marine Sanctuary (MBNMS) at long ranges using the shore-based NPS Ocean Acoustic Observatory (OAO) hydrophone array. In concert with the shore-based acoustic monitoring, an aircraft was assigned to locate whales and a research vessel was manned with observers and instrumented with a towed hydrophone array to determine whale locations and characterize their vocalizations in the near-field. Two transiting blue whales were observed and their vocalizations were recorded by the towed array in close proximity. In this thesis research, these towed array data were deverberated using modeled-based matched signal processing and least-squares fitting. The reconstructed source signals show time durations of 14.4±2.2 and 10.6±1.6 s and source levels of 162.4±7.0 and 166.2±10.5 dB re 1μPa for the 90 Hz "A" calls and 51 Hz "B" calls, respectively. Furthermore, correlation methods were used to quantify call-to-call variability. The analysis shows that the waveform of the "B" calls and the magnitude of the waveform of the "A" calls are robust, suggesting that these quantities should be exploited in the design of long-range auto-detection techniques and long-range, model-based localization and tracking algorithms for the OAO array.

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ABSTRACT

A four-day experiment was conducted to study the feasibility of locating, tracking, and counting blue whales acoustically in the Monterey Bay National Marine Sanctuary (MBNMS) at long ranges using the shore-based NPS Ocean Acoustic Observatory (OAO) hydrophone array. In concert with the shore-based acoustic monitoring, an aircraft was assigned to locate whales and a research vessel was manned with observers and instrumented with a towed hydrophone array to determine whale locations and characterize their vocalizations in the near-field. Two transiting blue whales were observed and their vocalizations were recorded by the towed array in close proximity. In this thesis research, these towed array data were deverberated using modeled-based matched signal processing and least-squares fitting. The reconstructed source signals show time durations of 14.4±2.2 and 10.6±1.6 s and source levels of 162.4±7.0 and 166.2±10.5 dB re 1μPa for the 90 Hz "A" calls and 51 Hz "B" calls, respectively. Furthermore, correlation methods were used to quantify call-to-call variability. The analysis shows that the waveform of the "B" calls and the magnitude of the waveform of the "A" calls are robust, suggesting that these quantities should be exploited in the design of long-range auto-detection techniques and long-range, model-based localization and tracking algorithms for the OAO array.

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I. INTRODUCTION

A. BACKGROUND

The distributions and relative abundance of populations, natural behaviors, and vocalizations of blue whales, balaenoptera musculus, are poorly understood. Efforts to census this whale population have in the past relied exclusively on visual survey methods. Unfortunately, the blue whale spends only five percent of its time on the surface making visual censusing efforts difficult. Drawbacks of these visual techniques include high cost, limited coverage, and poor accuracy. A better understanding of the whale population and their migration routes clearly requires improved censusing methods.

Acoustical monitoring of vocalizing whales using the existing Navy Sound Surveillance System (SOSUS) may offer some advantages over the visual techniques. If proven to be viable, whale monitoring could be done continuously on a global basis with the existing SOSUS assets and the acoustic data may be combined with the local and infrequent visual data to enhance global estimates. The acoustic transparency of the ocean to low-frequency sounds makes it relatively easy to detect whales at long range and to monitor vocal activity patterns for many whales simultaneously. Evidence from SOSUS data collected by Cornell's Bioacoustics Lab shows that whales are vocally active throughout the day as well as throughout large portions of the year (Clark and Fistrup, 1995).

The Whales '95 experiment (Clark and Fistrup, 1995) verified that low frequency calls of blue whales can easily be detected by the SOSUS array and other passive acoustic devices (as long as the whales' locations are within the array's detection

window). The Whales '95 experiment was carried out by Clark and Fistrup off of the southern California coast. Their results showed that the number of blue whales acoustically detected by a towed hydrophone array exceeded visual sightings by a ratio of 6:1. The towed hydrophone array employed was estimated to have a detection range of 20 km for the blue whale calls.

This detection range is far less than those found by Hager, 1997, for the Naval Postgraduate School (NPS) Ocean Acoustic Observatory (OAO) which operates a former SOSUS array at Pt Sur, California. Based on numerical modeling of the low-frequency transmission loss and accounting for the beamforming gain, Hager estimated the OAO detection range to be 500 km for blue whales' vocalizations. This range exceeds the dimension of the MBNMS.

In addition to estimating the low-frequency detection ranges of the NPS OAO, Hager (1997) also modeled the performance of this former SOSUS array in locating blue whales. Both coherent and incoherent time-domain matched signal methods were studied. The coherent method correlates the measured waveform to modeled waveforms at the receiver for a set of trial source (i.e., blue whale) positions defining a search grid. The best estimate is thus the trial source location that provides the best match (i.e., highest correlation) between data and model. Instead of the waveforms themselves, the incoherent scheme correlates the absolute value (i.e., magnitude) of the waveforms with phase information discarded. Although Hager found that both the coherent and incoherent schemes were able to determine synthesized whale locations unambiguously over a large area, a major assumption was used in his simulation study. It was assumed that the waveform of the source signal for coherent matching, or the magnitude of the

waveform of the source signal for incoherent matching, is known or robust. This leads to an important follow-up question: How variable the source signal waveforms and their magnitudes are, and which one is robust in reality? Part of this thesis is devoted to addressing this question.

Detecting, classifying, localizing and tracking vocalizing whales using receiver arrays at long ranges is a complex problem of signal processing, acoustics, and oceanography. Knowledge of the source level and frequency-time distribution of the blue whale sounds is required for detection and classification purposes. The basic structure and variability of the ocean sound channel must also be understood. The ocean scrambles the vocalized signal by its multipaths as the signal propagates to a distant receiver. The ability to predict the mean and variance of the propagation is thus required to unscramble the received signal and to constrain the uncertainty.

The blue whale produces a harmonically rich frequency-modulated moan with a fundamental frequency at 17.8 Hz that is designated the "B" call. A strong component of this call is a downsweep from 53.4 Hz to 51 Hz, which is thought to be the third harmonic of the fundamental frequency. The blue whale also produces a train of amplitude-modulated short pulses with a fundamental carrier frequency at about 18 Hz and a strong fifth harmonic at 90 Hz. A short duration (1 sec) downsweep from 98-25 Hz has also been recorded (Thompson 1996). This downsweep is thought to be an alarm call. The source level of the fundamental frequency component of blue whale vocalizations has been estimated to be about 188 dB by Cummins (1971).

A feasibility study to systematically collect and analyze the needed data to address all aspects of the problem of acoustically censusing blue whales using the NPS

OAO was proposed by Chiu et al (1997). A three-day experiment was conducted in the Summer of 1997. A number of factors were taken into account when planning the data collection. These included the following: blue whales arrive in the Monterey coastal waters in midsummer; the whales frequent the 100-500 fathom isobaths as they feed upon the krill patches that bloom in the nutrient rich upwelled water; and the OAO array's orientation on the downslope side of the Sur Ridge may prohibit unobstructed acoustic paths to some near shore regions. The timing and location of the whale cruise were planned accordingly.

The overall goals of the feasibility experiment include:

1. To investigate the feasibility of locating and tracking distant blue whales using a former SOSUS array and matched signal algorithms.
2. To explore the possibility of providing supplementary information on counts and transit paths of Pacific blue whales.
3. To enhance the understanding of low-frequency sound propagation physics in a littoral environment.

The analysis of the experimental data can be divided into four steps:

1. Unscramble the multi-path signals measured by the towed array to obtain true source signals.
2. Estimate call-to-call variability to determine the robustness of source signals.
3. Develop auto-detection and extraction procedures for the OAO data.
4. Test and refine long-range, shore-based localization and tracking methods.

The thesis work presented here focuses on the analysis of the near-field towed-array data, i.e., steps 1 and 2 listed above.

B. THESIS OBJECTIVES AND APPROACH

The primary objectives of my thesis are:

1. Plan and coordinate the feasibility experiment.
2. Collect near-field blue whale vocalization data using a towed acoustic array.
3. Reconstruct the source signals by deverberating the towed-array data and studying source signal characteristics such as source levels, signal duration, and vocalization depth.
4. Study call-to-call variability/robustness to aid in future development of long-range autodetection and localization algorithms for application to the NPS OAO data.

C. OUTLINE

The remainder of this thesis consists of three chapters. Chapter II contains a description of the approach. It describes the experimental design and execution and details the methodology for the towed array data analysis. The deverberation of the towed array data entails matched signal processing for the location of the vocalizing blue whale relative to the array with a multipath model. With the estimated whale locations, the multipath model is then fitted to data for the reconstruction of the actual source signals. Chapter III provides a discussion of the analysis results pertaining to the characteristics of the reconstructed source signals. These include source levels, call duration, and call-to-call variability (i.e., robustness of the source signals). Chapter IV presents the conclusions of this thesis.

II. METHODS

A. EXPERIMENTAL DESIGN AND EXECUTION

The characterization of the source signals projected by the blue whales was accomplished by deverberating the in situ acoustic measurements collected by six hydrophones of a towed array deployed during the 1997 Whale Monitoring Feasibility Experiment. A NOAA aircraft was assigned to locate blue whales in the Monterey Bay National Marine Sanctuary and to direct the research vessel, NOAA Ship McArthur, to a whale sighting/location. Radio contact with local fishing vessels was also employed to collect whale-sighting information. The McArthur was manned with observers from NPS, University of California, Santa Cruz (UCSC), Moss Landing Marine Lab (MLML), Monterey Bay Aquarium Research Institute (MBARI), National Oceanic and Atmospheric Administration (NOAA) Sanctuary Office, and NOAA's Teacher-at-Sea program. The ship was instrumented with a towed hydrophone array to measure the vocalization signals in close proximity. Visual observations were also logged to provide location information. Blue whales were located both visually by the aircraft and acoustically by beamforming the towed array data in real time. Observers on the research vessel then visually confirmed these sitings. The blue whales sited were transiting individually. The recordings made during the whale experiment were achieved during periods when one engine was intentionally shut down to reduce the background noise. Table 1 summarizes the environmental conditions, equipment used, and siting information.

At the NPS OAO, full-array data from the shore-based OAO array were archived continuously. However, the analysis and presentation of the OAO data is not within the scope of this thesis work.

DATES	25-28 August 1997
SHIP	NOAA Ship McArthur
AIRCRAFT	NOAA - Fixed Wing
SHIP-BASED ACOUSTIC DEVICE	165m ITI Towed Array
# OF BLUE WHALES SIGHTED BY OBSERVERS ON R/V	Two
BLUE WHALE ACTIVITY	Transiting
WATER DEPTH AT SHIP	1. Canyon: 1200m 2. Shelf: 240m
VOCALIZATIONS RECORDED	"A type" call (90 Hz AM tone) "B type" call (51 Hz FM tone) Fundamental Frequency (17 Hz)
OCEAN ACOUSTIC OBSERVATORY (OAO)	Almost Continuous Recording
ENVIRONMENTAL CONDITIONS	Sea State: 1-2 Wind: 10-15 kt
SCATTERING LAYER	No Significant Layer Observed

Table 1: A summary of the 1997 Whale Monitoring Feasibility Experiment.

Given the constraints of shiptime and weather conditions, the near-field sampling strategy during the whale cruise was to attempt to record blue whale vocalizations within 150 km of the shore-based OAO array. The OAO is a former Navy SOSUS array transferred to NPS for scientific research. The love point of the OAO array is at 36°17.950'N, 122°23.566'W, as shown in Figure 1. The array is cabled to shore. Visual sightings were made to confirm whale locations. CTD casts, utilizing the McArthur's

CTD, were performed at night and at other times when unable to visually sight whales. The ship collected routine weather observations and ADCP data.

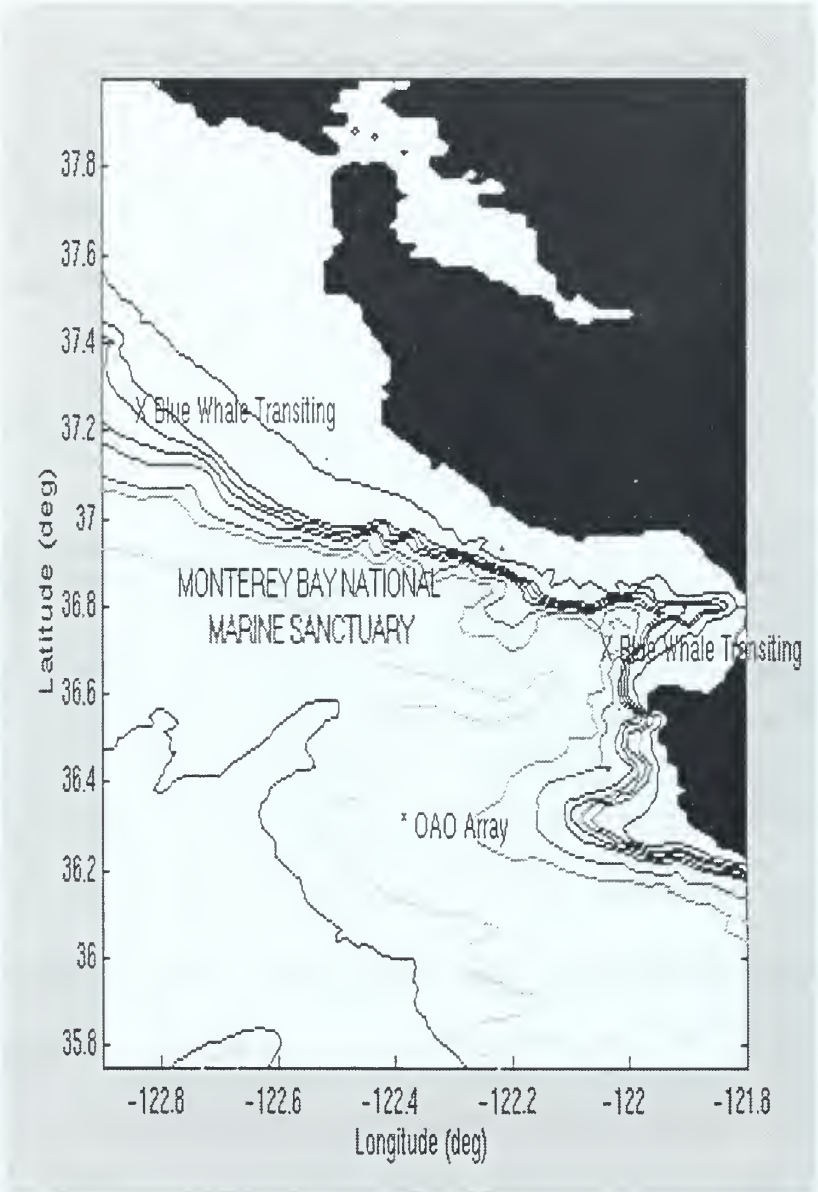

Figure 1: Visually confirmed locations of whales in the Monterey Bay National Marine Sanctuary (MBNMS) region during the 1997 NPS Whale Monitoring Feasibility Experiment.

The towed array used for in situ recording was a 165 m array built by Innovative Transducers, Inc. (ITI) of Haltom City, Texas. It is a 14-hydrophone array designed for both low and high frequency acoustic work. The hydrophone spacings are 6 m for the

midsection consisting of eight hydrophones and 0.25 m for the four-hydrophone elements at each end. The midsection spacing was designed for reception of acoustic signals at frequencies of 125 Hz and less and was, therefore, utilized for this experiment. The average hydrophone sensitivity is -186 dB re 1V/μPa with the low-end cutoff frequency around 8-10 Hz and the high-end cutoff frequency around 15 kHz (see Table 2 for information on the data archival equipment). A real-time beamformer was also utilized on the ship to determine the relative bearing to a vocalizing whale.

Equipment Used For Data Collection	**Gain**	**Owned/ Operated By**	**Comments**
165 m Towed Array	1	UCSC	-Average hydrophone sensitivity is -186 dB re 1V/μPa -6m spacing for the 8 phones in the midsection
High-Pass Filter	1	UCSC	10 Hz cutoff frequency
Pre-Amplifier	20 dB	MBARI	
TEAC Recorder	1	MBARI	Archived 8 channels of multiplexed hydrophone data on standard VHS tapes

Table 2: Equipment used for towed array data collection.

During the experiment, blue whales were detected and located using real-time beamforming. Visual contact with two blue whales was also achieved. The first whale was transiting through deep water (approximately 1200 m) in the Monterey Canyon near 36°41.82'N 122°02.70'W and hereafter will be referred to as the "deep water whale". The second whale was transiting through shallow water (approximately 240 m) in the coastal shelf region near 37°14.64'N 122°50.70'W and hereafter will be referred to as the "shallow water whale". The sound vocalized by these two transiting blue whales was used to study source signal characteristics. Visual contact with the shallow water whale was maintained for about an hour. Table 3 shows the times and locations at which the whale surfaced during this time.

UTC Time 1997 JD 241	Seconds into data set	Distance to whale (m)	Bearing to whale (deg)	Latitude of ship	Longitude of ship
20:45:44	124	1500	110	37 14.99N	122 51.56W
20:58:41	901	1500	110	37 14.82N	122 50.86W
21:06:52	1389	1000	130	37 14.60N	122 50.18W
21:17:54	2051	500	120	37 14.18N	122 49.61W
21:31:10	2847	250	140	37 13.70N	122 48.68W
21:36:13	3150	150	145	37 13.36N	122 48.24W

Table 3: Visual observation sightings of the shallow water whale.

The raw hydrophone data was digitized for analysis utilizing the equipment listed in Table 4. Since hydrophones 4 and 8 failed to function properly, only data recorded by hydrophones one through three and five through seven was analyzed. Used for reference, hydrophone one is the closest hydrophone to the ship.

Equipment Used For Data Digitization	**Gain**	**Owned/ Operated By**	**Comments**
TEAC Recorder	1	MBARI	Archived 8 channels of multiplexed hydrophone data on standard VHS tapes
Precision Filter	40 dB	MBARI	150 Hz Roll-off
ICS Beamformer	1	MBARI	8 Beams 22.5 deg apart
Digitizer	4	MBARI	Channels 1-8: Individual hydrophone data Channels 9-16: Beamformed data

Table 4: Equipment used for towed array data digitization.

B. TOWED ARRAY DATA PROCESSING: SIGNAL IDENTIFICATION AND EXTRACTION

Analysis of the blue whale data set began with the conversion of the digitized voltage data back to sound pressure units in Pascals. The gain factor applied to the voltage data was

$$\text{gain}=1/Dg(10^{Ag+Fg/20})/10^{Hs/20}/10^{6},$$

where Dg is the digitizer gain, Fg is the precision filter gain, Ag is the amplifier gain, and Hs is the hydrophone sensitivity (See Tables 2 and 4 for gain values). The sampling rate used was 500 Hz.

A confidence check on the gain factor was performed by estimating the power spectral density of the unfiltered sound pressure data using Welch's averaged periodogram method. The signal was divided into overlapping sections, each of which was detrended. The squared magnitudes of the discrete Fourier transforms of the sections are averaged to form the power spectral density estimate. Figure 2 shows the low-frequency (50-150 Hz) ambient noise to be in the expected range (~75 dB re 1μPa^2/Hz) for this region.

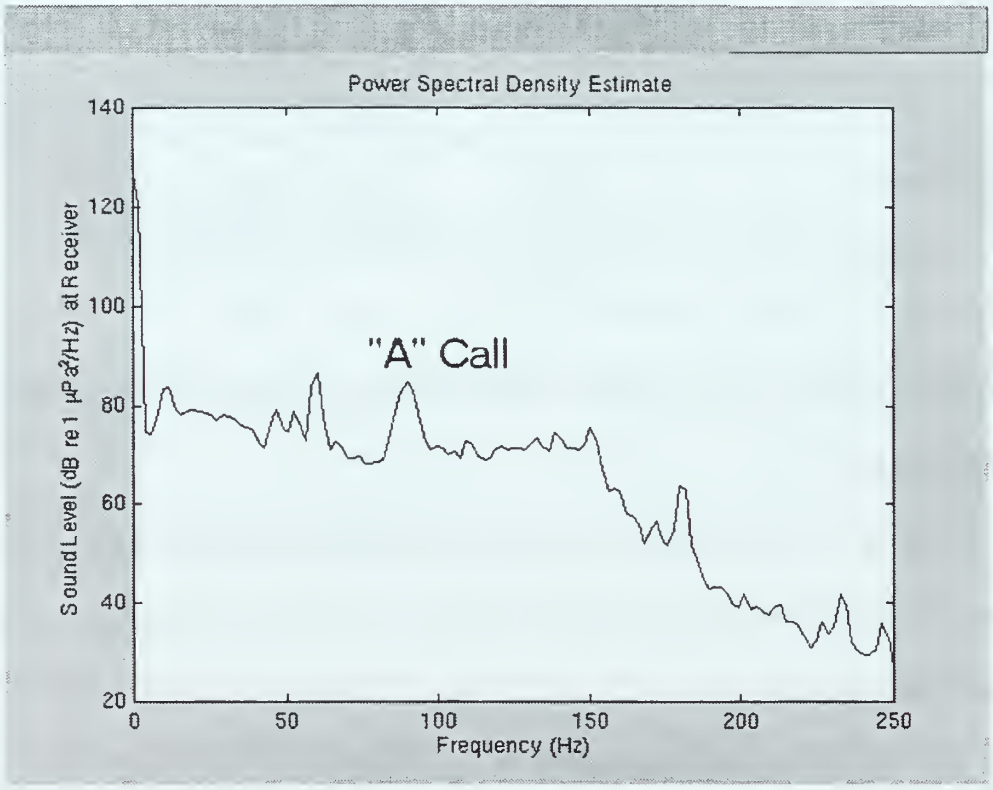

Figure 2: Power spectral density estimate for data segment containing an "A" call. A 75 dB re 1μPa^2/Hz ambient noise level is shown at low frequencies. The roll-off at 150 Hz is caused by the precision filter.

Screening through bandpass-filtered records with a 14-130 Hz window, two data sets containing all the calls of the shallow water whale and all the calls of the deep water whale were extracted. Hereafter, the two data sets will be referred as the "shallow water data set" and "deep water data set," respectively. The “A” call’s 90 Hz amplitude modulated signal component and the “B” call's strong 51 Hz embedded tonal are clearly seen in the towed array data, as shown in Figures 3, 4 and 5. As these calls propagate through the coastal water, they are modified and arrive at the receiver with a multi-path structure which consists of direct and surface and/or bottom reflected arrivals. The multi-path structure received by the towed array is unique to the range and depth of the whale. This forms the basis for achieving localization through matching model predictions to data and, subsequently, source signal retrieval via least-squares fitting of model to data. The corresponding mathematical details are presented in the next section.

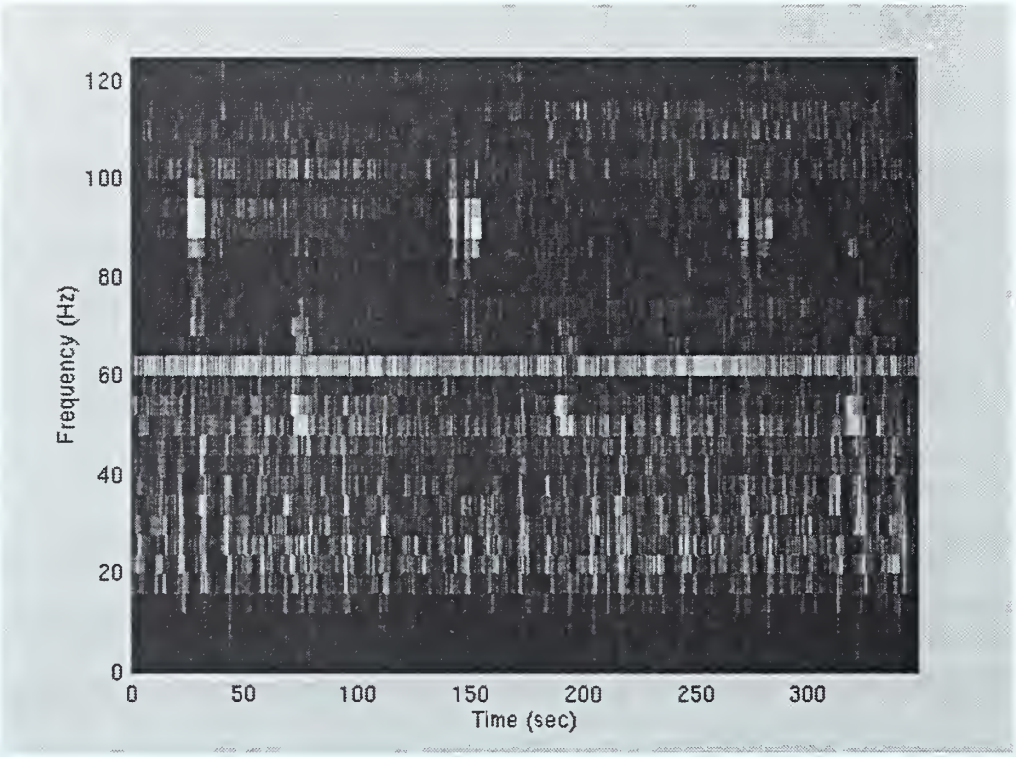

Figure 3: Time-frequency plot of a bandpass filtered (14 to 130 Hz window) data segment recorded by a hydrophone of the towed array. Three "A" call to "B" call pairs are easily identified.

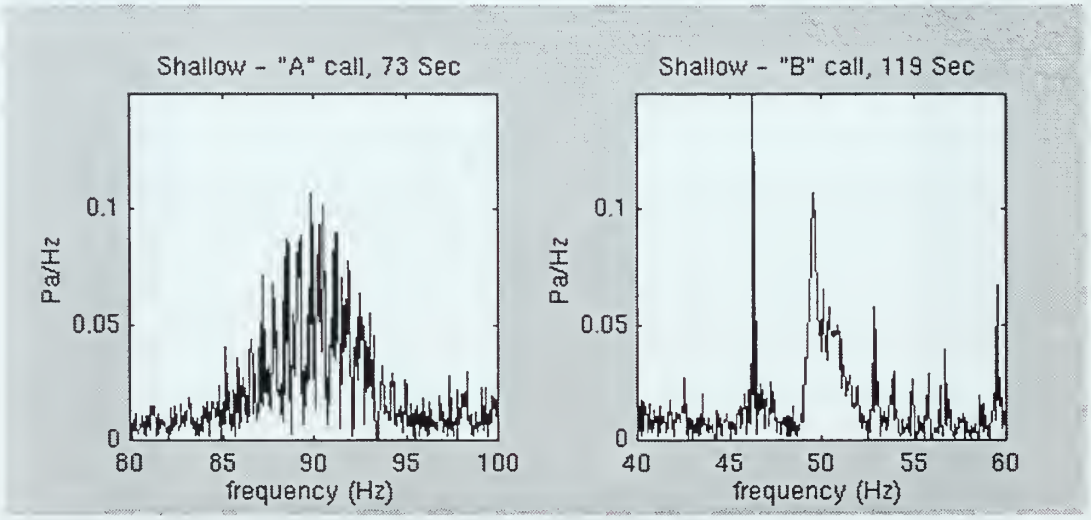

Figure 4: Single-phone frequency spectra of an "A" to "B" call pair starting 73 s into the shallow water data set. Time between "A" and "B" calls is 46 s.

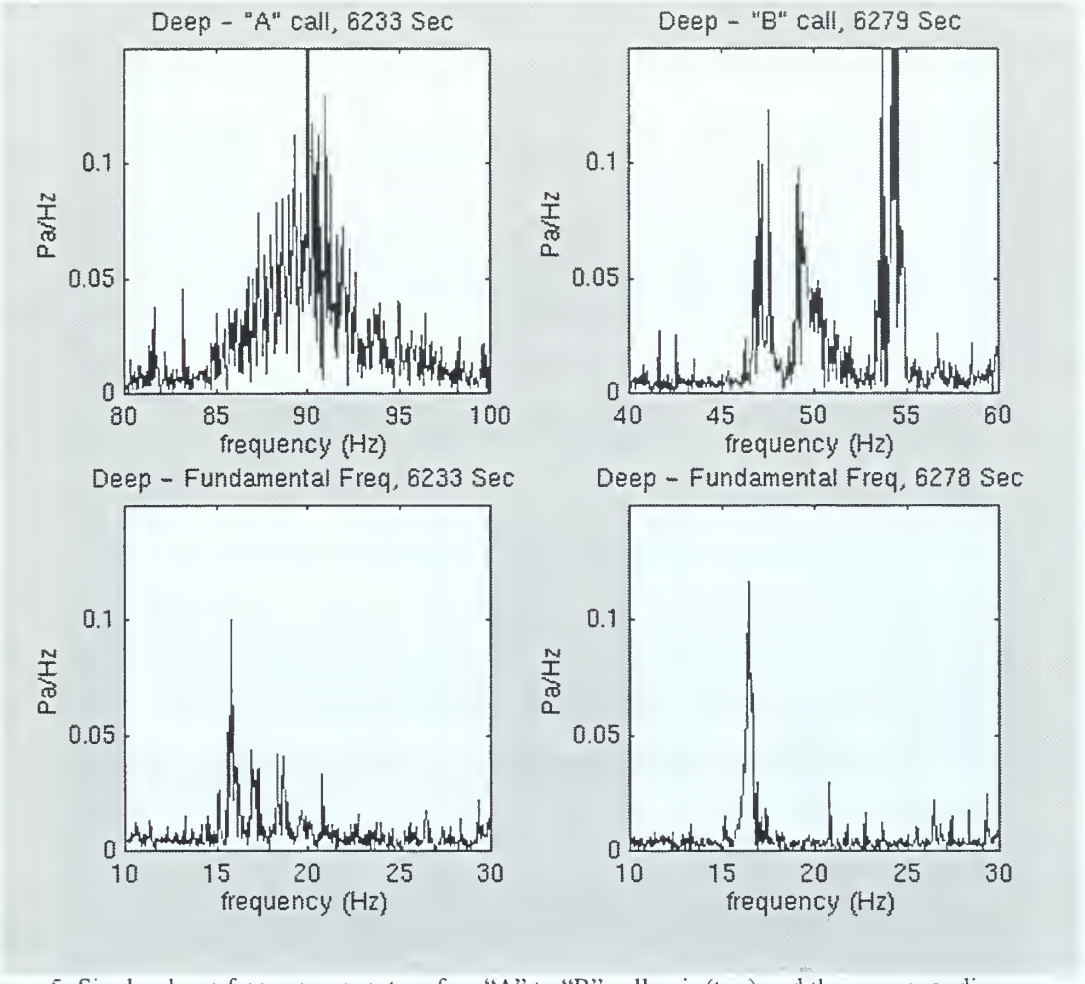

Figure 5: Single-phone frequency spectra of an "A" to "B" call pair (top) and the corresponding fundamental frequency spectra starting at 6233 s into the deep water data set (bottom). Time between "A" and "B" calls is 46s.

In order to isolate the individual "A" and "B" calls to minimize noise for the purpose of deverberation, an eighth-order bandpass Butterworth filter was applied to the data with narrow passband frequency windows of 85-95 Hz, 48-53 Hz and 15-25 Hz, respectively. Figures 6 displays some of the resultant bandpass-filtered "A" and "B" calls in the 85-95 Hz and 48-53 Hz bands, as well as the associated signals in 15-25 Hz band in the deep data set. Since the energy of the latter signals is confined between 17 and 18 Hz, it is indicative that the 90-Hz (center frequency) "A" calls and the 51-Hz (center frequency) "B" calls are the fifth and third harmonics of the fundamental frequency,

respectively. Figure 7 is similar to Figure 6, except that it is for the shallow data set. Note that there was an increase in ambient noise and the disappearance of the signal components in the fundamental frequency. The disappearance could be related to the whale's vocalization. However, this disappearance could also be just an effect of the waveguide, cutting off the propagation of very low-frequency sound with its shallow water depth. Whale vocalizations were identified by visual inspection of the filtered data sets and signal segments of 20 seconds for "A" calls and 15 seconds for "B" calls were extracted to support the remaining analysis of the thesis.

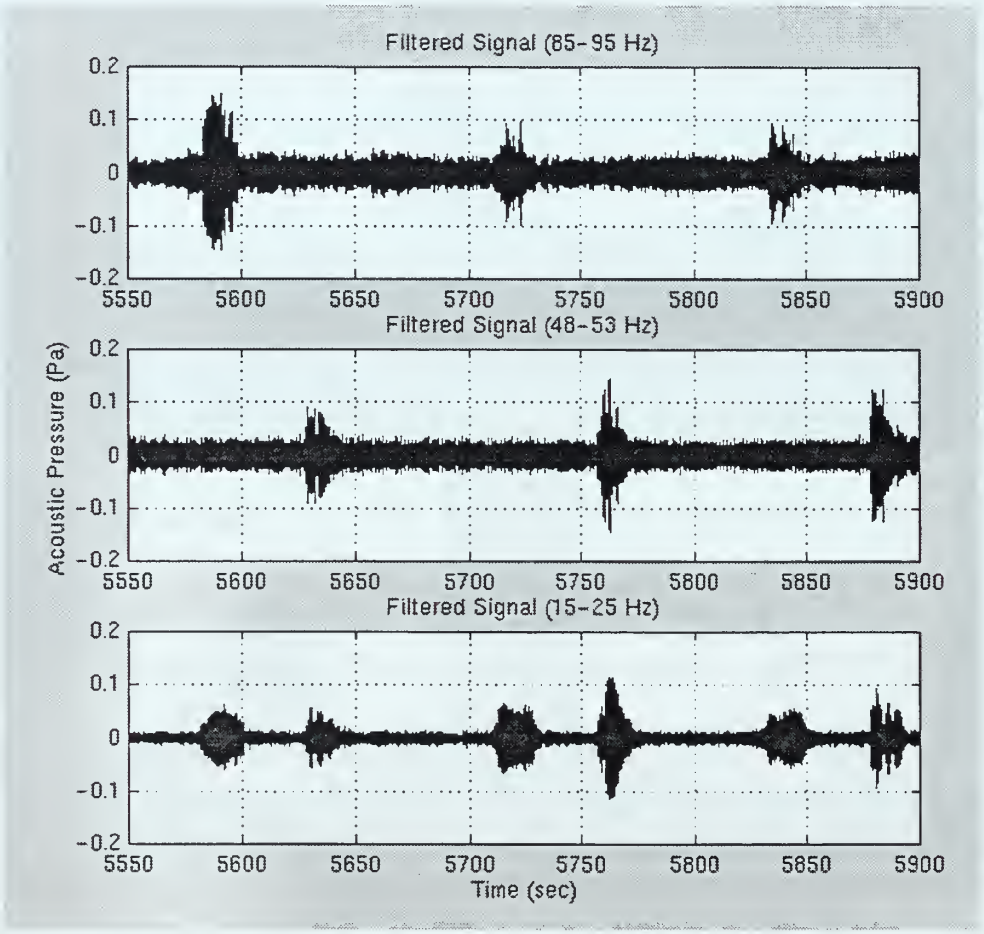

Figure 6: A segment of the bandpass-filtered time series in the deep water data set. The time series was bandpassed into three different bands, 85-95 Hz (top), 48-53 Hz (middle), and 15-25 Hz (bottom), to aid in the identification and extraction of individual "A" and "B" calls.

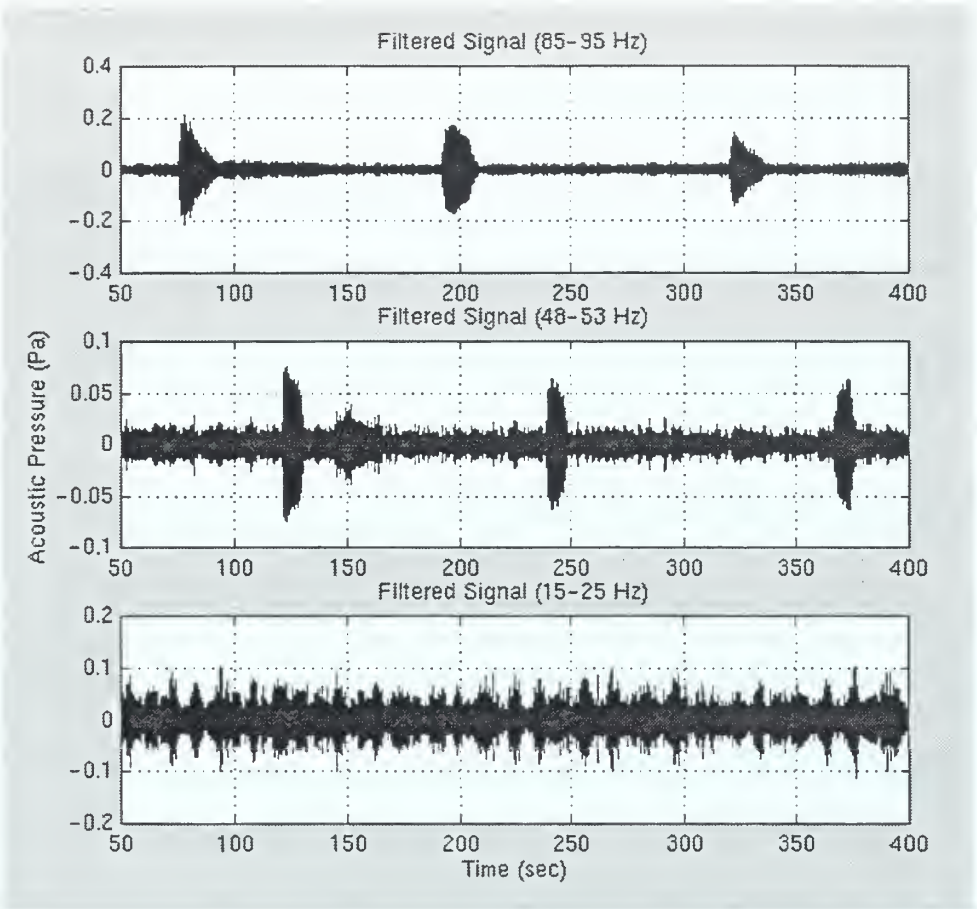

Figure 7: Same as Figure 6, except that it is for the shallow data set, showing the disappearance of vocalization signals in the 15-25 Hz band.

C. DEVERBERATION METHOD FOR RECONSTRUCTING SOURCE SIGNALS

The received blue whale signal is made up of the interfering multipath arrivals. The ocean scrambles the vocalized signal by its multipaths as the signal propagates to the receiver. The received signal is further contaminated by ambient noise. The experimental noise can be reduced to a great extent by bandpass filtering, however the location dependent multipath effects on the signal must also be removed in order to allow for a quantitative examination of the source level, source signal characteristics and call-to-call variability. The procedure to remove the multipath effects, i.e., reconstruct the

source signals, is called deverberation. The formulation of the deverberation procedure used is this thesis research is presented next:

The frequency spectra R_p of the received signals are related to the spectrum S of the source signal weighted by the source-to-receiver transfer function H, and contaminated by additive noise N:

$$R_p(f) = S(f;\vec{x}_w)\ H(f;\vec{x}_w,\vec{x}_p) + N(f). \qquad (1)$$

Because we are dealing with measurements near the whale site, it is adequate to model H with five multipaths:

$$H(f;\vec{x}_w,\vec{x}_p) = \sum_{j=1}^{5} \frac{w_j}{D_j} e^{-i2\pi f \tau_j}, \qquad (2)$$

where D_j is the path length of the jth path, τ_j is the corresponding travel time, and w_j is the corresponding weighting factor. The five paths include a direct path, one with one surface bounce, one with one bottom bounce, one with two surface bounces and a bottom bounce, and one with one surface bounce and a bottom bounce. w_j depends on the number of surface/bottom reflections, the surface/bottom reflection coefficients, the incident angle, and for the direct path it is unity.

This model assumes that the whale is a point source, the geometrical spreading is spherical, the water is isovelocity, the water depth is constant, Doppler effect is negligible, and the sediment sound speed and density are constant. It is clear in (1) that the reconstruction of $\mathbf{S}$ requires that the location $\vec{x}_w$ of the whale to be known first.

To estimate the whale location, we first plane-wave beamformed to determine the bearing. We then adopted the matched-signal processing method introduced by Parvulescu (1961 and 1995) to estimate range and depth. With an array of multiple elements at known relative positions $\vec{x}_p$, the matched-signal method can be generalized to become a space-time processor. An ambiguity surface, a function of range and depth, can be calculated by correlating the received signals with the transfer functions and then storing the maximum correlation value:

$$a(x,z) = \max_{\tau} \left\{ \int_{-\infty}^{+\infty} \underline{R}^H(f)\underline{H}(f;x,z)e^{i2\pi f\tau} \right\} \quad (3)$$

where $\underline{R}$ and $\underline{H}$ are now vector functions containing multiple received signals and transfer functions associated with each of the hydrophone elements. The best location estimate $(\hat{x},\hat{z})$ is where the ambiguity surface attains its maximum.

As an illustration, three ambiguity surfaces associated with three "A" calls over a nine-minute period recorded in deep water are displayed in Figure 8. During this nine minutes, the deep water whale appeared to be vocalizing in relatively shallow water and

was moving away from the towed array. These "A" call ambiguity surfaces show large "footprints" on the order of 200 m horizontal by 30 m vertical. The low resolution was due to the fact that these signals were coming in close to, although not exactly at, broadside of the towed array. This orientation constituted a bad geometry, although not the worst, for target localization for which little "independent" information on the target location is distributed across the array. Fortunately, time structure-rich "A" calls had provided enough temporal multipath information for resolving the source positions unambiguously.

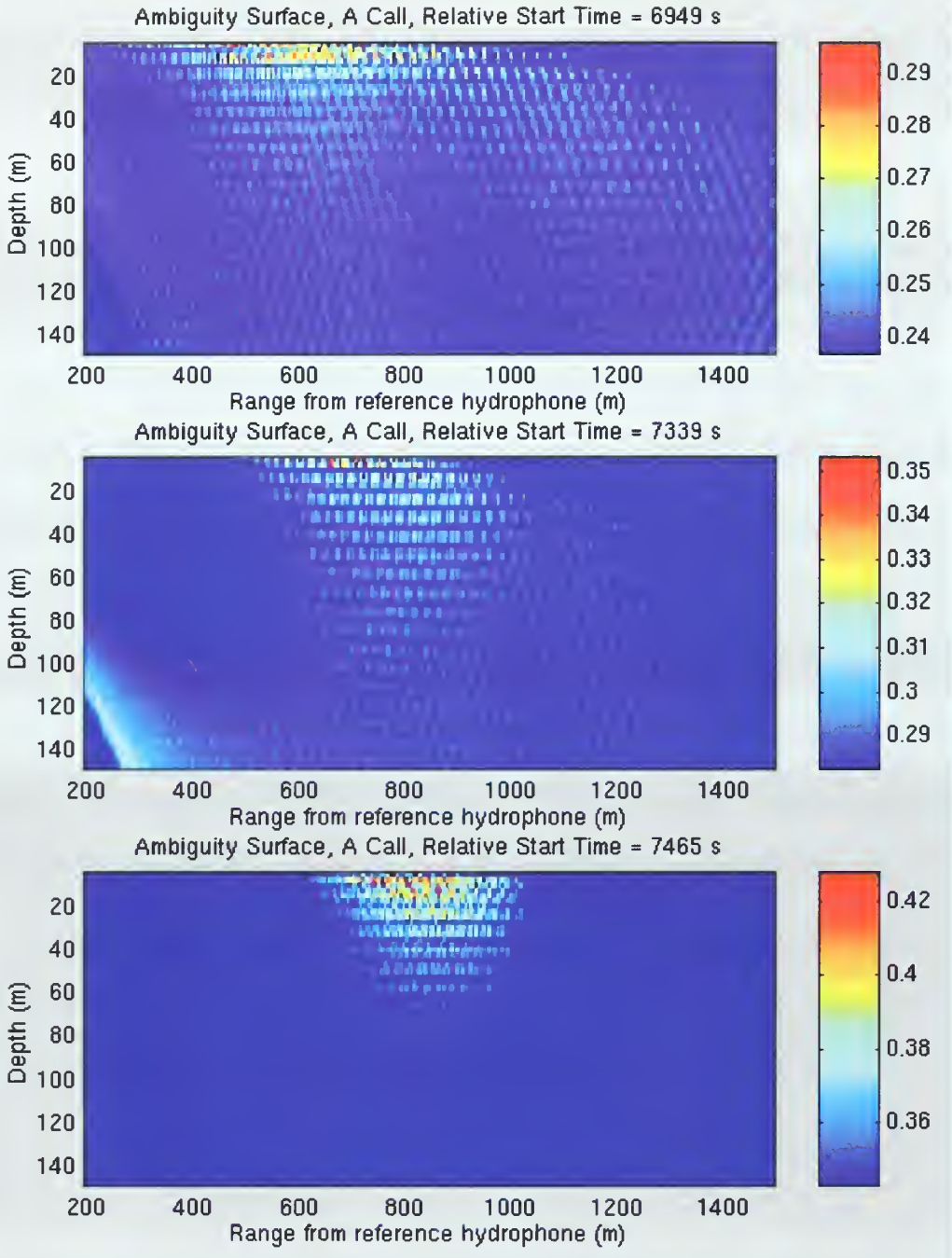

Figure 8: Ambiguity surfaces for blue whale "A" calls at 6949, 7339, and 7465 s into the deep water data set. The ambiguity surfaces show the maximum cross-correlation values between the measured and modeled sound fields. The trial range and depth showing the highest correlation should correspond to the true range and depth of the whale. During this nine minute period the whale appears to be moving away from the towed array.

Depending on the signal-to-noise ratio (SNR), richness of the signal structure, and orientation of the array relative to the whale location, the ambiguity surfaces may or may not exhibit multiple areas of high correlation leading to uncertainty in the determination of the whale's location. These multiple areas of high correlation away from the region of the main peak are referred to as "sidelobes" or "false targets". When sidelobe values become comparable to the main lobe values, localization becomes ambiguous. An example of an ambiguous localization is shown in Figure 9. It shows that the ambiguity surface for an "A" call in the shallow water data set has multiple significant sidelobes. Although one can still pick the best estimate to be the location where the highest correlation value occurs. The sensitivity of the source signal estimate must be examined carefully. This sensitivity can be studied by comparing the source signal estimates constructed using the different peak locations of the significant sidelobes to the estimate associated with the main peak. Fortunately, the comparison shows that the source signal estimates associated with the mainlobe and sidelobe peaks are almost identical.

It is worthwhile to mention that for the case shown in Figure 9, the existence of the multiple significant sidelobes was the result of a signal arrival bearing of exactly 90°. This orientation gives the poorest localization performance.

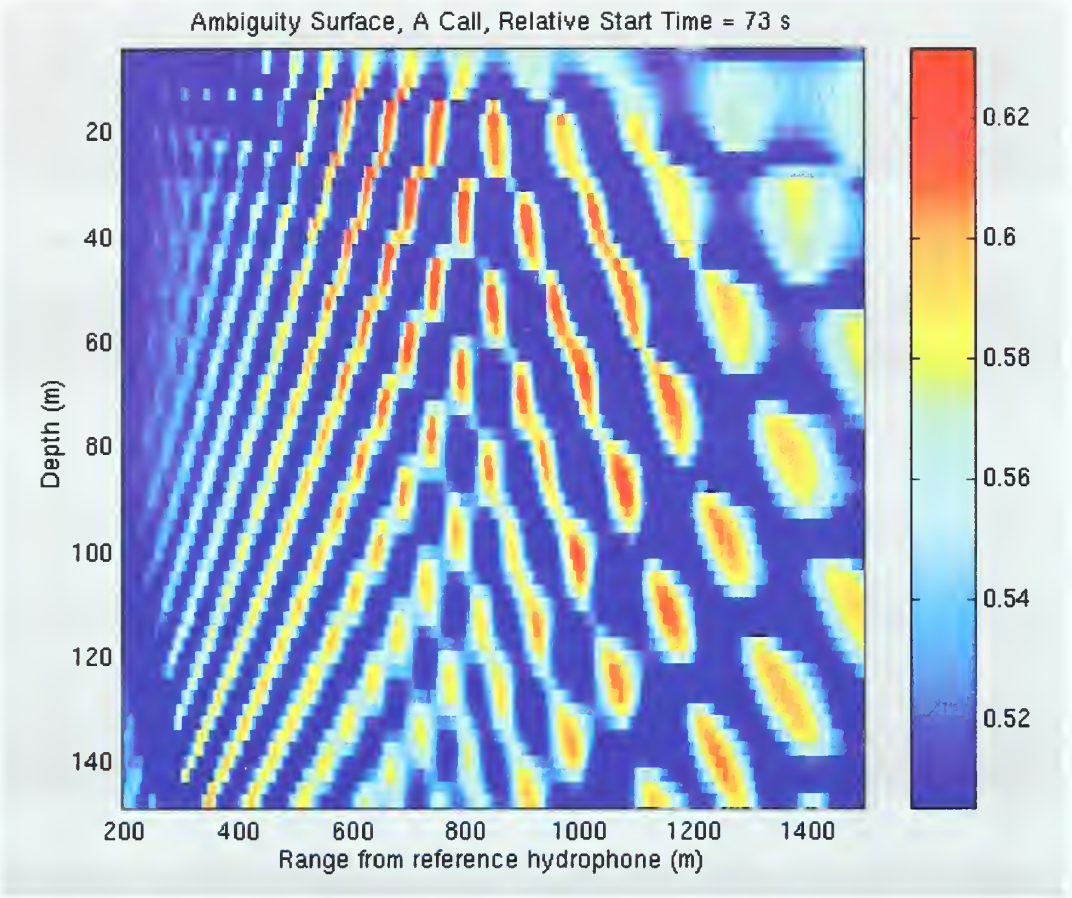

Figure 9: The ambiguity surface for a blue whale "A" call at 73 s into the shallow water data set.

With a good estimate of the range and depth of the whale, the transfer function is approximately known. The source signal spectrum can therefore be reconstructed by a least squares fit of the model to data. The least squares solution is

$$\hat{S}(f) = [H(f,\hat{x},\hat{z})^H H(f,\hat{x},\hat{z})]^{-1} H(f,\hat{x},\hat{z})^H R(f), \qquad (4)$$

where H^H is the conjugate transpose of the transfer function H. An inverse fourier transform of $\hat{S}(f)$ thus gives the source signal estimate $\hat{s}(t)$ in the time domain. Peak source levels SL can be estimated as

$$SL = 20\log_{10}\max\{\hat{s}(t)\}/10^{-6} \text{ re } 1\mu\text{Pa}. \quad (5)$$

Cross-correlation of source signals at different times can be used to assess the variability and robustness properties of the two call types, which affect long range autodetection and localization methods.

III. ANALYSIS RESULTS

A. SOURCE SIGNAL

Using the deverberation procedure detailed in Section C of Chapter II, the source signals, (i.e., the "A" and "B" calls) produced by both the shallow water and deep water whales were reconstructed. In short, the procedure consists of three steps. The first step involves horizontal plane-wave beamforming to determine the bearing of the incoming signal relative to the towed array. The second step corresponds to source range and depth estimation along the known bearing using a model-based, space-time matched signal technique. The final step is the construction of least-squares estimate for the source signal by fitting the product of the source signal spectrum and the known transfer function to the signal spectra measured by the towed array. Deverberation is required to counter the reverberant environment's multipath effects. These multipaths scramble the whales localization at the receiver and, therefore, must be removed in order to study the characteristics of the actual source signals, such as source levels, duration, fine structure, and other details of the vocalization including call-to-call variability. These types of information on the source signal characteristics are useful for designing auto-detection filters and long-range localization and tracking algorithms.

The results from beamforming the shallow water and deep water data sets are displayed in Figures 10 and 11, respectively. An expected left-right ambiguity suggesting two possible bearings is clearly seen. This left-right ambiguity is a well-understood limitation of any horizontal-line array systems. In this study, the ambiguity was resolved with the supplemental visual data.

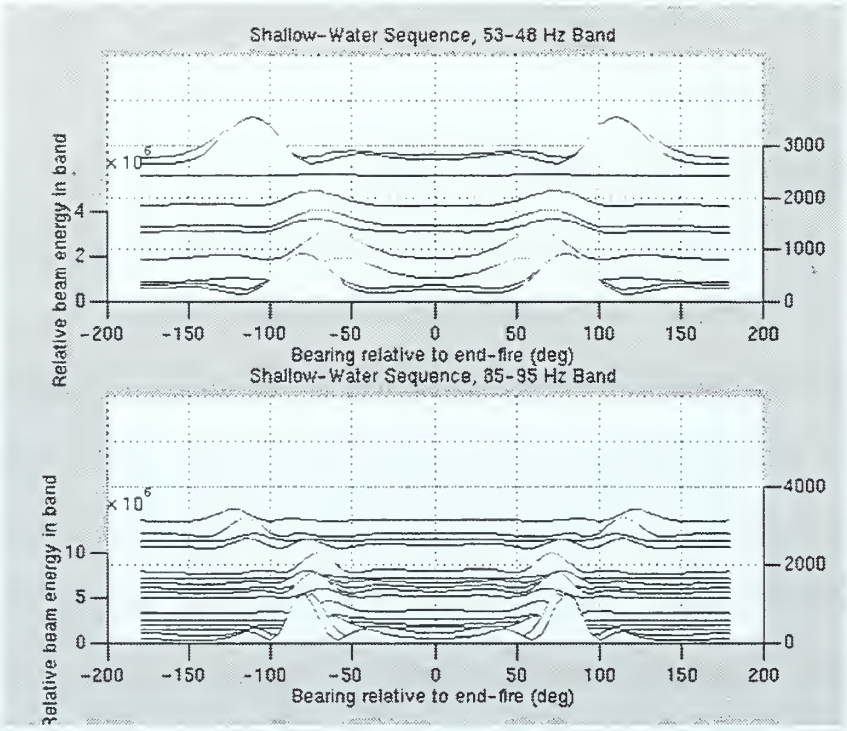

Figure 10: Beam energy versus bearing relative to the towed-array's end-fire direction associated with the "B" (top) and the "A" (bottom) calls of the shallow water whale.

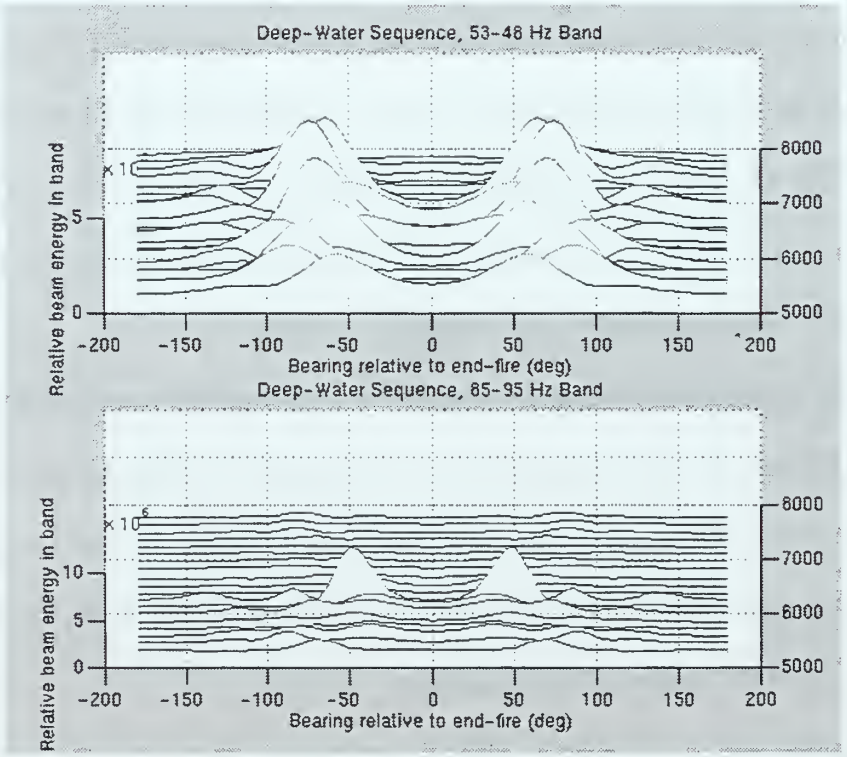

Figure 11: Beam energy versus bearing relative to the towed-array's end-fire direction associated with the deep water "B" (top) and the "A" (bottom) calls.

Some of the range-depth ambiguity surfaces computed for the purpose of estimating the whale positions at different times of vocalizations were presented and discussed in the Chapter II. The link between a localization and the subsequent reconstruction of the source signal is depicted in Figure 12. The ambiguity surface (top panel) of an "A" call provided an estimate of the whale location which, in turn, provided an estimate of the source-to-receiver transfer function. With the transfer function known, the multipath model for the received multi-phone signals, which have a linear relation with the source signal, was then fitted to the data (bottom panel) to attain a least-squares estimate of the source signal (middle panel). It is easily seen that although the mutli-phone (bandpassed with a 85-95 Hz window) data contain significant noise, the deverberated source signal is of high quality with a much improved signal-to-noise ratio. This implies that the noise in this 85-95 Hz band was largely uncorrelated from one hydrophone to another.

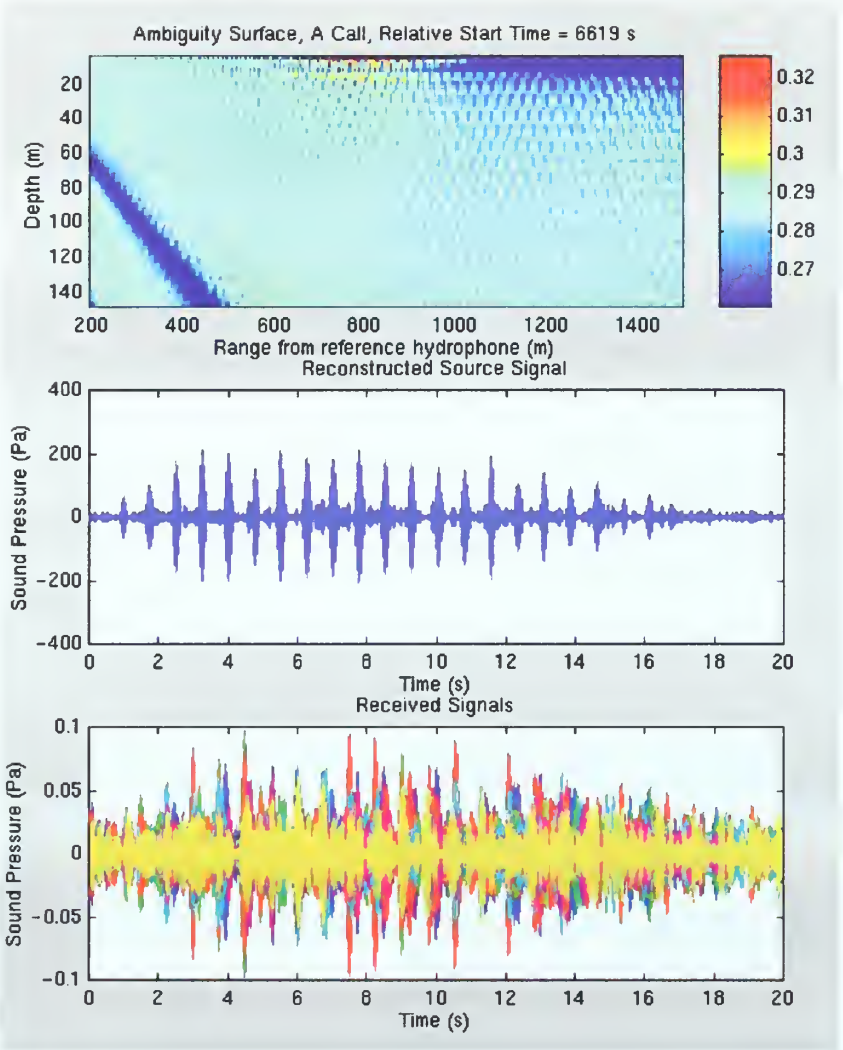

Figure 12: Blue whale "A" call at 6619 s into the deep water data set. Although the received signals (bottom) on six different hydrophones was quite noisy, reconstruction (middle) was successful utilizing the location estimate given by the ambiguity surface (top). The reconstructed source signal is shown in the middle panel. The multiphone data are displayed in the bottom panel. The different colors represent different hydrophones.

The deep water whale was located in the deep Monterey Canyon region where water depth is approximately 1200 m. Nineteen "A" calls and 19 "B" calls from the deep water data set were deverberated. The shallow water whale was located on the continental shelf region where water depth is approximately 240 m. Sixteen "A" calls and 10 "B" calls from the shallow water data set were deverberated.

For the shallow water whale, the reconstructed source signals' had a mean source level of 158.1 dB re 1µPa with a standard deviation of 5.2 dB re 1µPa for the "A" calls and 157.4 dB re 1µPa with a standard deviation of 6.1 dB re 1µPa for the "B" calls. The mean duration was 13.7 s with a standard deviation of 2.5 s for the "A" calls and 11.4 s with a standard deviation of 1.0 s for the "B" calls. The mean number of "A" call pulses was 20.3 pulses with a standard deviation of 1.3 pulses. The mean depth of vocalization for the shallow water blue whale was 51.6 m with a standard deviation of 31.3 m. Figure 13 and 14 each show four samples of the reconstructed "A" and "B" call source signals from the shallow water data set.

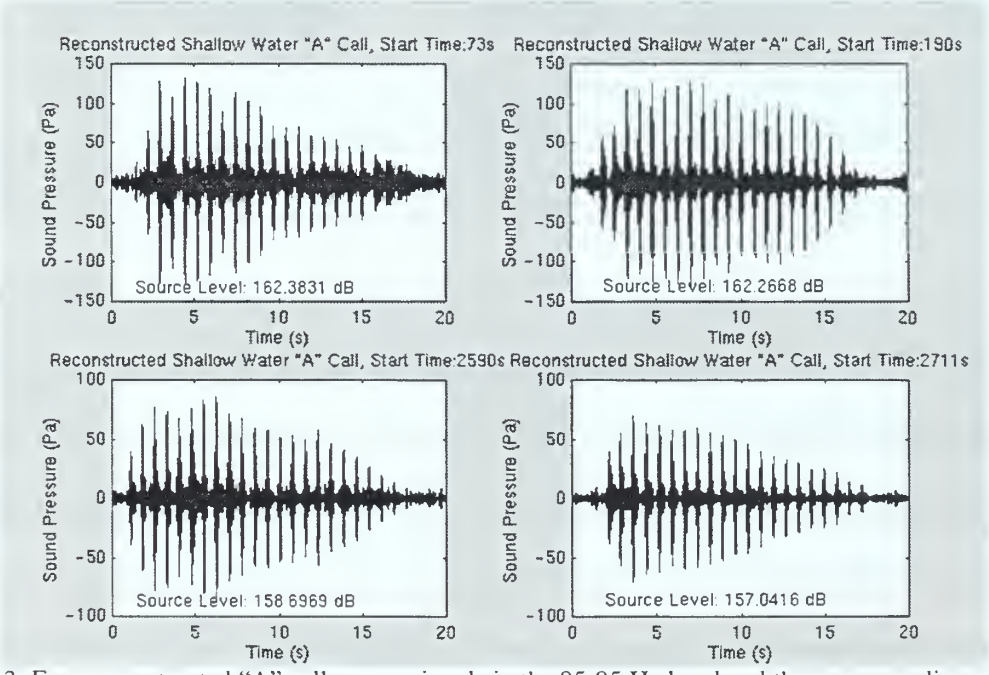

Figure 13: Four reconstructed "A" call source signals in the 85-95 Hz band and the corresponding source levels for the vocalizations produced by a transiting blue whale in shallow water. Start times are referenced to the time axis of the digitized time series.

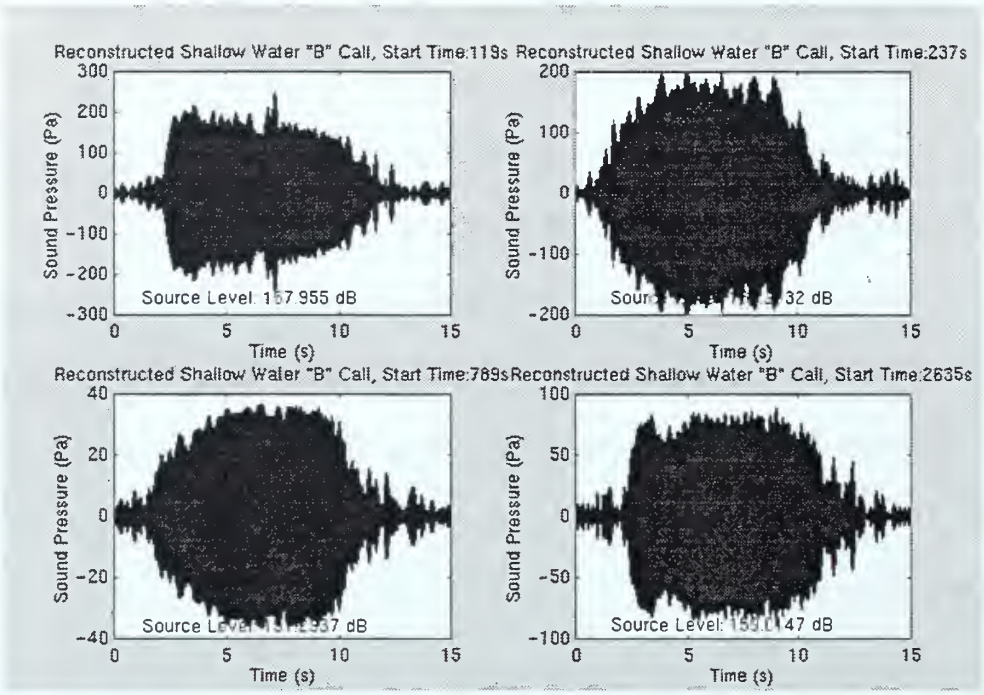

Figure 14: Four reconstructed "B" call source signals in the 48-53 Hz band and the corresponding source levels for the vocalizations produced by a transiting blue whale in shallow water. Start times are referenced to the time axis of the digitized time series.

For the deep water whale, the reconstructed source signals had a mean source level of 166.0 dB re 1μPa with a standard deviation of 6.3 dB re 1μPa for the "A" calls and 170.8 dB re 1μPa with a standard deviation of 9.3 dB re 1μPa for the "B" call. The mean durations were 15.4 s with a standard deviation of 1.0 s for the "A" calls and 9.9 s with a standard deviation of 1.7 s for the "B" calls. The mean number of "A" call pulses was 20.0 pulses with a standard deviation of 1.2 pulses. Figure 15 and 16 each show two samples of the "A" and "B" call source signals reconstructed from the deep water data set. The mean depth of vocalization for the transiting deep water blue whales was 18.2 m with a standard deviation of 24.4 m.

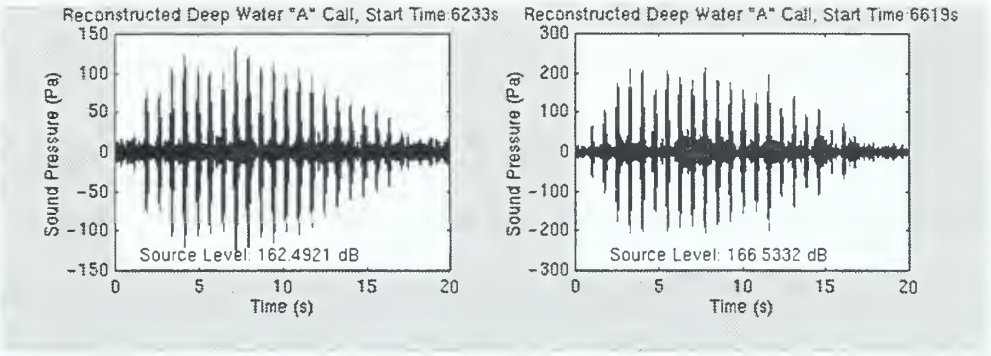

Figure 15: Reconstructed "A" calls in the 85-95 Hz band and estimated source levels for the transiting blue whale in deep water. Start times indicate seconds into the data set of the digitized time series.

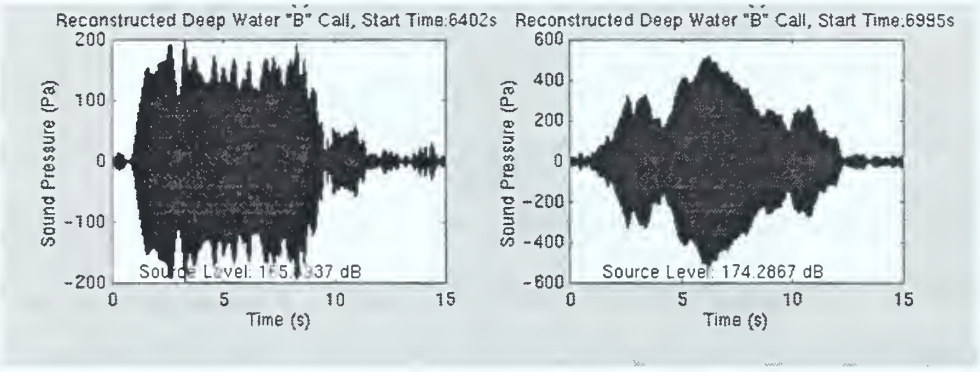

Figure 16: Reconstructed "B" calls in the 48-53 Hz band and estimated source levels for a transiting blue whales in deep water. Start times indicate seconds into the data set of the digitized time series.

B. CALL-TO-CALL VARIABILITY

Based on the reconstructed source signals, the variability of the "A" call and "B" call produced by blue whales were examined using correlation analysis. The cross-correlation results quantify which source signal quantities are robust and which are not, and therefore shed lights on what signal quantities might be exploited in the implementation of auto-detection and long-range localization and tracking algorithms for the NPS OAO array. These cross-correlation results are presented in this section in tabular form. The variability in the calls produced by the shallow water whale is discussed first. A discussion on the variability of the calls produced by the deep water

whale then follows. Finally, the correlation between the calls produced by the two different whales is described.

Table 5 presents the cross-correlation values for the waveforms as well as the magnitudes of the waveforms of the 16 deverberated "A" calls of the shallow water whale. While the lower triangle of the table contains the cross-correlation values for the magnitudes of the waveforms, the shaded upper triangle gives the cross-correlation values for the waveforms themselves. The cross-correlation value is a measure of signal similarity, and is defined as the maximum of the cross-correlation function between a pair of signals that have been demeaned and normalized to have unit energy. The values in Table 5 show that waveforms of the deverberated shallow water "A" calls are highly dissimilar with the majority of correlation values below 0.4, suggesting that the waveforms are highly variable from one call to another. On the contrary, the magnitudes of the waveforms are highly correlated with a mean cross-correlation value of 0.90 ± 0.03.

	0.37	0.30	0.22	0.30	0.27	0.30	0.49	0.37	0.27	0.31	0.28	0.34	0.34	0.39	0.34
0.94		0.37	0.30	0.37	0.32	0.35	0.29	0.25	0.37	0.37	0.34	0.39	0.27	0.36	0.28
0.93	0.93		0.21	0.25	0.33	0.28	0.33	0.31	0.28	0.28	0.26	0.39	0.26	0.40	0.35
0.85	0.8	0.84		0.22	0.22	0.30	0.33	0.25	0.32	0.25	0.23	0.23	0.24	0.28	0.20
0.94	0.93	0.92	0.84		0.28	0.32	0.31	0.28	0.54	0.33	0.24	0.40	0.37	0.35	0.27
0.93	0.94	0.92	0.83	0.92		0.32	0.37	0.36	0.34	0.29	0.29	0.45	0.36	0.35	0.27
0.93	0.94	0.91	0.83	0.93	0.93		0.34	0.27	0.24	0.25	0.33	0.34	0.38	0.35	0.24
0.93	0.93	0.92	0.85	0.93	0.94	0.94		0.29	0.38	0.33	0.22	0.30	0.35	0.32	0.30
0.90	0.89	0.87	0.86	0.90	0.89	0.88	0.89		0.34	0.24	0.37	0.35	0.27	0.42	0.33
0.91	0.90	0.89	0.84	0.92	0.90	0.92	0.92	0.87		0.23	0.29	0.29	0.30	0.33	0.29
0.89	0.86	0.86	0.85	0.88	0.86	0.88	0.88	0.89	0.88		0.18	0.33	0.30	0.31	0.32
0.92	0.90	0.9	0.85	0.91	0.90	0.90	0.90	0.89	0.90	0.90		0.40	0.22	0.30	0.29
0.95	0.94	0.92	0.84	0.92	0.92	0.93	0.93	0.88	0.90	0.88	0.92		0.27	0.42	0.46
0.93	0.95	0.90	0.80	0.92	0.93	0.94	0.93	0.89	0.90	0.86	0.89	0.92		0.35	0.24
0.95	0.95	0.92	0.81	0.93	0.93	0.93	0.93	0.89	0.89	0.84	0.88	0.92	0.93		0.29
0.93	0.94	0.92	0.81	0.92	0.92	0.92	0.91	0.87	0.89	0.86	0.92	0.94	0.91	0.92	

Table 5: Cross-correlation value for the source signals waveforms (shaded upper triangle) and magnitudes of the source signal waveforms (lower triangle) of the "A" calls produced by the shallow water whale.

Table 6 is similar to Table 5, except it is for the "B" calls of the shallow water whale. The cross-correlation results show that the "B" call waveforms, with a mean correlation value of 0.65 ± 0.21, are much more robust than the "A" call waveforms vocalized by this whale. Similar to the magnitudes of the "A" call waveforms, the magnitudes of the "B" call waveforms are extremely robust with cross-correlation values consistently higher than 0.9.

	0.89	0.62	0.8	0.79	0.67	0.83	0.25	0.87	0.77
0.98		0.55	0.86	0.81	0.59	0.77	0.26	0.88	0.84
0.96	0.98		0.73	0.51	0.77	0.55	0.24	0.64	0.69
0.97	0.99	0.98		0.71	0.77	0.7	0.26	0.84	0.9
0.97	0.96	0.94	0.95		0.63	0.85	0.32	0.76	0.71
0.95	0.93	0.94	0.93	0.96		0.69	0.33	0.65	0.78
0.93	0.91	0.92	0.91	0.93	0.96		0.33	0.79	0.70
0.86	0.87	0.88	0.87	0.82	0.87	0.87		0.23	0.26
0.98	0.98	0.96	0.99	0.96	0.93	0.90	0.86		0.84
0.99	0.98	0.97	0.98	0.97	0.95	0.92	0.86	0.99	

Table 6: Cross-correlation value for the source signals waveforms (shaded upper triangle) and magnitudes of the source signal waveforms (lower triangle) of the "B" calls produced by the shallow water whale.

The cross-correlation results for the "A" and "B" calls vocalized by the deep whale are shown in Tables 7 and 8, respectively. Cross-correlation values of 0.22 ± 0.05 for the "A" call waveforms, 0.80 ± 0.05 for the magnitudes of the "A" call waveform, 0.53 ± 0.11 for the "B" call waveforms, and 0.86 ± 0.05 for the magnitudes of the "B" call waveforms are obtained (the numbers following the ± sign are the standard deviations). These cross-correlation values are highly consistent with those associated with the calls of the shallow water whale, showing that the "A" call waveforms are highly variable from call to call but less variable for the "B" calls. The magnitudes of the waveforms are robust for both the "A" and "B" calls produced by the same whale.

	0.24	0.20	0.16	0.23	0.32	0.24	0.30	0.18	0.12	0.31	0.22	0.31	0.33	0.21	0.21	0.23	0.19	0.20
0.83		0.22	0.15	0.23	0.23	0.18	0.27	0.18	0.19	0.30	0.26	0.20	0.18	0.21	0.22	0.30	0.27	0.32
0.77	0.81		0.18	0.24	0.18	0.24	0.23	0.31	0.17	0.23	0.20	0.15	0.28	0.16	0.18	0.16	0.27	0.24
0.77	0.76	0.85		0.17	0.33	0.17	0.16	0.15	0.21	0.20	0.23	0.23	0.15	0.21	0.13	0.17	0.21	0.21
0.82	0.80	0.81	0.82		0.18	0.23	0.25	0.21	0.26	0.30	0.24	0.20	0.23	0.22	0.19	0.19	0.20	0.25
0.84	0.82	0.81	0.77	0.77		0.26	0.32	0.20	0.20	0.26	0.24	0.22	0.19	0.20	0.20	0.35	0.19	0.38
0.85	0.82	0.82	0.79	0.83	0.79		0.23	0.14	0.21	0.27	0.27	0.26	0.22	0.20	0.20	0.27	0.15	0.30
0.84	0.85	0.76	0.68	0.76	0.83	0.79		0.15	0.23	0.38	0.23	0.32	0.24	0.22	0.26	0.34	0.21	0.32
0.75	0.77	0.82	0.82	0.80	0.77	0.78	0.70		0.22	0.27	0.17	0.18	0.30	0.21	0.18	0.18	0.21	0.21
0.76	0.79	0.84	0.85	0.81	0.74	0.81	0.69	0.83		0.23	0.21	0.17	0.17	0.22	0.21	0.16	0.16	0.16
0.87	0.84	0.73	0.66	0.74	0.83	0.79	0.95	0.69	0.67		0.32	0.23	0.19	0.20	0.36	0.27	0.24	0.25
0.84	0.85	0.83	0.78	0.83	0.84	0.82	0.85	0.79	0.80	0.84		0.25	0.16	0.26	0.22	0.31	0.19	0.29
0.85	0.84	0.84	0.80	0.84	0.82	0.84	0.83	0.78	0.83	0.83	0.87		0.23	0.19	0.21	0.17	0.25	0.22
0.81	0.76	0.80	0.80	0.79	0.77	0.80	0.69	0.78	0.79	0.69	0.80	0.80		0.18	0.21	0.20	0.21	0.18
0.76	0.76	0.84	0.85	0.82	0.76	0.80	0.71	0.80	0.84	0.68	0.81	0.81	0.80		0.17	0.20	0.18	0.21
0.78	0.81	0.79	0.76	0.81	0.79	0.80	0.79	0.74	0.76	0.77	0.82	0.81	0.79	0.78		0.25	0.22	0.28
0.84	0.84	0.77	0.77	0.79	0.82	0.82	0.85	0.76	0.75	0.86	0.83	0.84	0.76	0.74	0.75		0.16	0.27
0.76	0.78	0.83	0.83	0.80	0.77	0.81	0.69	0.80	0.82	0.68	0.78	0.80	0.80	0.81	0.75	0.77		0.19
0.85	0.85	0.78	0.76	0.80	0.81	0.85	0.89	0.75	0.75	0.87	0.86	0.85	0.78	0.77	0.82	0.87	0.78	

Table 7: Cross-correlation value for the source signals waveforms (shaded upper triangle) and magnitudes of the source signal waveforms (lower triangle) of the "A" calls produced by the deep water whale.

	0.53	0.43	0.63	0.59	0.42	0.42	0.49	0.57	0.61	0.59	0.53	0.56	0.55	0.39	0.43	0.55	0.40	0.60
0.83		0.39	0.44	0.46	0.40	0.39	0.40	0.46	0.45	0.50	0.51	0.46	0.43	0.33	0.49	0.50	0.35	0.58
0.82	0.75		0.40	0.53	0.64	0.48	0.43	0.56	0.54	0.54	0.41	0.57	0.35	0.38	0.43	0.50	0.34	0.45
0.85	0.78	0.79		0.65	0.59	0.46	0.66	0.64	0.56	0.72	0.55	0.65	0.54	0.51	0.58	0.56	0.49	0.68
0.86	0.76	0.83	0.87		0.50	0.50	0.48	0.65	0.59	0.67	0.49	0.66	0.46	0.54	0.49	0.54	0.47	0.50
0.83	0.71	0.82	0.85	0.87		0.58	0.49	0.53	0.45	0.51	0.54	0.52	0.37	0.58	0.53	0.55	0.39	0.47
0.93	0.80	0.82	0.91	0.92	0.87		0.61	0.67	0.72	0.83	0.52	0.71	0.38	0.54	0.40	0.53	0.46	0.49
0.83	0.76	0.86	0.87	0.90	0.89	0.88		0.62	0.51	0.56	0.51	0.58	0.49	0.49	0.56	0.56	0.44	0.70
0.93	0.80	0.81	0.89	0.91	0.86	0.97	0.86		0.84	0.74	0.65	0.86	0.46	0.54	0.68	0.85	0.5	0.64
0.89	0.81	0.80	0.92	0.91	0.85	0.94	0.87	0.93		0.72	0.59	0.80	0.38	0.50	0.56	0.69	0.52	0.60
0.92	0.81	0.83	0.94	0.89	0.88	0.96	0.89	0.94	0.94		0.58	0.68	0.46	0.50	0.51	0.68	0.48	0.59
0.89	0.81	0.82	0.87	0.88	0.89	0.92	0.89	0.91	0.88	0.89		0.66	0.40	0.41	0.66	0.52	0.44	0.58
0.91	0.77	0.82	0.90	0.88	0.90	0.95	0.91	0.93	0.90	0.96	0.92		0.48	0.53	0.63	0.68	0.44	0.51
0.84	0.75	0.76	0.86	0.86	0.85	0.88	0.84	0.90	0.87	0.89	0.87	0.86		0.49	0.41	0.42	0.30	0.47
0.85	0.74	0.82	0.92	0.86	0.88	0.90	0.88	0.90	0.89	0.91	0.87	0.89	0.87		0.54	0.32	0.44	0.40
0.87	0.81	0.87	0.87	0.82	0.86	0.88	0.87	0.85	0.86	0.89	0.87	0.90	0.83	0.85		0.66	0.48	0.50
0.92	0.84	0.81	0.87	0.90	0.83	0.94	0.85	0.95	0.89	0.91	0.90	0.89	0.86	0.82	0.85		0.50	0.66
0.76	0.74	0.86	0.77	0.80	0.77	0.77	0.81	0.79	0.78	0.79	0.79	0.76	0.76	0.82	0.84	0.78		0.49
0.90	0.85	0.80	0.86	0.92	0.84	0.91	0.88	0.90	0.90	0.88	0.87	0.87	0.82	0.83	0.87	0.91	0.78	

Table 8: Cross-correlation value for the source signals waveforms (shaded upper triangle) and magnitudes of the source signal waveforms (lower triangle) of the "B" calls produced by the deep water whale.

Tables 9, 10, 11, 12 display the inter-whale cross-correlation results which quantify the similarity (or dissimilarity) of the source signals produced by the two different whales. The dissimilarity of the "A" call waveforms, similarity of the "B" call waveforms, and robustness of the magnitudes of both waveforms are clearly shown in the inter-comparison. This constitutes an important overall result of this study of call-to-call variabity.

	SHALLOW															
	0.22	0.48	0.27	0.13	0.34	0.24	0.26	0.20	0.17	0.20	0.23	0.24	0.34	0.23	0.25	0.24
	0.23	0.31	0.32	0.16	0.23	0.35	0.22	0.27	0.23	0.23	0.21	0.36	0.33	0.31	0.28	0.36
	0.19	0.23	0.19	0.17	0.18	0.22	0.24	0.22	0.18	0.17	0.21	0.19	0.20	0.24	0.17	0.25
	0.16	0.21	0.23	0.15	0.16	0.18	0.17	0.22	0.19	0.25	0.25	0.21	0.18	0.14	0.15	0.18
	0.25	0.23	0.17	0.17	0.26	0.22	0.24	0.21	0.19	0.19	0.19	0.21	0.24	0.38	0.19	0.21
	0.22	0.35	0.25	0.22	0.21	0.29	0.35	0.29	0.17	0.28	0.25	0.23	0.33	0.27	0.20	0.38
	0.33	0.22	0.28	0.23	0.19	0.18	0.35	0.30	0.22	0.23	0.24	0.22	0.24	0.19	0.26	0.22
D	0.32	0.25	0.30	0.18	0.20	0.30	0.35	0.32	0.24	0.20	0.25	0.27	0.38	0.29	0.31	0.40
E	0.16	0.16	0.19	0.14	0.18	0.18	0.21	0.17	0.14	0.19	0.17	0.16	0.17	0.21	0.14	0.25
E	0.17	0.21	0.22	0.13	0.17	0.18	0.18	0.21	0.16	0.16	0.17	0.13	0.16	0.2	0.19	0.17
P	0.32	0.32	0.34	0.18	0.52	0.37	0.30	0.31	0.26	0.36	0.42	0.20	0.42	0.45	0.35	0.38
	0.23	0.23	0.28	0.21	0.21	0.24	0.38	0.25	0.28	0.21	0.17	0.22	0.36	0.26	0.36	0.28
	0.25	0.31	0.21	0.12	0.23	0.24	0.19	0.21	0.17	0.24	0.18	0.21	0.25	0.19	0.25	0.26
	0.25	0.23	0.26	0.22	0.18	0.18	0.19	0.17	0.15	0.17	0.18	0.19	0.21	0.15	0.18	0.21
	0.17	0.19	0.20	0.18	0.18	0.15	0.25	0.23	0.18	0.21	0.18	0.27	0.27	0.17	0.20	0.20
	0.33	0.24	0.25	0.18	0.24	0.26	0.25	0.25	0.26	0.29	0.27	0.23	0.24	0.34	0.28	0.26
	0.25	0.31	0.28	0.25	0.20	0.26	0.32	0.32	0.24	0.20	0.24	0.24	0.36	0.29	0.28	0.26
	0.20	0.19	0.19	0.16	0.20	0.18	0.17	0.17	0.21	0.20	0.19	0.22	0.19	0.15	0.18	0.18
	0.26	0.21	0.27	0.25	0.26	0.32	0.27	0.28	0.25	0.27	0.29	0.31	0.42	0.24	0.28	0.36

Table 9: Cross-correlation values corresponding to an intercomparison of the source signal waveforms of the "A" calls produced by two different whales.

SHALLOW

	0.89	0.87	0.89	0.86	0.89	0.89	0.87	0.89	0.88	0.85	0.86	0.88	0.88	0.86	0.86	0.86
	0.83	0.84	0.82	0.80	0.84	0.85	0.85	0.85	0.84	0.85	0.85	0.87	0.86	0.83	0.79	0.86
	0.75	0.70	0.73	0.80	0.79	0.74	0.74	0.76	0.79	0.79	0.82	0.79	0.76	0.70	0.68	0.74
	0.69	0.64	0.68	0.79	0.73	0.70	0.70	0.72	0.75	0.74	0.78	0.74	0.70	0.65	0.63	0.65
	0.76	0.73	0.75	0.83	0.78	0.76	0.76	0.79	0.80	0.80	0.82	0.81	0.78	0.73	0.71	0.74
	0.82	0.80	0.80	0.79	0.83	0.80	0.80	0.83	0.81	0.82	0.81	0.84	0.82	0.80	0.80	0.82
D	0.82	0.78	0.81	0.85	0.82	0.81	0.81	0.82	0.84	0.82	0.86	0.84	0.81	0.79	0.78	0.79
E	0.91	0.89	0.89	0.80	0.88	0.87	0.87	0.87	0.84	0.87	0.85	0.93	0.93	0.88	0.86	0.94
E	0.70	0.64	0.69	0.77	0.74	0.68	0.68	0.71	0.72	0.74	0.76	0.74	0.70	0.65	0.63	0.67
P	0.71	0.65	0.69	0.80	0.74	0.70	0.70	0.73	0.74	0.76	0.79	0.75	0.70	0.65	0.64	0.67
	0.94	0.94	0.93	0.81	0.91	0.92	0.90	0.91	0.87	0.89	0.85	0.92	0.94	0.92	0.92	0.95
	0.85	0.81	0.83	0.82	0.87	0.83	0.83	0.85	0.84	0.84	0.86	0.86	0.85	0.81	0.80	0.83
	0.84	0.80	0.82	0.84	0.84	0.84	0.83	0.85	0.84	0.84	0.86	0.87	0.82	0.80	0.79	0.82
	0.71	0.67	0.71	0.78	0.74	0.72	0.71	0.74	0.77	0.72	0.77	0.75	0.71	0.67	0.66	0.68
	0.72	0.66	0.70	0.81	0.74	0.70	0.71	0.74	0.75	0.75	0.80	0.76	0.72	0.67	0.63	0.69
	0.77	0.77	0.77	0.78	0.77	0.76	0.76	0.78	0.83	0.76	0.84	0.79	0.79	0.76	0.74	0.77
	0.84	0.83	0.84	0.8	0.85	0.84	0.83	0.84	0.83	0.84	0.82	0.86	0.85	0.82	0.81	0.83
	0.71	0.65	0.69	0.79	0.74	0.70	0.70	0.73	0.76	0.75	0.77	0.75	0.71	0.66	0.65	0.68
	0.88	0.84	0.85	0.82	0.85	0.85	0.85	0.85	0.87	0.84	0.86	0.88	0.87	0.84	0.82	0.86

Table 10: Cross-correlation values corresponding to an intercomparison of the magnitudes of the source signal waveforms of the "A" calls produced by two different whales.

SHALLOW

	0.66	0.63	0.61	0.61	0.67	0.47	0.57	0.21	0.60	0.56
	0.48	0.46	0.56	0.45	0.41	0.43	0.37	0.22	0.47	0.45
	0.38	0.47	0.42	0.53	0.57	0.39	0.47	0.25	0.41	0.45
	0.71	0.66	0.64	0.64	0.65	0.59	0.59	0.18	0.69	0.64
	0.73	0.66	0.67	0.66	0.74	0.67	0.74	0.26	0.67	0.63
	0.48	0.49	0.41	0.49	0.49	0.46	0.46	0.28	0.45	0.42
	0.52	0.5	0.41	0.60	0.62	0.49	0.59	0.27	0.46	0.52
D	0.55	0.59	0.46	0.52	0.57	0.47	0.50	0.24	0.57	0.56
E	0.80	0.88	0.55	0.83	0.86	0.62	0.80	0.31	0.87	0.85
E	0.65	0.75	0.60	0.78	0.75	0.51	0.62	0.27	0.72	0.74
P	0.67	0.68	0.51	0.61	0.81	0.54	0.71	0.22	0.67	0.64
	0.55	0.62	0.61	0.61	0.60	0.52	0.53	0.28	0.59	0.62
	0.71	0.79	0.71	0.86	0.80	0.65	0.69	0.20	0.78	0.80
	0.48	0.43	0.68	0.54	0.50	0.64	0.47	0.30	0.46	0.68
	0.52	0.45	0.58	0.56	0.53	0.68	0.60	0.29	0.52	0.66
	0.70	0.71	0.56	0.67	0.56	0.51	0.60	0.20	0.80	0.69
	0.77	0.85	0.42	0.71	0.79	0.39	0.72	0.29	0.83	0.73
	0.50	0.54	0.47	0.51	0.41	0.39	0.47	0.21	0.52	0.49
	0.75	0.71	0.55	0.62	0.60	0.44	0.58	0.24	0.65	0.57

Table 11: Table 8: Cross-correlation values corresponding to an intercomparison of the source signal waveforms of the "B" calls produced by two different whales.

	SHALLOW									
	0.94	0.94	0.93	0.94	0.92	0.89	0.86	0.82	0.94	0.94
	0.79	0.81	0.79	0.81	0.79	0.76	0.73	0.75	0.81	0.79
	0.83	0.82	0.80	0.82	0.83	0.79	0.78	0.78	0.82	0.82
	0.90	0.91	0.91	0.91	0.86	0.87	0.89	0.85	0.90	0.89
	0.90	0.90	0.90	0.90	0.90	0.88	0.86	0.79	0.89	0.91
	0.87	0.88	0.88	0.87	0.86	0.87	0.86	0.81	0.86	0.88
	0.97	0.98	0.97	0.98	0.96	0.93	0.90	0.86	0.98	0.98
D	0.88	0.88	0.87	0.88	0.86	0.85	0.84	0.82	0.87	0.88
E	0.98	0.97	0.96	0.97	0.97	0.94	0.91	0.85	0.97	0.98
E	0.93	0.94	0.94	0.94	0.91	0.92	0.90	0.85	0.93	0.93
P	0.96	0.96	0.94	0.96	0.94	0.92	0.89	0.87	0.96	0.96
	0.90	0.92	0.91	0.92	0.89	0.89	0.86	0.82	0.90	0.92
	0.95	0.96	0.94	0.96	0.93	0.90	0.91	0.87	0.96	0.96
	0.90	0.89	0.88	0.88	0.90	0.91	0.91	0.82	0.88	0.89
	0.90	0.90	0.90	0.89	0.91	0.93	0.93	0.84	0.88	0.91
	0.87	0.88	0.88	0.89	0.86	0.86	0.86	0.85	0.90	0.87
	0.94	0.94	0.92	0.94	0.95	0.89	0.84	0.80	0.95	0.94
	0.79	0.77	0.76	0.76	0.82	0.81	0.78	0.70	0.77	0.79
	0.88	0.9	0.89	0.90	0.87	0.86	0.83	0.79	0.89	0.88

Table 12: Cross-correlation values corresponding to an intercomparison of the magnitudes of the source signal waveforms of the "B" calls produced by two different whales.

IV. CONCLUSIONS

The blue whale, weighing up to 200 tons with a length of 100 feet, is highly endangered. Blue whales still range temperate and cold waters worldwide but in small numbers. Its pre-whaling population of perhaps 200,000 has been reduced to 5,000-10,000 animals (Darling, 1990). All that we know is only a small fraction of what we do not know about blue whales. We do not know their migratory routes, breeding or calving grounds, or what the loudest, lowest voice in the world is used for. Hypotheses as to acoustic activity range from communication to bathymetric echolocation to echolocation of zooplankton masses (Clark, 1995). Long-term monitoring of where and when whales vocalize is required to test the validity of these theories and to adequately census blue whales.

The work presented in this thesis supports the 1997 Whale Monitoring Feasibility Experiment designed to study the feasibility of remotely detecting, localizing, tracking, and counting whales in the MBNMS using the NPS Ocean Acoustic Observatory (OAO) acoustic array. This work accomplishes two of four steps required to complete the feasibility study. The first two steps were:

1. Unscramble the multi-path signals measured by the towed array to obtain true source signals.
2. Estimate call-to-call variability and quantify the robustness of the source signal.

To accomplish the first step, a deverberation procedure utilizing plane-wave beamforming, matched signal processing and least-squares estimation was developed. The procedure was then applied to the whale calls measured by the towed array to reconstruct the whales' source signals. The second step was accomplished by performing cross-correlation

analyses on the deverberated signals. Major overall results pertaining to source signal characteristics including signal structure, time duration, level, nominal vocalization depth, and variability/robustness are summarized in Table 13. These analyzed source signal features are important to the future design and implementation of auto-detection filters and long-range, model-based localization and tracking algorithms for achieving long-term, real-time monitoring using the shored-based OAO array at Pt. Sur. For example, the cross-correlation results clearly indicate that the waveform of the "B" call and the magnitude of the waveform of the "A" calls are rather robust, suggesting that these two structure-rich quantities are the preferred observables for matched filtering and matched signal/field processing to detect and to localize, respectively. Note that although the magnitude of the "B" call waveform is also robust, a speculation is that this quantity may not possess a complex enough structure to allow for unambiguous detection and localization. This speculation remains to be tested in future work.

An important lesson pertaining to the use of a towed array to survey whale locations and vocalizations was also learned. From studying the quality of the ambiguity surfaces for whale location estimates, it was found that the resolution of the footprint (i.e., mainlobe) was maximized and the sidelobes were minimized when the signals were arriving in the end-fire direction. As the bearing of the signal arrival deviates from end fire, the quality of the ambiguity surface degraded gradually, and attained the poorest resolution when the bearing approached broadside. Therefore, there existed an optimum towing geometry for localizing and deverberating whale vocalizations. This endfire (or close to endfire) orientation should be utilized in future whale cruises using a towed array.

Call Types	Number of Overall Calls Analyzed	Mean Number of Pulses	Depth of Vocalization (m)	Mean Duration (s)	Mean Source Level (dB re 1μPa)	Call-to-call Correlation: Waveform	Call-to-call Correlation: Magnitude of Waveform
"A" CALL (85-95 Hz band)	26	20.2 ± 1.2	33.50 ± 32.07	14.35 ± 2.20	162.35 ± 6.97	0.26 ± 0.07	0.84 ± 0.07
"B" CALL (48-53 Hz band)	38	N/A		10.55 ± 1.59	166.19 ± 10.49	0.56 ± 0.14	0.88 ± 0.06

Table 13: Summary of results for two transiting blue whales in the MBNMS

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