PASSIVE ACOUSTIC DETECTION AND LOCALIZATION OF VOCALIZING EAST PACIFIC GRAY WHALES *(ESCHRICHTIUS ROBUSTUS)* BY MEANS OF AUTONOMOUS SENSORS IN MULTIPLE ARRAY CONFIGURATIONS

INDEX OF PROPOSAL

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I. SUMMARY:

Under this proposal, I would acoustically detect and localize Pacific gray whales (Eschrichtius robustus) in azimuth, range, and depth in San Ignacio lagoon, Baja California and possibly along their migration route. Acoustic data would be collected by means of horizontal line arrays containing autonomous hydrophone recorders and assembled in a variety of configurations and apertures.

Data analysis would involve (1) using ambient noise to time-align each recorder with other recorders along a given line array, (2) spatially identifying each line array location and orientation using noise from a small boat, (3) implementing a semi-automated detection procedure for detecting gray whale calls, (4) estimating acoustic bearings for each call from a pair of line arrays, (5) crossing the bearings to obtain a range estimate of the call, and (6) using a propagation model to estimate the depth of the calling animal. Once the animal position has been fixed, a call's source level would be estimated using the same propagation model used to estimate the source depth. From the source level and ambient noise measurements the theoretical propagation range of the calls would be estimated.

The method would be checked by matching localization fixes of acoustic signatures of gray whale surface events (like breaching and slapping) in San Ignacio Lagoon with visual ranging estimates of these behaviors. Acoustic tracks of local pangas would also be performed and compared with GPS tracks.

As a byproduct of this analysis, call rates of gray whales across multiple years would be obtained and compared with historical measurements conducted in the 1980's (Dahlheim, 1987), as well as with visual counts of animals in the lagoon. We would also collect potential gray whale sounds off a single hydrophone deployed off Piedras Blancas, CA during an independent simultaneous visual survey (Perryman et al, 2002), and use the semi-automated detection scheme to compare call rates vs. visual observations.

The significance of this work is that it would demonstrate a low-cost method that provides 2- and 3-D fixes of animals without resorting to a vulnerable vertical array. The 3-D fix would provide source level and detection range estimates of various gray whale calls, which would provide insight into the acoustical ecology of the animals, and serve to evaluate the efficacy of passive acoustic measurements for population monitoring. The semi-automated detection algorithm would be a useful tool for measuring trends in long-term call rates over a 20 year interval and in evaluating whether passive acoustic monitoring would be a useful tool in detecting gray whales along their migration route.

II. BACKGROUND:

This section summarizes previous research relevant to the dissertation topic. Part A provides background about previous gray whale acoustics work, and selected uses of passive acoustic localization on marine mammals. Part B summarizes field research that has been performed to date, detailing the instrumentation used, the location of the experiment and the configurations applied. This field data will be used to illustrate some of the steps of the proposed future analysis.

A. Literature and past work

Past research regarding gray whale acoustics in San Ignacio Lagoon is scarce and limited to sporadic seasons over the course of the last 20 years. Between 1982 and 1984, Marilyn Dahlheim performed research on the vocalization rates and call types of gray whales in the lagoon (Dahlheim, 1987), to investigate if and how gray whales circumvent ambient noise by varying their call structure. Her dissertation presented a classification of six call types emitted in these particular grounds, as well as call rates for each during different phases of the reproductive season. Using a long-term hydrophone deployment off the narrowest portion of the lagoon, Punta Piedra, (Figs. 1 and 4), she also computed average call rates of animals throughout the breeding season.

Fifteen years later, Sheyna Wisdom (Wisdom, 2000) recorded acoustic activity in close proximity to mothers and calves in the lagoon, focusing on vocal development (ontogeny). She compared calls to sounds produced by JJ, a stranded gray whale calf rescued and rehabilitated at SeaWorld San Diego.

Other than these efforts, no other baseline work has been conducted on gray whale acoustics in San Ignacio Lagoon. However, some data on underwater sounds of migrating gray whales have been attempted to be recorded, for example by Hubbs and Snodgrass (1950) and Eberhardt and Evans (1962).

Generally speaking, gray whale calls have proved difficult to collect. In the paper “The quiet gray whale” (Rasmussen and Head, 1965), after failing to record identifiable gray whale sounds off of San Diego and in Scammon’s Lagoon, the authors concluded that this particular species appeared not to use acoustic methods for navigation or communication.

Later studies (e.g. Asa-Dorian and Perkins, 1967; Cummings and Thompson, 1968) quantitatively described common low-mid frequency calls named “cries”, “moans” and “belches” that were attributed to gray whales. The calls had low signal-to-noise ratios (SNR), partially explaining why they had been difficult to document.

There are numerous papers on using marine mammal sounds to track the animals in range and azimuth. Among those relevant here, Watkins and Schevill (1972) implemented a technique of recording on a 4-element array deployed from a ship and later calculated time of arrival differences (TOAD) between these sensors spaced 30m apart. A later application of such a system tested the viability of locating Southern Right whales by utilizing the pressure-wave's phase information to estimate differences in signals recorded in three hydrophones (Clark, 1980). Several studies have also investigated the factors that incorporate errors into these calculations (Wahlberg, 2000) and shed light on how to minimize them. All these studies assume that a widely-spaced array can be constructed where all the elements are simultaneously sampled, and therefore time-synchronized.

To estimate the depth of low-frequency calls in shallow water, Thode, D'Spain and Kuperman (2000) used a vertical array to perform matched-field processing (MFP) on blue whale calls near the Santa Barbara Channel. Because low-frequency sounds in shallow water cannot be accurately modeled as ray paths but as the propagation of a sum of normal modes, MFP methods are necessary to determine the source depth of a baleen whale in shallow water, as will be discussed later.

Recent efforts on acoustic tracking have examined how to time-align independent recording devices with large clock drift. These instruments have been demonstrated in studies that tracked large whales, such as sperm whales in Alaska (Thode et al, 2004 and Thode et at, 2005) and humpbacks in Australia (Thode et al, 2004). Novel techniques to utilize these sensors would form the basis of this thesis research.

B. Fieldwork performed

Over the past two years, preliminary acoustic data has been collected in San Ignacio Lagoon (Fig.1), the only undeveloped lagoon within the El Vizcaíno Biosphere Reserve, and a wintering site for gray whales (Jones and Swartz, 1984). The lagoon presents certain convenient characteristics for testing acoustic detection and localization techniques. Being enclosed with only one inlet towards the sea allows scientists to account for parameters that are otherwise difficult to measure in the open ocean, such as changes in environmental conditions or human activity. Furthermore, from its shores research parties have easy access to instrument stations in the water and an advantageous site from which to perform visual verification observations. Finally, acoustic research (Dahlheim, 1987) was conducted in this same lagoon over two decades ago, providing an interesting opportunity to observe how the acoustic environment of the reserve may have changed over this time period.

FIG 1: Map of Laguna San Ignacio

Instrumentation and electronics have improved to allow for portable, inexpensive, low-power, autonomous recorders to gather data while submerged over extended periods of time.

The first generation of these instruments (Fig.2) is a model developed by Greeneridge Sciences Inc., a variation from tags intended for attachment to a variety of marine wildlife. The core elements of these instruments are the electronic motherboard, the batteries and the memory-chip, all packed inside a pressure casing. Data collected includes not only acoustic information, but also local pressure, temperature and the device's acceleration in two axes.

FIG 2: Pressure-case autonomous acoustic device

Preliminary acoustic data were collected in Laguna San Ignacio in February 2005 and 2006 with such instruments configured into two- and three-element horizontal line arrays (refer to here as "stations"). Each array station included two mushroom anchors on the extremes to secure it on the bottom and a recovery line connecting it to a marker buoy on the surface (Fig 3). Three such stations were deployed at the mouth of the lagoon in front of Punta Piedra (Fig 4). In 2005, the recorders collected data over a 10-day period with a bandwidth of 2000 Hz.

During the February 2006 field season two underwater stations were deployed four times, programmed at a sampling rate of 1560Hz, allowing continuous monitoring of about four days, and over 290 hours of total acoustic data were collected.

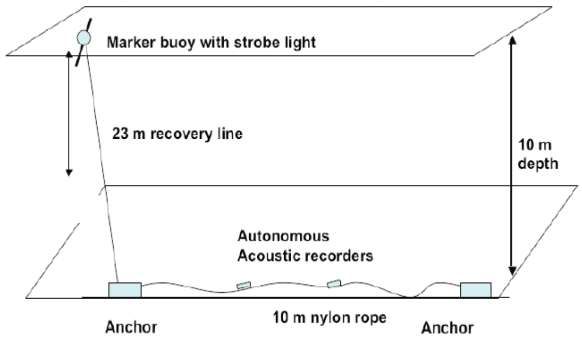

FIG. 3: Configuration of bottom-mounted acoustic recording stations

To maintain uniformity with past studies, we also made recordings from a small panga (boat) using a portable audio recorder during opportunistic close interactions with whales. The digital audio unit, a Fostex FR-2 field recorder, sampled at 44.1 kHz and collected over 10 hrs of data.

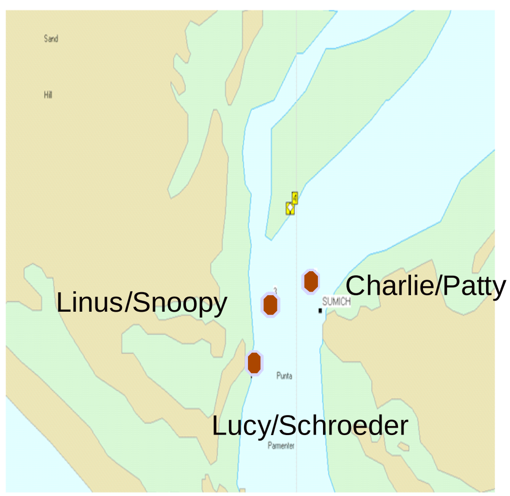

FIG. 4: Location of bottom-mounted acoustic recording stations in February 2005 at the mouth of the lagoon

III. PROPOSED WORK:

My thesis proposal is divided into two parts. Part A explains the techniques that would be implemented to analyze the data, specifically procedures for (1) detecting calls among a large acoustic dataset, (2) time-synchronizing sensors experiencing clock drift, (3) estimating acoustic bearings to the whale, (4) calculating the whale's range and (5) computing a calling whale's depth. Part B outlines how these techniques would be used for (1) estimating call rates in the lagoon (2) estimating call source levels, (3) predicting the propagation ranges of calls and (4) relating call rates to visual surveys.

A. Techniques

1. Call detection procedures

The analysis of the acoustic data will focus on gray whale calls type 1b (Wisdom, 2000), which has been reported as the most common sound produced by these animals while in these grounds (Dahlheim, 1987). This call also presents the most variability in its parameters.

A spectrogram of a 1b call collected in 2005, computed using a 128-point FFT with 50% overlap (Fig. 5) shows that these sounds contain most of their energy in short broadband pulses, grouped in sets ranging from 2 to more than 20 units. The detectable energy is distributed within a frequency range from 100Hz up to 1000Hz. Peak frequency can vary between pulses and while some of this variation is likely due to propagation effects, much of the variation must be under the control of the whale. Following Wisdom's parameter nomenclature, pulses are separated from each other by a temporal spacing labeled the inter-pulse interval (IPI). From the spectrogram, a high IPI variation is noticeable, a feature also reported by Wisdom (2000) and Dahlheim (1987) when statistically analyzing the IPI variance. Finally, the timing separating calls is labeled an inter-call interval (ICI). Pulses with shorter spacing between them will be considered to be within one call.

High variability in the parameters leads to the lack of a stereotypical type 1b gray whale call, which in turn prevents the formation of a kernel to cross-correlate the data. Therefore conventional automated methods based on matched-field processing (MFP) or spectrogram correlation (Mellinger, 2002) proved ineffective.

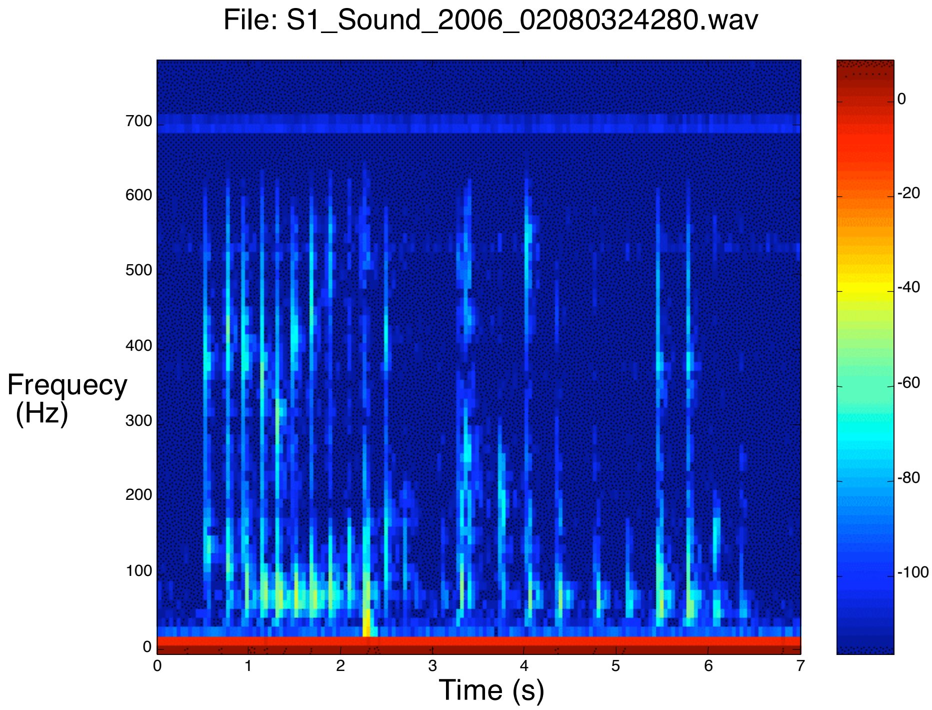

FIG. 5: Whale call spectrogram showing variability in frequency and time (sampling rate = 1560Hz, 128-point FFT, 50% overlap)

In addition to these difficulties, gray whale calls are embedded in a noisy background consisting of three overlapping signatures:

1) sounds produced by physical processes (for example surf, rain, tides and currents);
2) anthropogenic sources (largely dominated in this environment by boats and vessels);
3) biological sources like snapping shrimp (*Alpheus heterochaelis*), croaker fish (Sciaendae family) and bottlenose dolphins (*Tursiops truncatus*).

A spectrogram of these biological sources (Fig. 6) illustrates five gray whale pulses towards the end of the image (between the 1.6 and 3 seconds). Below them, croaker fish produce frog-like grunts in the lower frequency range centered between 10.8 to 86.96Hz although their energy can extend up to 400Hz (Ollervides, 2001). In the higher frequency band, snapping shrimp are an extremely energetic component of underwater ambient noise, extending as high as 30kHz (Li et al, 1999). Much of this background noise is pulsive in nature, and thus easily confused with gray whale type 1b sounds.

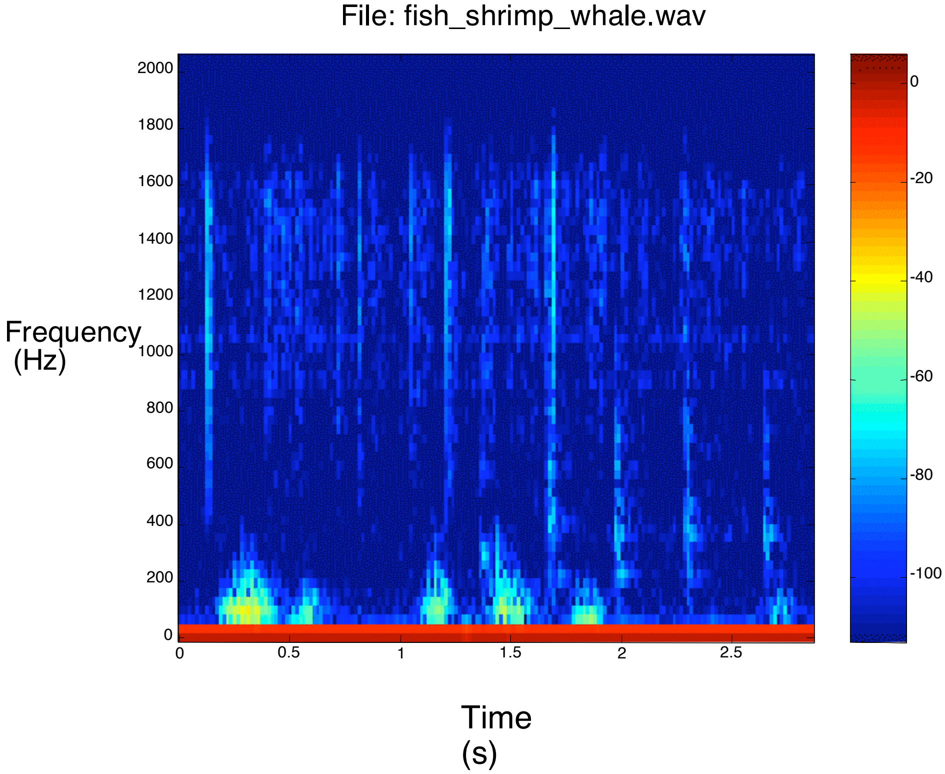

FIG. 6: Biological noise spectrogram:
croaker fish (<250Hz), gray whales (100-800Hz) and snapping shrimp (>700Hz)
(sampling rate = 4096Hz, 256-point FFT, 50% overlap)

Detection of gray whale calls can be approached manually or through an automated procedure. In the first method, the analysis software ISHMAEL (Mellinger, 2002) was utilized to simultaneously inspect the time series and the spectrogram of one-channel input data (Fig. 7). Gray whale calls were manually extracted as well as their (referenced) absolute time. Histograms of call detection density were then plotted.

Larger datasets are time-consuming to analyze by hand, hence a semi-automated sequence of programs was designed and tested.

The first step of the automation procedure was to apply ISHMAEL's "energy detection" method, which is based on integrating the spectrogram vertically within a bounded frequency band determined by the user. The combination of sums generates a detection function, seen as a yellow line in the bottom window (Fig. 7). A threshold is defined, which, if exceeded by the detection function, triggers MATLAB to save information about the absolute time when the pulse occurred.

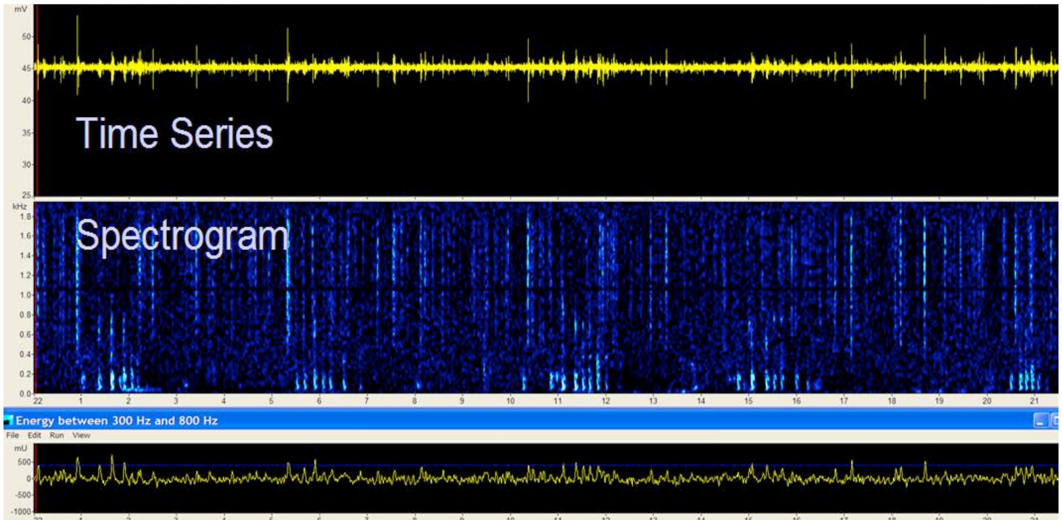

FIG. 7: ISHMAEL interface window: time series, spectrogram and detection function viewer

The data contained in this file is then analyzed in MATLAB. Using a mean IPI value and the average pulse duration, a certain minimum number N of consecutive detections are examined, checking that the total elapsed time concurs with typical gray whale timings for these events. More precisely, it is assessed whether N-average pulse durations and (N-1) mean IPIs fit adequately in between these N detections. For the results presented below, N was selected to be three. We found that more than 80% of false detections generated during the "energy detection" stage could be eliminated with this step, saving a great deal of manual effort.

If a combination of pulses passes the initial test, a sound file is created and again viewed and listened to using ISHMAEL. Human intervention is necessary at this stage to assign "hotkeys", a letter in the keyboard that categorizes the sound as "Gray whale" or "False detection". A log is created summarizing all the true calls and the absolute times are extracted. Finally, density histograms of vocal activity in time are created.

Portions of the 2006 dataset were analyzed both manually and by automated inspection, to validate the capability of the automated sequence. Histogram results (Fig. 8) demonstrate the performance of the automated sequence implementation, as both trend and absolute number of detections show agreement. Each bin represents calls per 20-min period over four hours on February 7th, 2006.

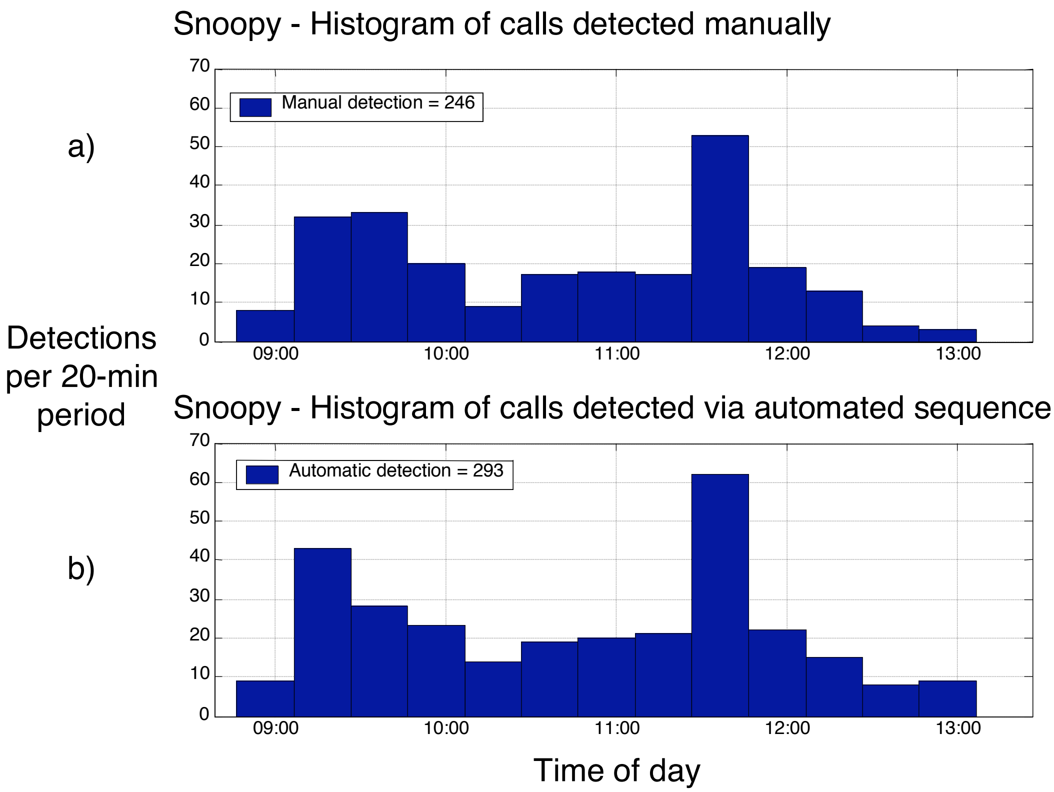

FIG. 8: Comparative histograms: manual and automated estimates of gray whale calls per 20-min period over 4 hours: a) manual detection; b) automated detection

2. Time-synchronization

Independent sensors, like the ones I propose to use, offer benefits like freedom of configuration and easier in-situ usage when compared to heavy, cabled arrays. However, sampling individual recorders presents the challenge that a relative temporal drift exists between elements. Therefore, further analysis of this dataset requires time-synchronization of the elements of the arrays.

The technique proposed to time-align makes use of transient noises such as boat drive-bys, whale calls and diffuse ambient noise to generate a cross-correlation function between recordings of two or more sensors. The resulting temporal offset is a combination of clock-drift and physical travel time differences (Sabra et al, 2005). By using various sound sources, the contribution from each factor can be allocated. Two examples are shown below, one using a panga boat, and one using a set of pulsive whale calls.

During the period of data recording in San Ignacio Lagoon, a panga boat performed daily circular maneuvers around the marker buoy at each station (Fig. 9). This exercise generates a broadband acoustic signal that gets recorded on both sensors of the particular station. When a cross correlation of these sounds is performed, the temporal offset between them becomes evident. For example, the point at which the boat passes the "endfire" of the array would yield the largest lag between arrival times from both sensors. The peak of the cross-correlation will be shifted from $\tau = 0$ by a value $\Delta\tau = |t_1 - t_2|$ where t_1 is the arrival time to receiver 1 and t_2 to receiver 2. Therefore $\Delta\tau$ will be related to the sound speed in the medium and the additional distance the acoustic wave needs to travel in order to reach the furthest sensor. Similarly, the peak will present no lag and be centered at $\tau = 0$ if t_1 and t_2 are identical, which occurs when the source is directly broadside.

(Later on when the recorders have been properly time-aligned, the information of this known surface sound source will be useful to localize and orient the instruments. The boat noise can also serve as a model of transmission loss.)

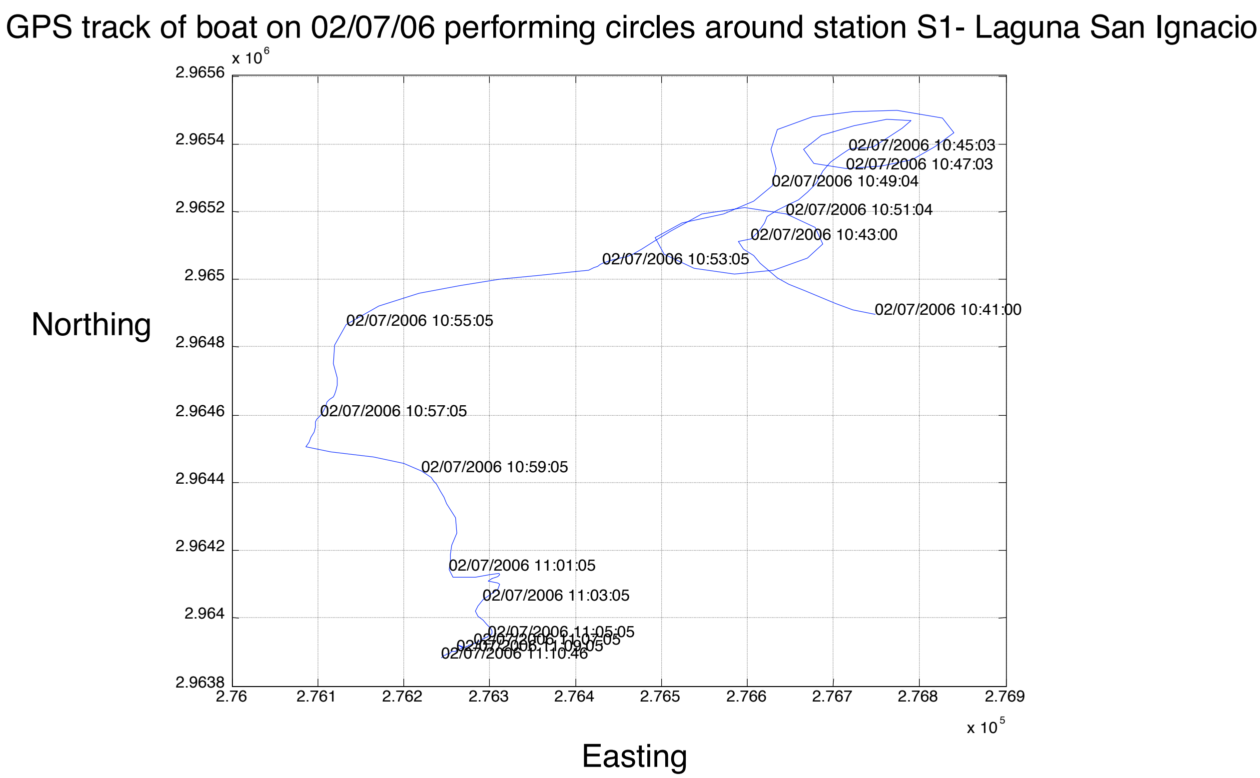

FIG. 9: Example of circular boat track around a recording station

An example of this time synchronization is provided here. The specific boat circling event in Fig. 9 was studied to demonstrate the technique of inferring clock offset from this known surface source. Results display the lags corresponding to the cross-correlation maxima (Fig. 10) for 20 min of data around the time of the drive-by. As explained, the cross-correlation peaks before 10:50 mark the shift in the relative boat location; when sound wavefronts arrive simultaneously at both sensors, $\Delta\tau$ equals zero and as the boat advances towards endfire, $\Delta\tau$ increases to a peak or decreases to a trough.

From this plot, it can be seen that when the boat is the main acoustic contribution (10:43 to 10:50am) the cross-correlation follows a rough sine pattern. However, the later portion of the black curve (10:53 to end) exhibits parallel lines diverging from the main curve as a result of sources of ambient noise (possibly snapping shrimp) distributed on patches along the lagoon bottom. Extracting information from the noise, (Sabra et al, 2005) this double-peaked cross-correlation function would be used to make a final precise correction in the clock offset and drift.

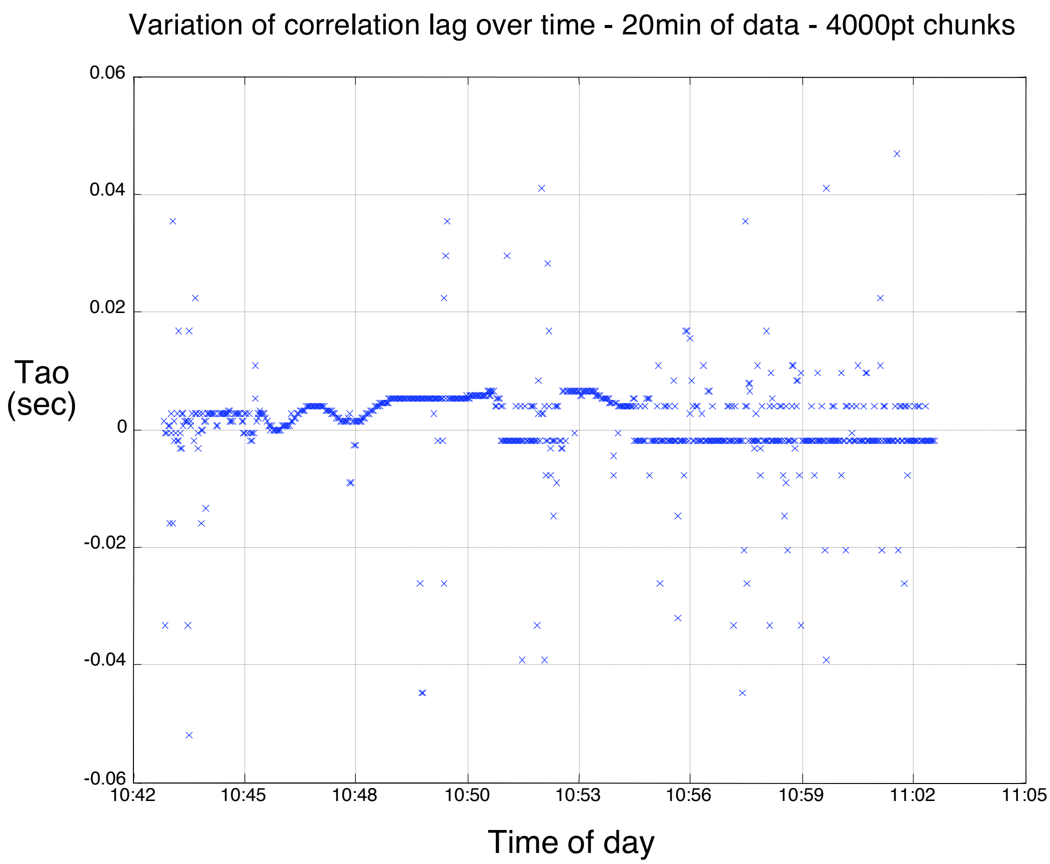

FIG. 10: Ambient noise analysis around the time of a boat circling event: lag corresponding to maximum cross-correlation versus time of day. Times before 10:50 are dominated by panga noise; times afterward are dominated by snapping shrimp and other diffuse ambient noise.

Figure 10 requires the hydrophones to be roughly time-aligned. Over long time intervals the recorders can become completely desynchronized, requiring an additional preliminary step to roughly time-align the signals. To do this we use impulse-like whale calls to map the rough clock drift.

A 3-hour segment of the 2006 dataset was explored in search of transient signals. Fourteen useful whale calls were detected in two stations, high-pass filtered and cross-correlated. The lag corresponding to the cross-correlation peak was selected and plotted as a function of elapsed time (Fig. 11) and the trend then fitted to a linear polynomial displayed as a blue line, whose slope represents the rate of change of drift in time.

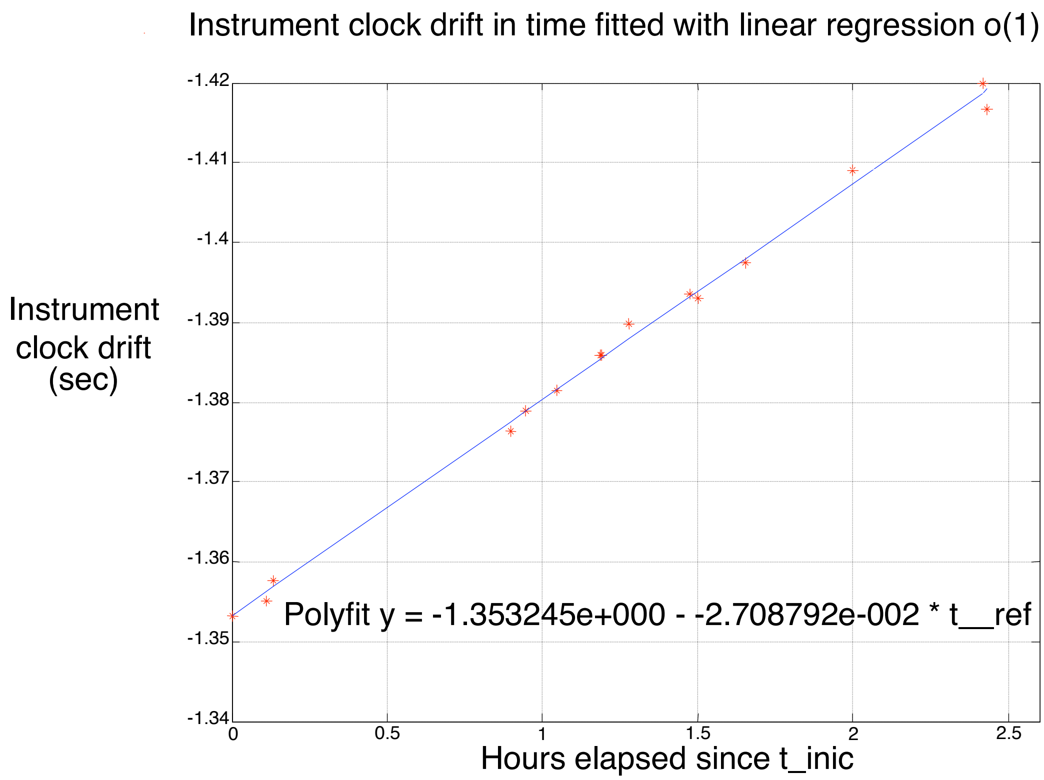

FIG. 11: Instrument clock drift versus elapsed time

With this information the residue between the original lag and the polynomial fit is calculated (red circles in Fig. 12). This linear fit is applied to time-shift the data before it is loaded, thus correcting the rough clock-drift. Therefore, once a new cross-correlation between sensors is estimated, the new offsets (blue dots in Fig. 12) are almost identical to the previous residues. The time-alignment for this longer time set can now be further corrected using both diffuse ambient noise and sounds from known noise sources, such as the pangas.

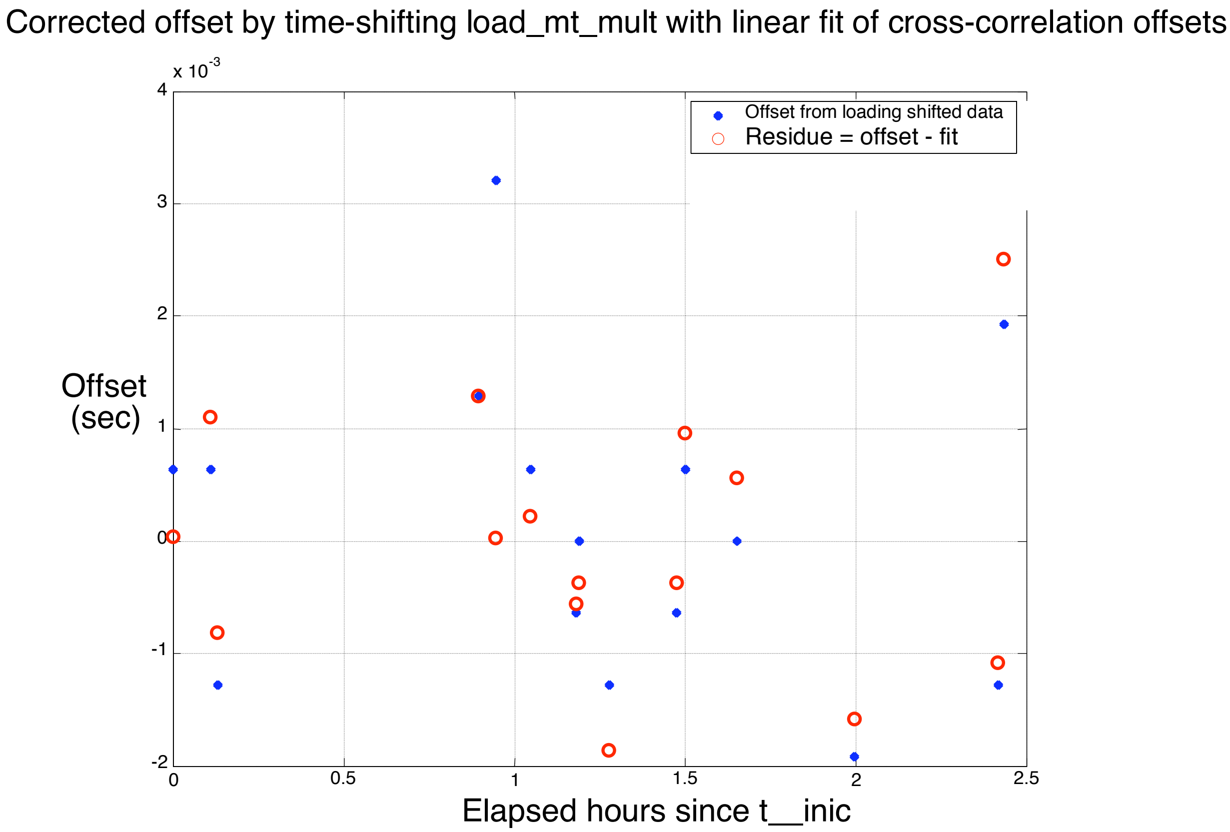

FIG. 12: Original residue from (offset – fit) compared with offset from shifted data

3. Bearing estimation

A variety of techniques exist that allow the estimation of a source's bearing. One of the methods suggested for this project calculates source direction from time of arrival difference (TOAD) by cross-correlation of signals corresponding to a pair of sensors (Altes, 1980; Clark et al, 1986; Clark et al, 2000).

The angle of arrival ϕ is calculated from geometry (Fig. 13) as:

$$\cos\phi = \frac{c\tau}{d} \tag{2}$$

where:

c: sound speed in medium
τ: time of arrival difference
d: array spacing

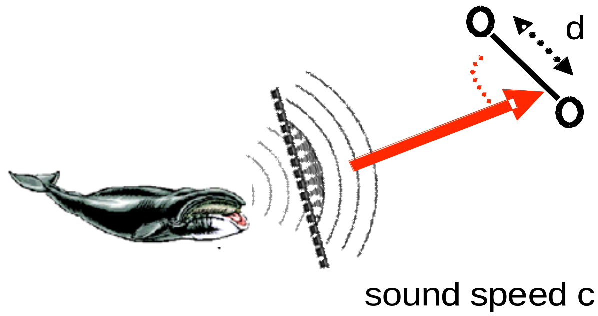

FIG. 13: Angle of arrival geometric calculation

However, array constrains limit the ability to only resolve angles separated by more than the beamwidth or angular resolution (Johnson and Dudgeon, 1993):

$$\theta = 1.22 \frac{\lambda}{D} \tag{1}$$

with the parameters:

θ: beamwidth in radians
λ: wavelength of target source
D: array aperture

The resolution as calculated by a single frequency yields a specific array beamwidth. Still, as more frequency contributions are added to the estimation, especially from the higher frequencies, a narrow angle is emphasized and the resolution is improved.

When estimating bearings it is also critical to identify possible sources of error, for example how inaccuracies in TOAD will translate into a widening of the bearing angle.

4. Ranging

Oftentimes in marine mammal research, hyperbolic fixing methods are successfully used to localize calling animals (Mitchell and Bower, 1995 and Tiemann and Porter, 2003). However, these techniques assume time-synchronized instruments.

Under this proposal, a method of triangulating bearings from different line arrays would be used, because under this approach the acoustic data would not have to be time-synchronized between widely-separated array stations (although the elements within a single array station would have to be synchronized with each other). Bearings from the same call can be crossed to yield a 2-D fix in range and azimuth for the whale calling (Fig. 14), provided that the call is within 5-10 times the separation between the two array stations.

As a consequence of bearing uncertainties, the actual location will consist of a region bounded by the bearing inaccuracies (Fig. 14). Geometrically, the area of the quadrilateral DEFG can be estimated from subtraction of triangles ABD, ADE and BDG from ABF, leading to the knowledge of the search area where the source is most likely located.

The range estimation procedure would be tested on small transiting pangas and on surface behaviors of gray whales that can be visually ranged, such as breaches and slapping.

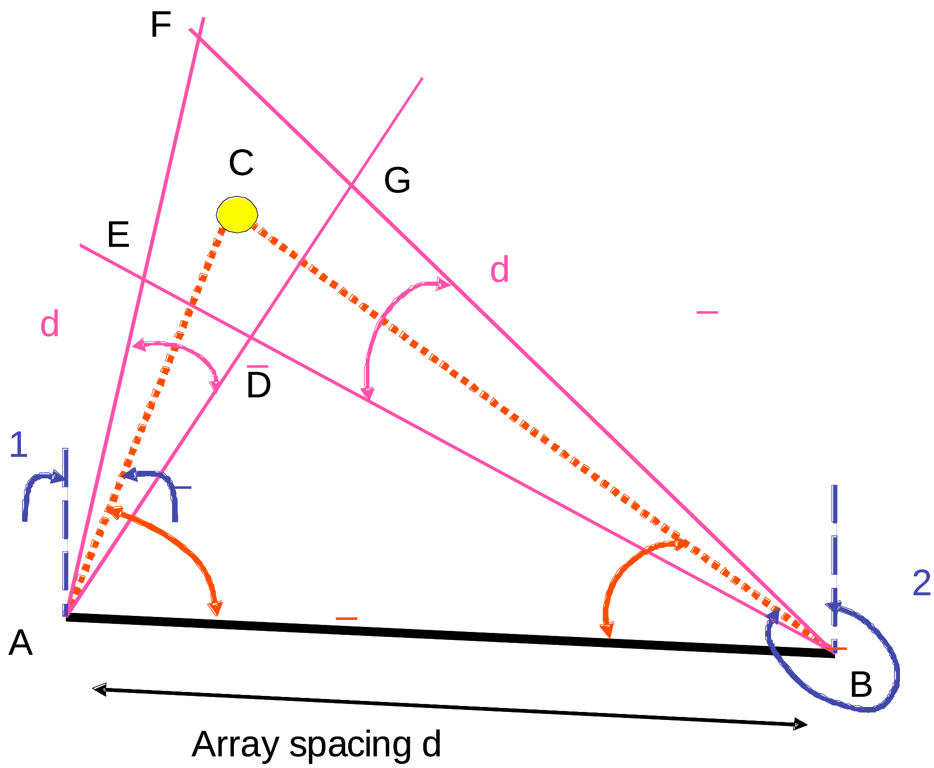

FIG. 14: Two-element array inaccuracies in bearing and ranging

Localization results have not yet been demonstrated in the preliminary data, although it has been established that the dataset collected in 2005 presents the potential for cross-bearing ranging, since several calls were recorded on more than one station on numerous occasions (Fig. 15). This suggests that this particular acoustic channel supports sounds at these frequencies and allows them to travel at least 2km. Results for bearings to these calls are not yet available.

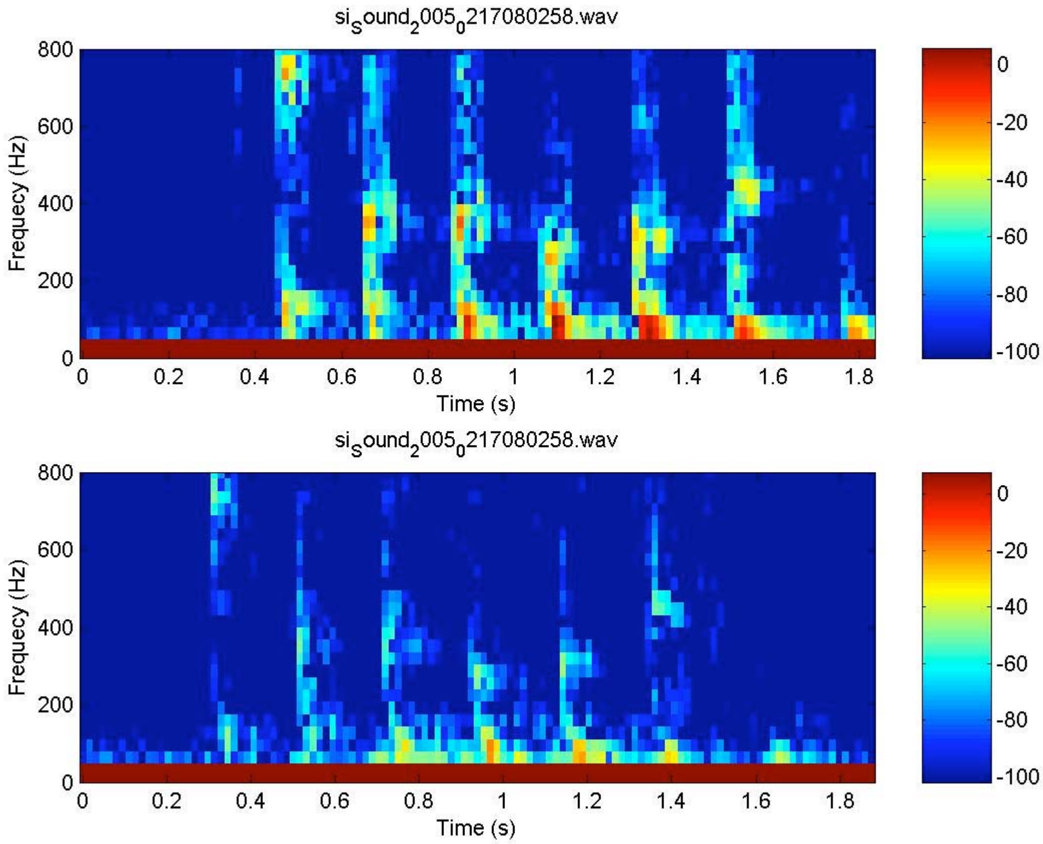

FIG. 15: Spectrogram of one call recorded on two different stations across the mouth of the lagoon in front of Punta Piedra (sampling rate = 4096Hz, 256-point FFT, 50% overlap)

5. Depth estimation

Once section A.4 has been completed, the rough range and azimuth of the whale would have been bounded to a restricted search area, but its depth in the waveguide remains unknown.

The whale depth would be estimated by modeling an acoustic source at various candidate depths. This method is a variant of MFP techniques demonstrated in the literature for similar purposes (Thode et al, 2000 and Nosal and Frazer, unpublished). First, we would measure the ratio of a given call's received level spectrum on an element on one array station (Array 1) to the received spectrum on an element in another station (Array 2). In the case that received levels vary greatly along a given array station, the average spectrum on all elements may also be required. This received level RL_i is equal to the convolution of the waveform time-series with the frequency-dependent, acoustic channel's impulse response or in the frequency domain, the product of the signal spectrum with the transmission loss (TL). Thus the ratio of the two received levels in the frequency domain becomes:

$$r(f)_{measured} = \frac{RL_i}{RL_{i+1}} = \frac{S(f)*TL(f)_i}{S(f)*TL(f)_{i+1}} = \frac{TL(f)_i}{TL(f)_{i+1}} \quad (2)$$

with:
r: measured ratio of spectrum
S(f): signal spectrum
TL_i: transmission loss to i^{th} array
RL_i: received pressure level at i^{th} array

Thus, taking the ratio of the two spectra cancels out the unknown source spectrum, leaving only the contribution of the transmission loss (propagation effects). Other work (Nosal and Frazer, unpublished) uses similar tricks to remove the effect of the unknown source spectrum.

Next, we apply a MFP technique to get the source depth of the sound. A propagation model would be used to simulate the acoustic field generated by a set of sources at the estimated whale range, but at different depths. For each candidate depth the ratio in equation (2) would be calculated as a function of frequency. By comparing modeled ratios across depth with $r_{measured}$ a source depth estimate can be obtained. We are assuming that the propagation environment in the lagoon is complex enough that the ratio in equation (2) will vary greatly with depth. Given the complexity of the bathymetry, the frequency of the calls, and the shallow depth of the water, we expect this assumption to hold. The method could be extended to estimate a more precise range of the whale within the uncertainty bounds as well.

Information about the propagation environment would be obtained from detailed bathymetry maps of the area, collected by various researchers. In addition, the bottom sediments have been mapped rigorously off Punta Piedra. Finally, to check the propagation model, noise from a known surface source, such as a panga, would be used to confirm the source depth estimator. Potentially an inversion procedure could be used on either the panga noise or a whale call to further optimize the environment.

B. Applications of data analysis

1. Call rates in San Ignacio Lagoon, MX

As a result of developing a call detector for this dataset, an estimate of gray whale call rates in San Ignacio is obtained. We propose to analyze call rates in the lagoon over a three year period (2005-2008), obtain the original data tapes from Marilyn Dahlheim’s work in the mid-80’s, and recompute the call rates in the lagoon for that period, to see if there exists a long-term change in call rate. Furthermore, we would also explore if a correlation exists between acoustic call rates and visual surveys performed in the region around the acoustic monitoring stations. An example of this latter exercise is now discussed.

Visual census data of gray whales in San Ignacio were taken in the winter months of 2005 and 2006 by collaborating researchers from the National Oceanic and Atmospheric Administration (NOAA) and the Universidad Autonoma de Baja California Sur (UABCS) in La Paz. This effort follows standard census methods that require the tally of adult animals from a boat platform traveling through the middle of the lagoon. The lagoon area was broken down into four "zones" with censuses made for each of them individually (Fig. 16). Data on direction of travel was taken, as well as classifying the animals as singles vs. mother/calf pair. These numbers have been generously made available to our research efforts by Dr. Jorge Urban (UABCS) and Dr. Steven Swartz (NOAA).

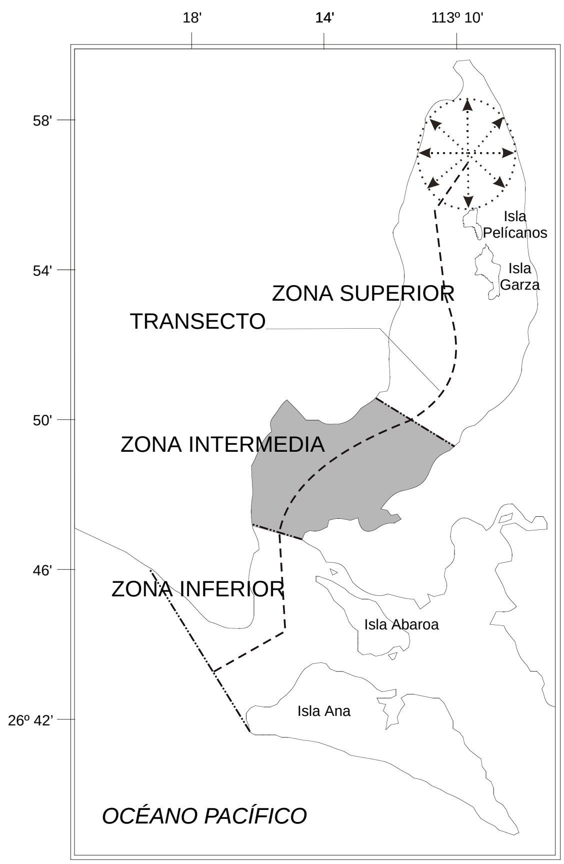

FIG. 16: Segmentation of San Ignacio Lagoon for censusing purposes

Results for all four deployments of 2006 are presented, with the bin-width representing the number of gray whale calls detected over a six-hour period over time (Fig. 17). These histograms are overlaid by the line joining the four boat-based census points taken during the three-week period. Red represents the total number of adult animals inside the complete lagoon and green corresponds to the number of adult animals inside the middle area (Fig. 16), where the sensors are located. In general a tendency is exhibited towards increasing call rates over time, matching increasing numbers of animals present.

Between the five day period between February 10th and February 15th a doubling of animals took place. Similarly, the mean call rate grew by a factor of 2, from 6.6 calls/hr (st.dev = 10.8) to 13.4 calls/hr (st.dev = 13.5). Large standard deviations are likely to be the results of these raw counts not yet incorporating changes in background noise.

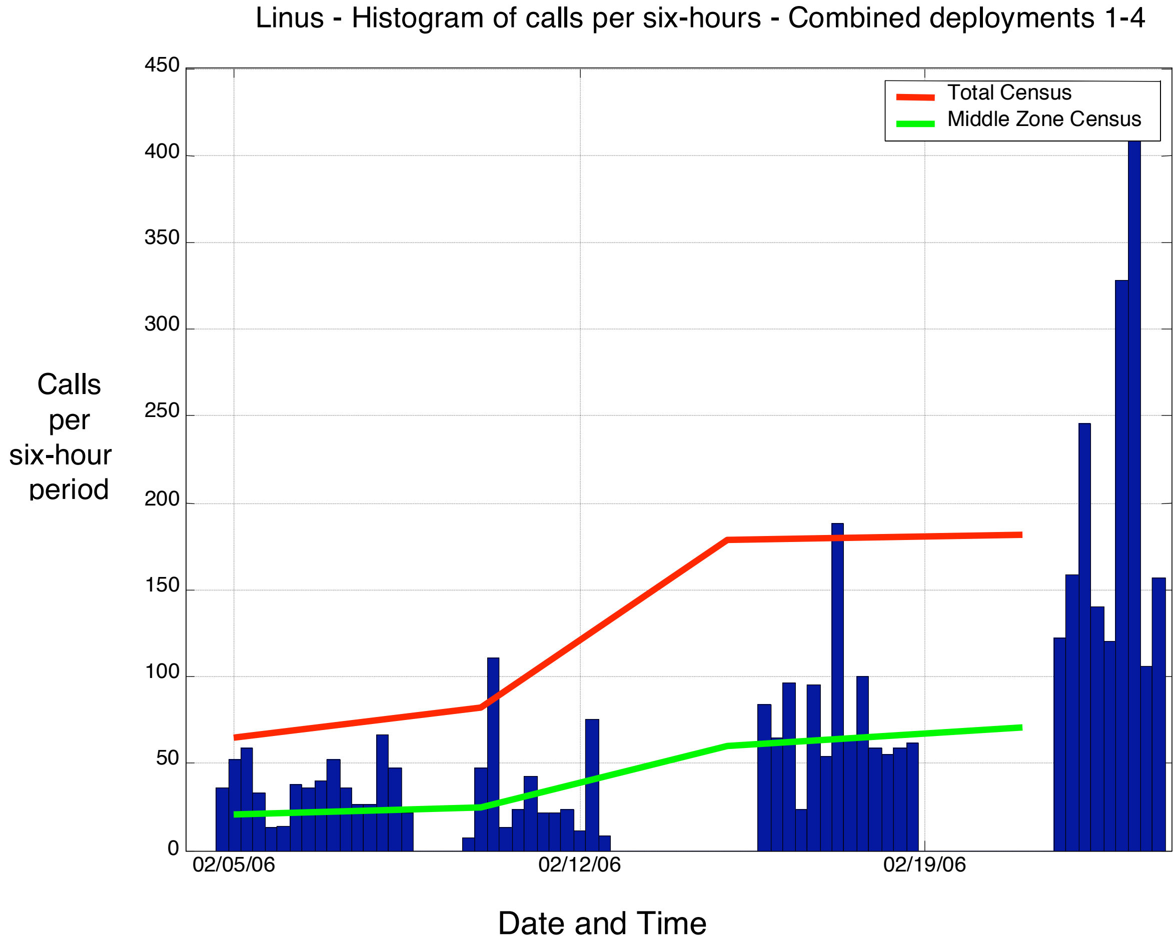

FIG. 17: Histogram of calls per six-hour period for all four 2006 deployments overlaid with independent visual census data

Masking occurs when the threshold required to detect a sound is raised by the presence of noise. In this particular environment, ambient noise presents deviations from the baseline. Physically, this means that the effective acoustic range of the array becomes reduced to that dictated by the new threshold and whale calls beyond that distance would become masked.

These results need to be corrected for variations in background noise level, which may influence the detection range of the instruments. Extending the study on ambient noise power spectral density would allow a better assessment of range as a function of local time, which in turns makes the probability of detecting a gray whale call dependent on the time of day. Statistical corrections would have to be applied for those calls that fall below the threshold.

2. Source levels

Calculations of source levels would be performed using information about transmission loss gained from the depth estimation technique (part A.5) and applying a simplified version of the sonar equation:

$$RL = SL - TL - (NL - AG) \qquad (3)$$

where all levels are in units of $dB_{re:1\mu Pa\ at\ 1m}$
RL = received level
SL = source level
TL = transmission loss
NL = noise level (see section c below)
AG = array gain (not expected to be significant under these circumstances)

Similar multichannel deconvolution techniques (Finette et al, 1993 and Mignerey and Finette, 1992) have been tested on baleen whales to recover source levels (Thode et al, 2000)

3. Propagation ranges of calls

Based on the sonar equation (Equation 3), knowledge about the propagation range can be obtained, if one knows the source level of a call, has a good propagation model to compute transmission loss as a function of range and azimuth, has a representative ambient noise levels, and has assumed a minimum detectable signal-to-noise ratio (SNR).

All of these factors have previously been discussed, with the exception of ambient noise. Ambient noise power spectral density for one sensor over a particular 36 hour deployment of 2005 is presented (Fig. 18). It can be seen that most of the energy is concentrated in the lower frequencies and that the energy increases at around mid-afternoon on both days. This level is maintained until approximately 9pm. Power integration along these frequency ranges suggest that changes in ambient noise of approximately 10dB are common throughout daily cycles, implying repercussions on detection range that need be corrected by means of statistics.

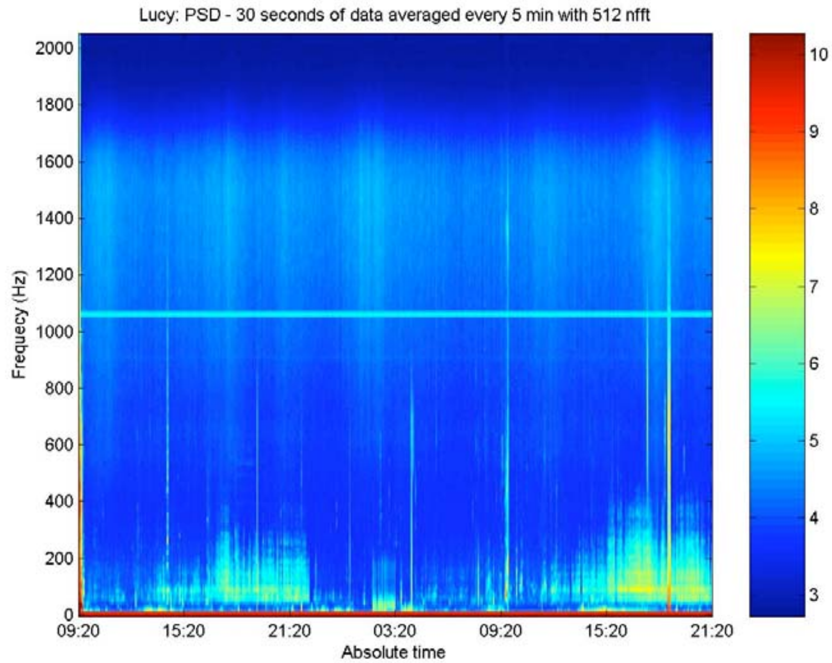

FIG. 18: Power spectral density of ambient noise during two days of February 2005 (512-point FFT, sampling frequency = 4096Hz, 30s of data averaged every 5min)

Prior studies have reported spatio-temporal patterns in croaker fish chorusing in waters around San Diego and Mexico (D'Spain and Berger, 2004) as well as increases in ocean sound levels by factors of 2 to 5. Snapping shrimp are also believed to display a higher acoustic activity after sunset according to experiments performed in La Jolla and other Southern California sites (Everest et al, 1948).

Thus, measurements of ambient noise levels (in terms of power spectral density) would be used to estimate the detection range of various calls that have been localized under this work. Additional thought needs to be made as to how to define a detection threshold for an impulsive sound embedded in impulsive background noise.

4. Call rates along migration route

An implementation of the proposed acoustic data collection would assist an existing platform of visual census and associations would be derived between detections counted and whales sighted. Contact has been made with the project's principal investigator, Dr. Wayne Perryman at NOAA, as well as with the Monterrey Bay National Marine Sanctuary, to verify the viability of this collaboration. Shore-based census observations have been conducted at Piedras Blancas, CA, by this group for 13 consecutive years (1994-present), in an effort to assess fluctuations in calf production (Perryman et al, 2002) and migration rates (Perryman et al, 1999).

Results from this proposed testing would establish if a correlation between call rates and sighted animals can be drawn and if this relationship gives insight into possible missed detections. However, studies regarding the area's bathymetry and therefore, the sound's propagation have not yet been evaluated. In addition, this study would enlarge the limited compilation of gray whale sounds collected along their migration route (Crane and Lashkari, 1996 and Cummings et al, 1968).

IV. SCHEDULE:

The timeline of field work includes two more seasons in San Ignacio Lagoon, BCS and Piedras Blancas, CA.

In the months of February and May of 2007 low level research would be performed respectively at those locations. In San Ignacio, acoustic data would be collected by means of a 2-element horizontal line array for analyses of localization and using a single hydrophone off Punta Piedra, to estimate call rates.

At Piedras Blancas, a single hydrophone would be lowered to record calls from traveling animals.

During the same periods in 2008, more sensors would be available to extend coverage. Acoustic instruments used in this field season would accommodate greater memory capacities, (8 Gb) permitting longer temporal coverage with less human intervention. Power would be supplied by four D-cell batteries, lasting an estimated period of 10 days. These sensors would be purchased with funds from a separate grant and their assembly would be done by members of our lab group, who have similar previous experience.

The underwater station set-up would be re-designed to guarantee easier deployment and retrieval procedures, as well as minimize the probabilities of mishaps, like entanglements with traveling whales or drifting due to currents. Housing the hydrophones to avoid them rubbing the bottom would be specially considered, in an effort to reduce noise within the dataset, especially around times of strong tides.

Also in 2008, theodolite measurements of surface events (such as breaching and slapping) would be taken from Punta Piedra. Dr. Steven Swartz of NOAA has kindly offered his expertise in such equipment to train me in operating the device and assist in the logistics of acquiring the pieces of equipment.

Data analysis towards a final dissertation would offer the possibility of publishing at approximately three stages, corresponding to the topics of implanting the automated detector, calculating bearings in two methods and finally establishing ranges to calling gray whales by cross-ranging and by calculating transmission loss.

I would aim for the ultimate goal of presenting a defense exam in 2008.

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