NOAA Technical Memorandum NMFS-SEFSC-441

WINDWARDS 2000
ACOUSTIC CRUISE REPORT

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U.S. DEPARTMENT OF COMMERCE
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National Marine Fisheries Service
Southeast Fisheries Science Center
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U.S. DEPARTMENT OF COMMERCE
William M. Daley, Secretary

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National Marine Fisheries Service
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NOTICE

Summary

A visual and acoustic survey of the Eastern Caribbean Islands from St. Kitts to Trinidad, and from Venezuela to Guadeloupe, was conducted from 9 February to 3 April 2000 for humpback whales on the 224 foot NOAA research vessel Gordon Gunter. Three or four observers using 150 mm objective binoculars and handheld binoculars maintained a visual watch. The acoustic survey was conducted using directional (DIFAR) sonobuoys. Humpback whales were counted acoustically based on the number of singing animals. Acoustic and visual whale detections were compared. Other bio-acoustic sounds detected are described.

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WINDWARDS 2000
ACOUSTICS CRUISE REPORT

Mark A. McDonald
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Introduction

A visual and acoustic survey for humpback whales was conducted in the waters of the Eastern Caribbean Islands, the "Windwards", from St. Kitts and Nevis south to Trinidad, and from Venezuela north to Guadeloupe, was conducted from 9 February to 3 April 2000 on the 224 foot NOAA research vessel Gordon Gunter. The survey was sponsored by the U.S. National Marine Fisheries Service, Southeast Fisheries Science Center as part of its program of cooperative research with the International Oceanographic Commission's IOCARIBE organization. Three or four observers using 25x binoculars and 7x handheld binoculars maintained a visual watch. An acoustic survey was conducted using directional (DIFAR) sonobuoys. Some islands were bypassed because research permission could not be obtained from the subject country. Humpback whales were counted acoustically based on the number of singing animals. Given the time of year and the location of the cruise most of the male humpbacks are expected to be producing song most of the time, while the females and calves are expected to be silent.

Background

The total North Atlantic humpback population is estimated at 10,600 animals with a 95 percent confidence interval of 9,300-12,100. The northern Caribbean areas of Silver and Navidad Banks now seasonally contain about 6000 humpbacks while no surveys have been done in the southern Caribbean since 1972. The wintering grounds for the remaining 4000 animals are unknown. In the breeding areas the sex ratio is skewed with 63 percent of the animals being males. All adult males and only males are believed to sing in the breeding areas (T.D. Smith et. al., An ocean-basin-wide mark-recapture study of the North Atlantic humpback whale (*Megaptera novaeangliae*), Mar. Mamm. Sci., 15(1), 1-32, 1999). In 1972 the best estimate for the total Caribbean humpback population was 1018 animals, of which only four animals, encountered near Guadeloupe, were within areas surveyed during this cruise (H. E. Winn, R. K. Edel, and A. G. Taruski, Population estimate of the humpback whale (*Megaptera novaeangliae*) in the West Indies by visual and acoustic techniques, J. Fish. Res. Board Can., 32:499-506).

Methods

DIFAR sonobuoys

Sonobuoys for this research are obtained from the Navy after the shelf life of the buoy has expired. The acoustic survey was conducted using type AN-SSQ 53D sonobuoys.

These sonobuoys contain a compass in the sensor head and transmit three types of continuous signal back to the ship. These signals are acoustic sound pressure, east/west particle velocity and north/south particle velocity. The buoy transmits these signals on a VHF radio carrier in an analog multiplexed format. The manufacturing specification for magnetic bearing accuracy to a sound source using these buoys is plus or minus ten degrees, but in practice we find the bearing accuracy to have a standard deviation of two degrees. If the same calling whale is detected on two or more buoys with a sufficient baseline separation, it is possible to precisely locate the calling whale by crossing two or more bearings. Due to the vagaries of acoustic propagation in the ocean, it is difficult to estimate range to a calling whale by received amplitude alone.

The DIFAR sonobuoys can be pre-set to deploy the sensor package to depths of 100, 400 or 1000 feet. When a 100 foot or shallower depth was desired it was standard practice to use a wrap of duct tape around the buoy and wire to ensure the sensor did not fall deeper than desired. The life of the buoy can be set for various times from 1 to 8 hours, at which time the buoy scuttles itself, thus avoiding the possibility of it drifting up to on a beach. These times were selected in accordance with the proximity to shore and the time we anticipated being in the radio reception area. The buoys are stripped of all packing materials and unnecessary components before being deployed. The sensor head is deployed first such that the buoy unfurls to full length in the air, streaming into the water fully deployed, while the ship is underway at normal speeds. Some buoys were also deployed from the small Zodiac to increase the coverage area.

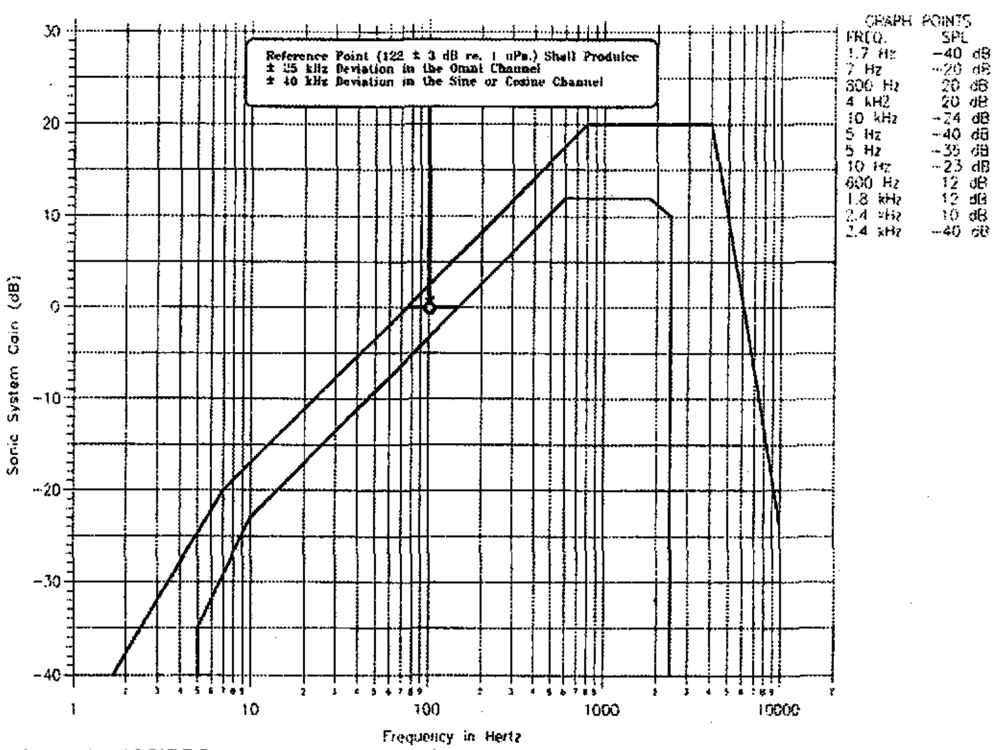


Figure 1. AN/SSQ-53D (DIFAR) sonobuoy specification of the audio frequency response envelope. The rising slope at low frequencies counters the falling slope of ambient sea noise.

The DIFAR sonobuoy frequency response rolls off above 2.4 kHz to allow the directional information to be multiplexed within the 20 kHz bandwidth available on the VHF radio receiver. The practical upper frequency limit for loud sounds is about 4 kHz. The frequency response of a type 53 buoy is shown in Figure 1.

Receiving and recording systems

The VHF radio signal from the sonobuoys was received using a pair of antennas mounted on the aft mast of the Gunter. The base of each antenna was at 85 feet above waterline. One antenna was designed for a tuning range of 144-148 MHz, and the other for frequencies near 165 MHz. A narrow band mast pre-amp was used with the 165 MHz 4.5 dB gain antenna. The 146 MHz 7.8 dB gain antenna was amplified 16 dB by a TV pre-amp just before entering the splitters for the radio receivers. Sonobuoy frequencies were chosen near the frequency band of one or the other antenna, depending on how much other radio interference was in that band. Representative radio reception ranges are shown in Figure 2.

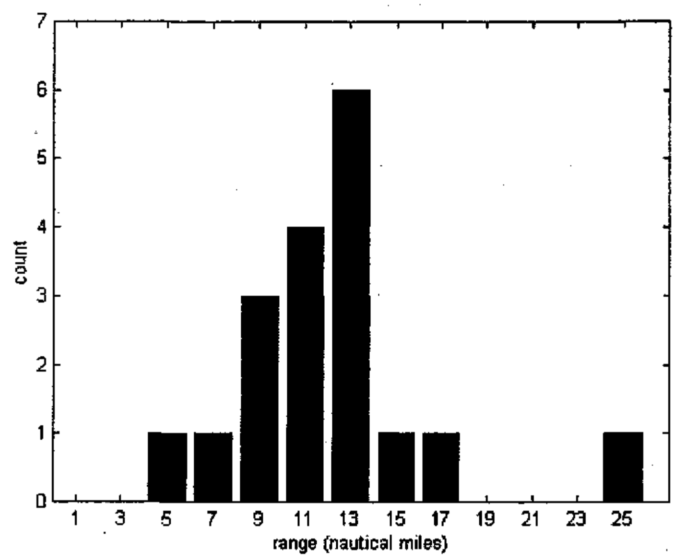


Figure 2. The histogram shows radio reception ranges for 18 sonobuoy deployments from this cruise.

The radios used to receive the sonobuoy signals are five ICOM R-100's specially modified and calibrated by GreeneRidge Sciences to provide flat frequency response from about 10 Hz to 20 kHz. The signals from the radios were recorded at a 48 kHz sampling rate on Sony TCD-D8 digital audio tape recorders. All sonobuoy signals were recorded on two-hour tapes to be available for further processing and for archival purposes. When the ship is at full speed, each sonbuoy is generally recorded for one hour and ten minutes before the ship moved out of radio reception range.

Digital Processing

The magnetic bearing to calling animals was determined by first selecting a segment of the sonobuoy signal of interest in a commercially available signal analysis software package, SpectraPlus. SpectraPlus was run on laptop PC's with the radio signal being digitized by the built in sound cards. This signal was then stored as a binary file and de-multiplexed using software developed by GreeneRidge Sciences. The three de-multiplexed signals were then processed by software written in MATLAB by Mark A. McDonald, based on methods developed by Gerald D'Spain. The software produces a 3D plot showing signal intensity as a function of frequency and bearing angle from 0 to 360 degrees. Magnetic bearing angles to calling animals were selected with the cursor from this plot for each segment of signal selected. An example of the bearing angle output screen is shown in Figure 3.

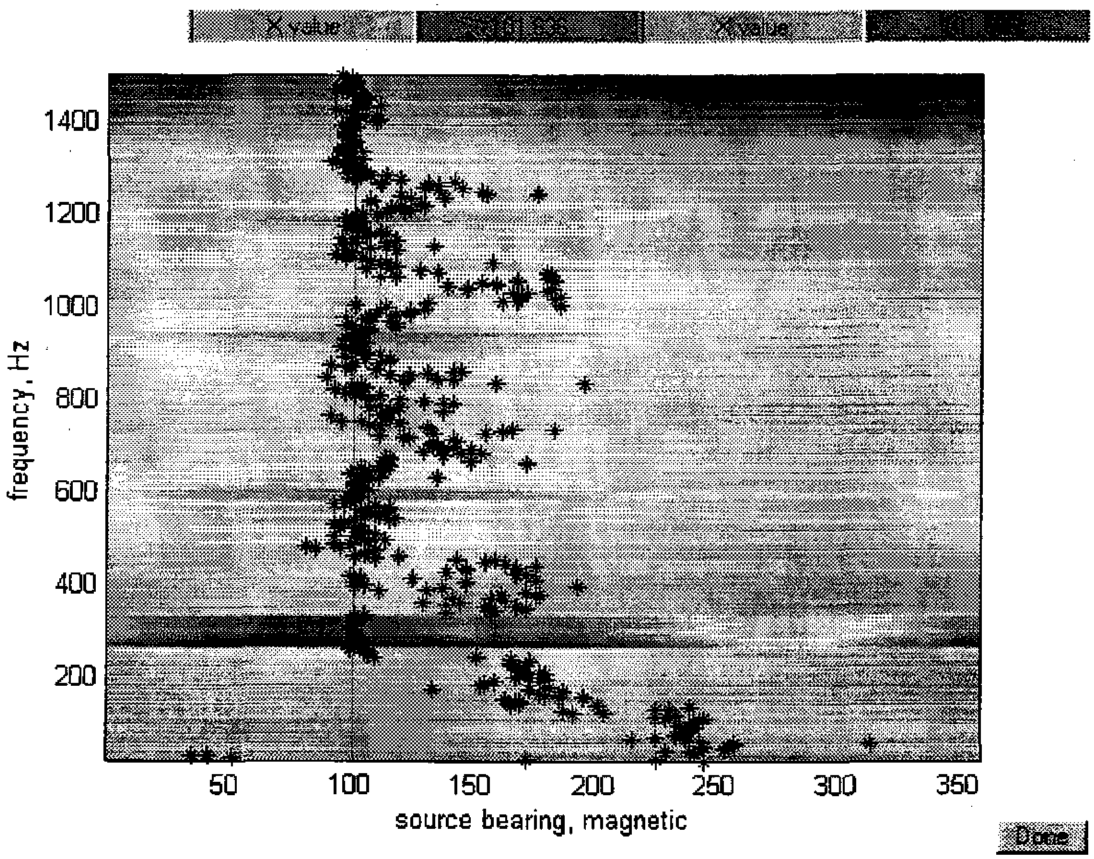


Figure 3. A single calling whale at a bearing of 101° magnetic from the sonobuoy. The harmonics of the call are also evident in this bearing plot, confirming the direction of the whale.

Data Collection

The sonobuoys deployed for acoustic survey purposes are listed in Tables 1 and 2, of Appendix I. Other sonobuoys were occasionally deployed when animals of special acoustic interest, such as pilot whales, were encountered. Buoys were normally placed such that the acoustic detection fields of consecutive buoys overlapped. A map of the entire survey area showing all survey sonobuoy locations is shown as Figures 6 and 9.

Results

Humpback whale detection

A series of maps (Appendix I) are presented showing the acoustic survey of each island or other area. The true bearings of each whale detected are plotted as red arrows from each buoy location. It is often possible to see where these arrow vectors intersect from multiple buoys, indicating the location of a calling humpback. In some cases where the whale was moving or where several whales were on similar bearings we have generalized the bearing vector plot for simplification. The minimum number of whales acoustically detected is noted on each map. The whales are normally heard singing full songs except when calls were very faint and appeared to be received intermittently. The spectrogram of a recording from a song encountered during leg 1 is shown in Figure 4.

Other acoustic signals

The most common acoustic signal encountered during the survey, other than humpback whales calls, was the well known but little understood thump train (Figure 5). This signal has been attributed to the minke whale (Distribution and sounds of the minke whale, with a review of mysticete sounds, Howard E. Winn and Paul J. Perkins, Cetology, No. 20, 1976, pp. 1-11.), though we believe this attribution is incorrect or at least incomplete. There is a possibility the minke whale mimics the thump train sound, but we believe it to be more commonly produced by some species of fish, yet to be identified. The minke whale is considered uncommon or absent south of Puerto Rico and the Virgin Islands in the Caribbean. One stranding was reported in Surinam in 1964 and no stranding or sighting data are known for the Leeward Islands. The region of the abundant thump trains, therefore, does not correspond to any known minke whale population.

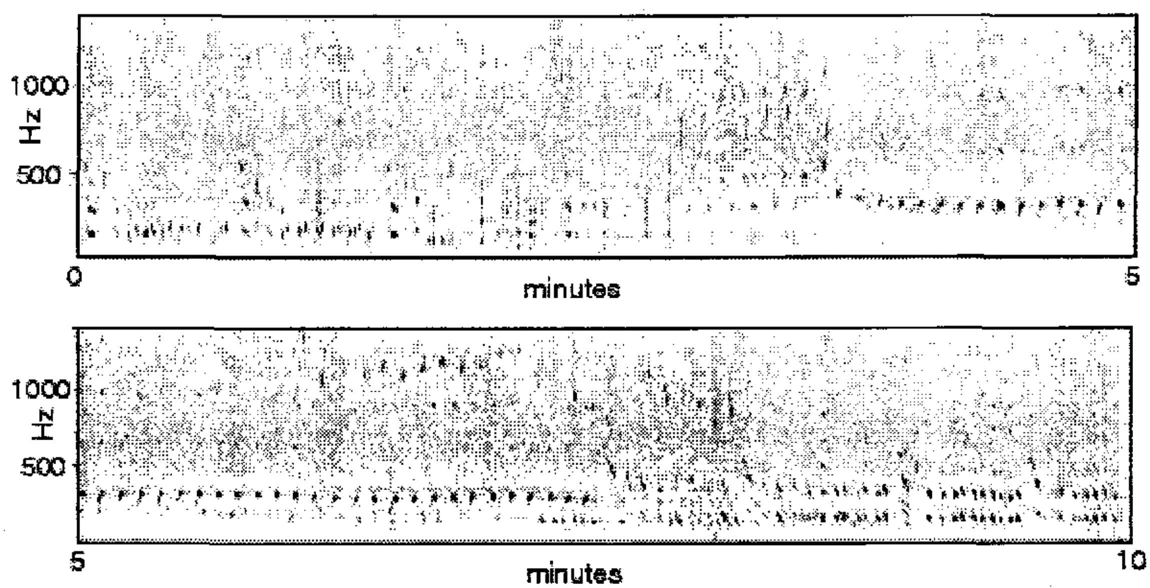


Figure 4. This spectrogram shows ten minutes of continuous humpback song from within an 18 minute dive recorded during leg 1. This singer was located a little more than a mile from the sonobuoy.

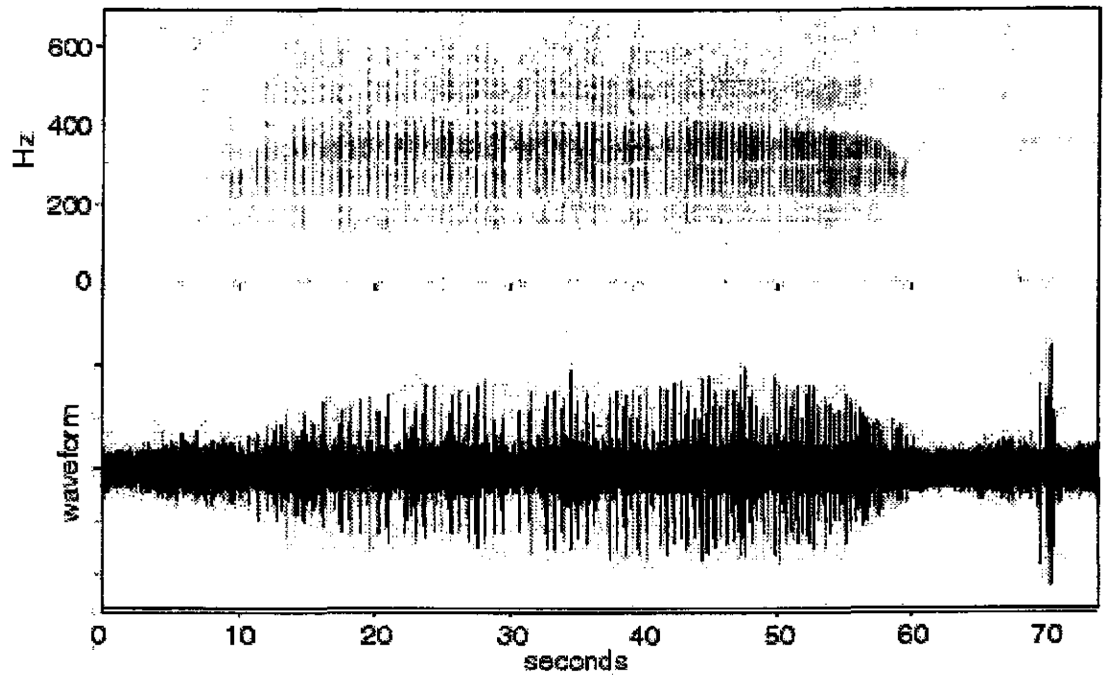


Figure 5. The time series and spectrogram of a typical thump train show increasing repetition rate throughout the call. Occasionally a 2 kHz sound occurs after the thump train as shown at 70 seconds in the time series above.

Sperm whales

DIFAR sonobuoys are not ideal for sperm whale recording because of the frequency roll-off beginning at 2.4 kHz. Sperm whale detections were made routinely in any case, but detection numbers might have been slightly higher with full band sonobuoys, since sperm whale signal are best detected in the 3-7 kHz range. Sperm whales produce a series of clicks in rapid succession, often with several animals simultaneously calling. Aloud clicks at several second intervals are thought to be produce by males, whereas both males and females are thought to produce the rapid sequences of moderate intensity clicks.

Leg 1, February 9 to March 7, 2000
Pascagoula, MS to Port of Spain, Trinidad
Mark A. McDonald

Introduction

Although a small numbers of sonobuoys were deployed through the Gulf of Mexico and along Silver and Navidad Banks to test and to calibrate the acoustic equipment, acoustic survey effort did not begin until reaching the waters of St. Kitts. The song recorded from buoy deployments in these non-survey areas may assist in the determination of population distribution and structure. A total of 96 sonobuoys used for survey purposes were deployed during leg 1. A map of sonobuoy deployments is shown in Figure 6.

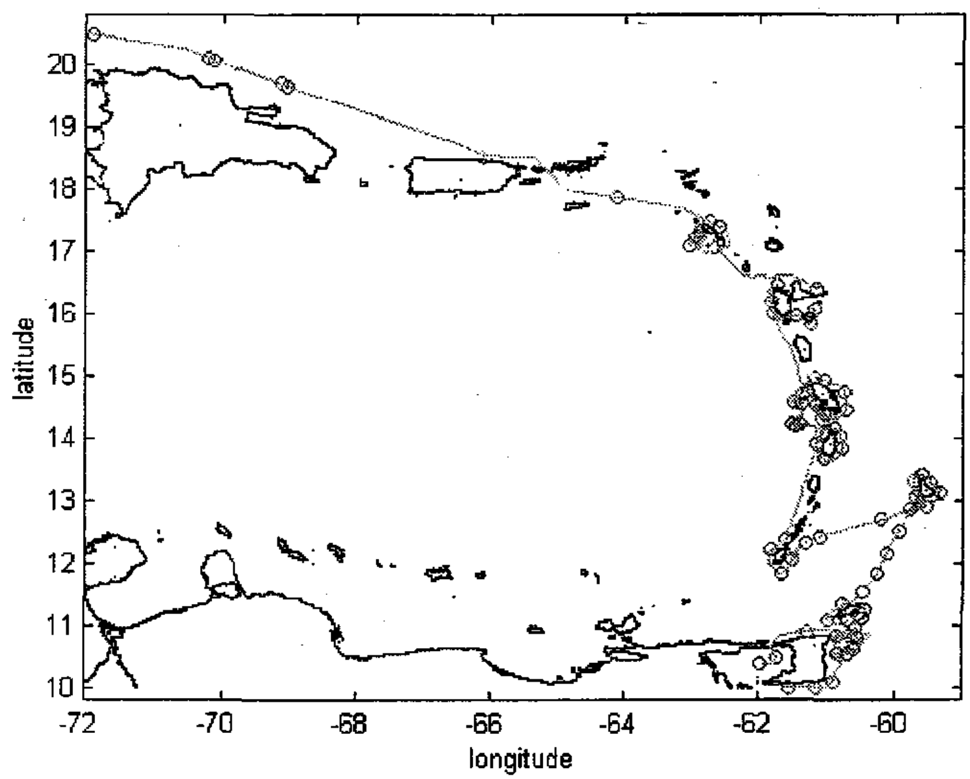


Figure 6. The ship survey track is shown in green, with each survey sonobuoy deployment position shown as a red circle.

Humpback acoustic detection range

The acoustic detection range for humpback whale song is believed to vary from less than ten miles in shallow water with a high Beaufort sea state, to as much as 85 miles in deep water areas with a strong thermocline and relatively low Beaufort sea state. These impressions were formed from a number of specific cases where acoustically detected whales were pursued for visual verification of location and a series of cases where singers previously located with acoustic cross bearings apparently continued to be detected on subsequent sonobuoys as the ship sailed to long ranges. The short-range locations and relative signal strengths were obtained using crossed bearing angles from multiple sonobuoys.

Cases of only five to ten mile detection ranges were common in the East Trinidad area where water depths are highly variable from a few meters to 50 meters and sea states were typically high. It was common to be unable to detect the same whales on two buoys separated by as little as five miles. On some occasions only one buoy of a pair at the same range from a known singers location could detect the animal because of a shallow bank shadowing the other buoy. On some occasions a more distant sonobuoy received a louder song than the closer buoy. We attribute such variations primarily to rapid fluctuations in water depths between 10 and 75 meters in the area off East Trinidad.

One case of a 36 nautical mile detection range took place on the lee side of Martinique with a sea state of Beaufort two. In this case the acoustic detection was pursued with the ship, being recorded on five additional buoys at various intermediate ranges before the whale was localized precisely and observed visually. The longest detection range of leg 1 was 85 miles. Long range localization is necessarily subjective given the time required to move the ship a long distance from a known singer and the chance of a singer being replaced by another at closer range on the same bearing. The cross bearing baseline length is limited by radio range to make cross bearing localization imprecise at such long ranges.

The instance of 85 mile detection took place off the north coast of Barbados where two buoys with a nine mile baseline for cross bearings detected a whale which we suggest was on the southeast shore of Martinique, where a singer had been acoustically localized previously. The average bearing angle differences to this animal are consistent with the necessary six degrees of bearing closure, appropriate to the 85 mile range and nine mile baseline, but it is beyond the accuracy of the buoys to consider such small bearing angle differences entirely reliable. If it had not been for the very strong signal to noise ratios from singers known to be twenty or more miles distant at Martinique, we might not have believed in this 85 mile detection.

Number of humpbacks in survey area

The minimum number of humpbacks detected acoustically in the vicinity of each island is listed in Table I and illustrated in the Figures of Appendix I. The figures in Appendix I plot each bearing angle to a humpback from each sonobuoy and note our estimate of the minimum number of whales detected by each buoy. Sometimes more than one whale per bearing angle is noted because overlapping songs could be observed at the same bearing. The length of the red bearing angle vectors was arbitrarily chosen and does not indicate range estimates. All bearings were corrected from magnetic to true using a fifteen degree magnetic variation.

Table I

AREA	acoustic detections	Detected plus virtual adult males	Total adult males 1.8 X	adult females 37/63 X	calves 30 % of females	totals
Kitts & Nevis	7	7	12.6	7.4	2.22	22.22
Saba & Saba Bank	no survey	9	16.2	9.51	2.85	28.56
Barbuda, Antigua	no survey	9	16.2	9.51	2.85	28.56
Montserrat	no survey	3	5.4	3.17	0.93	9.5
Guadeloupe	7	7	12.6	7.4	2.22	22.22
Dominica	no survey	5	9	5.29	1.58	15.87
Martinique	7	7	12.6	7.4	2.22	22.22
St. Lucia	2	2	3.6	2.11	0.63	6.34
St. Vincent	no survey	2	3.6	2.11	0.63	6.34
Grenada	0	0	0	0	0	0
Barbados	0	0	0	0	0	0
Tobago & East Trinidad	7	7	12.6	7.4	2.22	22.22
Other Trinidad	0	0	0	0	0	0
total	30	58	104.4	61.31	18.39	184.1

A number of islands were not surveyed and must be accounted for if we are to estimate the total Caribbean Island humpback population. These areas include Antigua, Barbuda, Saba Bank, Montserrat, Dominica, St. Vincent and the Grenadines. We exclude St. Croix, St. Martin and other islands north as not being included in our survey effort. By examining the habitat and proximity to surveyed areas on a chart, we estimated the number of detections likely if we had been able to survey those areas (Table I). We also account for the singing whales missed due to the monitoring interval being too short to coincide with a period of song production. Based largely on the experiences from leg 2 off Trinidad and Venezuela, where we acoustically monitored regions with singing whales all day long and noted the appearance and disappearance of singers within our detection range, we estimate we detected fifty-five percent of the singing whales when in survey mode (discussion in leg 2 report). Using the fifty-five- percent detection rate the total number of singers in the Leeward Islands south of St. Croix would be 1.8 times 58, or 104. Using the 63 percent adult male to adult female ratio, the assumption that all adult males sing, and none of the females sing, we have 166 adults. Accounting for calves with a 30 percent pregnancy rate would increase the total number of animals to 184.

Acoustic Assistance in Biopsy Efforts

From March 1 through March 6, efforts were directed towards obtaining biopsy samples and photographs of humpbacks in the East Trinidad area. Whales were located acoustically and there was some success in predicting the surfacing of a whale based on a decrease in call amplitude just before the whale first surfaces. This amplitude decrease may be caused by a surface cancellation effect as the sound source moves nearer the surface. It appeared some of the whales continued to call, though at decreased amplitude, throughout the surfacing period.

The opportunity to listen to an array of sonobuoys all day in the presence of singing humpbacks allowed us to form a better opinion of what percentage of time individuals sing and of the typical duration of a singing period. While the repetitive song appears to be timed to coincide with dive intervals, the duration and frequency of occurrence of periods of singing are essential to judge how many whales were missed by our one hour and ten minute monitoring periods with survey buoys.

Other acoustic signals

Thump trains

DIFAR sonobuoys are well suited for direction-finding on thump trains. When continuous overlapping thump trains have been recorded, it is possible to see there are many animals at various bearings. A map of thump train distribution is shown in Figure 7. The highest thump train abundance was found on the windward side of Martinique, Guadeloupe and Barbados.

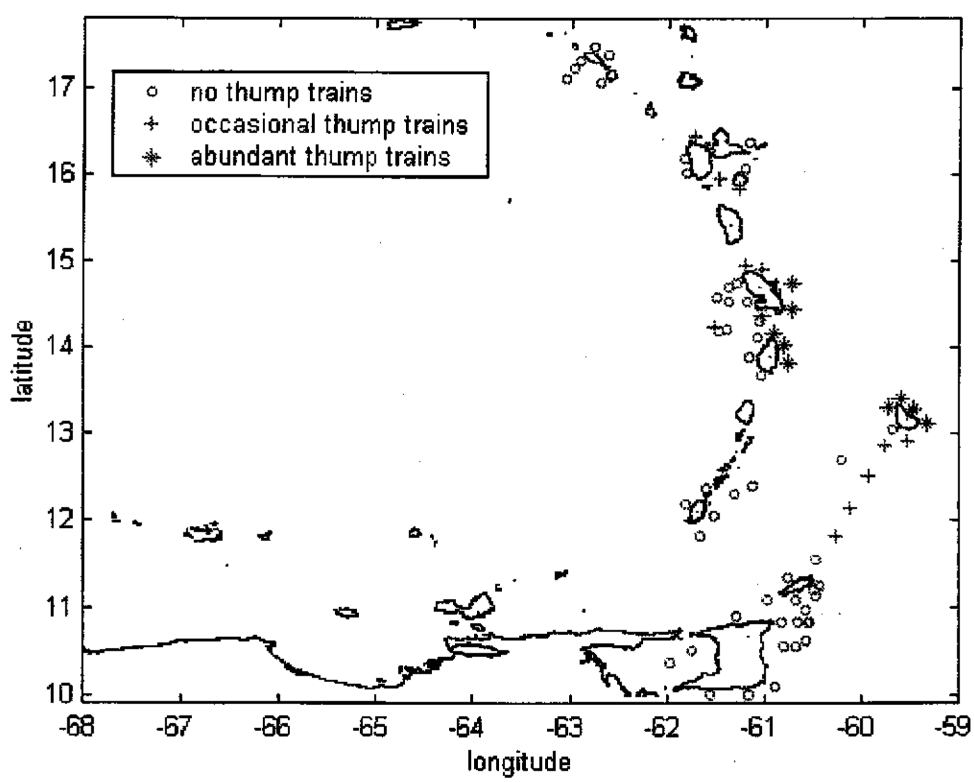


Figure 7. The distribution of thump train sounds based on 77 sonobuoy deployments during leg 1.

Sperm whales

The distribution of sperm whale acoustic detections is shown in Figure 8. In most cases more than one sperm whale is believed to be present based on the high density of clicks heard. Sperm whales were commonly detected during leg 1 of this survey.

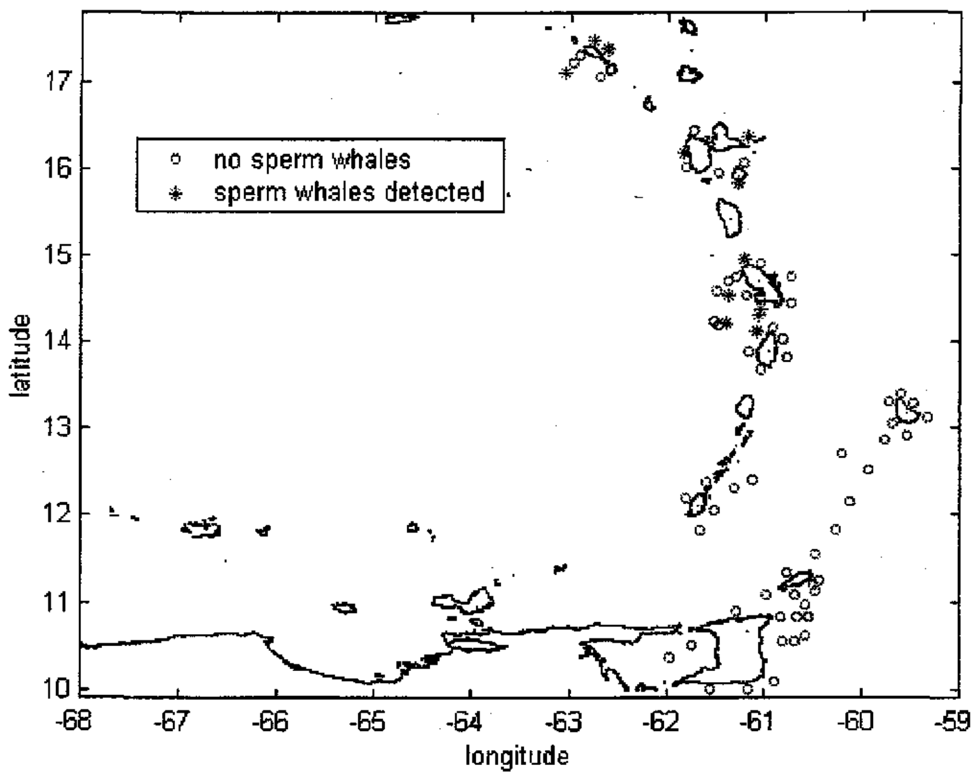


Figure 8. Sperm whale detections are plotted as asterisks. Sonobuoys with no sperm whale detections are plotted with a circle.

Summary

Our estimate for the total number of humpbacks in the Windward Islands south of St. Croix during the first leg of the cruise is 184 animals. Two visual sightings, both cow/calf pairs were obtained during the survey part of the cruise without acoustic assistance to locate whales and 30 acoustic detections were roughly localized during survey efforts. An additional cow/calf visual sighting was obtained without acoustic assistance during the East Trinidad work. In the East Trinidad work some of the whales sighted were undoubtedly not singers, yet acoustics led the ship to stay in areas where singers were frequently heard.

Leg 2, March 9 to April 3, 2000
Port of Spain, Trinidad to Pascagoula, MS
Erin M. Oleson
John A. Hildebrand

Introduction

Survey effort for leg 2 began in Venezuelan waters and progressed north through the Windward Islands, ending in the vicinity of Guadeloupe. Many islands were bypassed during the survey because we did not have permission to survey in their waters. Sonobuoys were deployed north of Guadeloupe in an effort to determine the continuity of song characteristics as the ship moved into Puerto Rican and Dominican Republic waters where wintering humpbacks have been well studied. A total of 80 sonobuoys were deployed for acoustic survey of the Windward Islands and Venezuela. Twenty-four buoys were used for song recordings from St. Croix to the Bahamas. A map of sonobuoy deployment locations is shown in Figure 9.

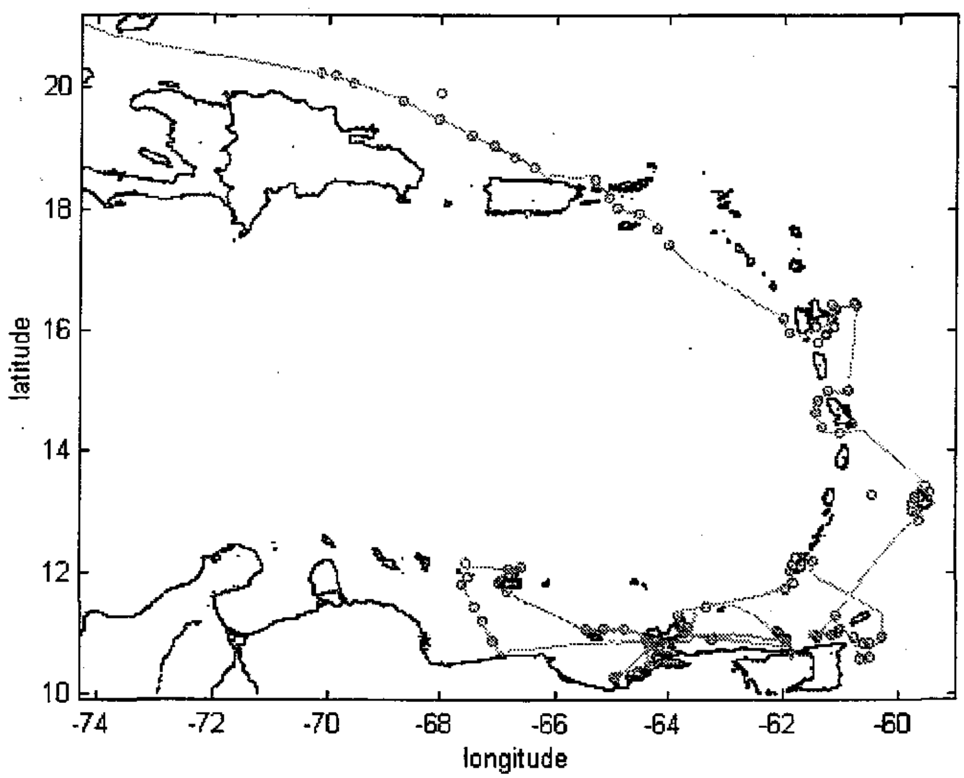


Figure 9. Sonobuoy deployments during leg 2. The ship track is shown in green and red circles represent sonobuoys.

Humpback acoustic detection range

The furthest detection confirmed during leg 2 was approximately 25 miles, occurring off the west coast of Barbados. Although many whales were detected acoustically, few were visually confirmed. The distance from the whale to the buoy was determined by forming a cross bearing between two buoys receiving the same call. Because a closer buoy may have received a weaker signal than a further buoy, time of arrival of the song was also used to determine relative distances to the animal between buoys. This method was used most often to check cross-bearings and to determine if the animal was moving.

On many occasions one or more singing whales were monitored for an extended period of time. Within an eight to ten hour period, many of these humpbacks could be heard singing continuously without significant pause. The use of bearing angles and signal to noise ratio often confirmed that we were listening to the same animal throughout the extended period.

Number of humpback whales in survey area

The minimum numbers of humpbacks detected during survey effort around each island are listed in Table 2 and illustrated in Figure 2 of Appendix I. The Figures in Appendix I plot bearing angles to whales from each sonobuoy. A maximum of two bearing angles, representing two whales is plotted for clarity, although more whales may have been heard, and are noted in the figure. The length of the arrow representing bearing angle is arbitrary and does not represent range estimates.

Many islands were not surveyed, including St. Kitts, Antigua, Barbuda, Saba bank, Montserrat, Dominica, St. Lucia, St. Vincent and the Grenadines. These islands were

Table 2

AREA	Acoustic detections	detected plus virtual adult males	total adult males 1.8X	adult females 37/63 X	Calves 30% of females	**totals**
Trinidad and Tobago	7	21	37.80	22.20	6.66	**66.66**
Grenada	5	5	9.00	5.28	1.58	**15.86**
St. Vincent	no survey	5	9.00	5.28	1.58	**15.86**
St. Lucia	no survey	5	9.00	5.28	1.58	**15.86**
Barbados	5	8	14.40	8.46	2.54	**25.40**
Martinique	7	9	16.20	9.51	2.85	**28.56**
Dominica	no survey	6	10.80	6.34	1.90	**19.04**
Guadeloupe	9	14	25.20	14.80	4.44	**44.44**
Montserrat	no survey	4	7.20	4.23	1.27	**12.7**
Barbuda, Antigua	no survey	14	25.20	14.80	4.44	**44.44**
Saba & Saba Bank	no survey	14	25.20	14.80	4.44	**44.44**
St. Kitts & Nevis	no survey	14	25.20	14.80	4.44	**44.44**
Total- Islands	**33**	**119**	**214.20**	**125.80**	**37.74**	**377.74**
Venezuela	**11**	11	19.80	11.63	3.49	**34.92**
Grand Total	**44**	**130**	**234.00**	**137.43**	**41.23**	**412.66**

bypassed either due to time constraints or for lack of a permit to survey those waters. When surveying around most of the islands, buoy locations had overlapping detection ranges to get the most complete coverage. In many cases, however, time did not allow for a survey that circumnavigated the entire island, leaving many areas unsurveyed. The number of detections presented here is clearly not representative of the total population of males around each of the surveyed islands. Assuming that humpback whales are randomly distributed throughout the Caribbean Islands a correction has been applied to account for the areas not surveyed. Although this assumption is likely violated, it provides a means to account for the entire population of Caribbean humpback whales. However, to obtain more accurate estimates of the Caribbean humpback population, the actual distribution of whales, as well as suitable habitat area, should be examined. The correction is noted in the "virtual plus actual adult males" column of Table 2. Venezuela has been noted separately from the Caribbean Island chain to allow comparison of the leg 1 and leg 2 estimates.

Following the methods of leg 1, the total number of animals in the survey area during leg 2 has been estimated. A sex ratio of 63% males, and a pregnancy rate of 30% have been applied to this estimate. A correction of 55% detection probability has been applied to the detections from all surveyed and unsurveyed areas based on the assumption that the locations from which we derived a detection probability of 55% are representative of the entire Eastern Caribbean. The total population estimate for leg 2, encompassing the Caribbean chain and the north coast of Venezuela is 413 humpback whales.

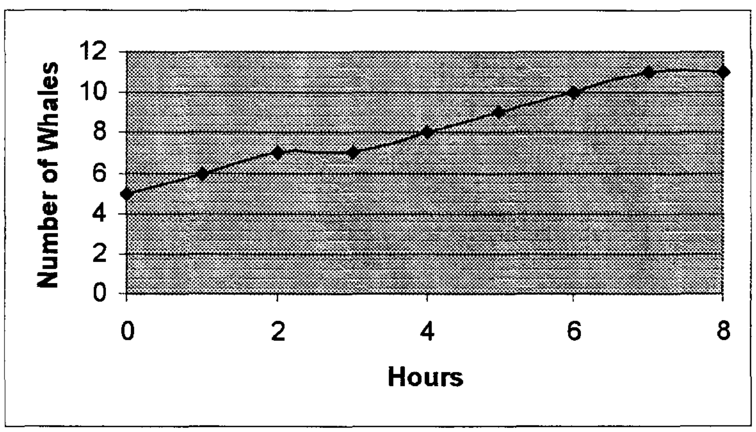


Figure 10. The cumulative number of whales acoustically encountered on sonobuoys in 5 separate locations monitored for at least 8 hours.

Under the assumption that all males present within an area will sing within 8 hours and that whales do not move, we have estimated a 55% detection probability for singing males. Figure 10 shows the cumulative number animals observed on five sonobuoys (or groups of closely spaced sonobuoys) that were monitored for 8 or more continuous hours during leg 2 of the cruise. These buoys were deployed in various survey locations throughout the second leg on the cruise, including Venezuela (March 14, Sonobuoy #136, and March 16, Sonobuoy #143-146), Trinidad March 21, Sonobuoy #167,168), Barbados

March 22, Sonobuoy #172,173), and Guadeloupe (March 25, Sonobuoy #191). The initial detection of 5 whales is, thus, the sum of the initial detection on all 5 sonobuoys. Whales that are identified as new singers, ie. having a distinctly different bearing angle, are added to the cumulative plot at the time they are heard. Whales that stopped singing during the monitoring window have not been subtracted from the graph because we wish to show the total number of detections possible within the life of a buoy, not the number of whales present at the end of 8 hours. By dividing the number of whales detected at the end of 8 hours (11) by that detected within one hour (6), we arrive at a detection probability of 55%. A crude binomial standard error for this detection probability is estimated from the sample size as,

$$S.E.(p) = \sqrt{(pq/N)} = 0.15$$

Where p = 0.55, q = (1 – p) = 0.45, and N = 11. The 95% confidence interval for this detection probability is calculated as 0.55 $\pm$ 0.334 or, 0.216 to 0.884.

There are two biases associated with this estimate. Because the graph does not show a clear asymptote at 8 hours, it is possible that some males present at the start had not yet started to sing. This would lead to an overestimate in our detection probability. However, it should be noted that on three separate occasions, twice in Venezuela and once in Trinidad, multiple buoys covering the same area, but deployed at different times were combined to represent one monitored area, spanning time greater than 8 hours. In each of these cases no new humpback whales were heard singing after 8 hours had past, lending validity to a detection probability estimate of 55%. Alternatively, new animals may have entered our survey area and started to sing within our 8 hour window. This would lead to an underestimate in our detection probability

Acoustic assistance in biopsy efforts

In the vicinity of north Trinidad, and again north of Barbados, acoustic detections were used to locate animals for biopsy samples. Only once were we able to confirm acoustic and visual detection of the same animal, although we believe that we had joint detections of a singer on other occasions. It was difficult to predict surfacing intervals, and to identify the start and end points of a song cycle. Rarely was there a pause in the song long enough to allow the animal to surface for a breath. It was also difficult to detect a decrease in the amplitude of the song, which is thought to occur as the whale continues singing while moving toward the surface. No attempt at biopsying a singing whale was successful during this leg of the cruise.

One confirmed visual and acoustic detection of the same whale came off the north shore of Barbados. Wireless headphones were connected at the flying bridge so that the song could be monitored as the whale was visually tracked. During this encounter, a sound similar to the ratchet, previously described in other studies of humpback song, was observed just prior to surfacing. This ratchet noise was not always detected in the song of other humpbacks recorded during this cruise.

Other attempts at precisely locating a singing whale for biopsy included the use of a sonobuoys altered to be easily mobile for use with the small Zodiac. The rigid sections of the buoy were taped together with most of the wire sequestered within the rigid sections. Only the stabilizing baffles, and a small section of spring-like cord were left to be deployed from the small boat. The radio signal was received at the ship and the direction of the whale from the Zodiac position was relayed to the Zodiac. The use of this mobile buoy was very successful at steering the biopsy team close to singing male humpbacks, however, a visual sighting took precedence, and the buoy was abandoned as the team got close to the whale.

Preliminary West Indies humpback song analysis

Although many different humpback songs were recorded during this cruise, one song was heard most often throughout the second leg of the cruise. The spectrogram of this song is shown in Figure 3 of Appendix I. Many recordings of this song are now archived onto 2-hour DAT tapes for further analysis. This song was heard in the vicinity of Barbados, Martinique, Guadeloupe, and on the Venezuelan and Trinidad sides of the Dragon's Mouth. Other songs were also encountered during this cruise, especially during leg 1 when it is apparent that many different song types were present.

Twenty-four sonobuoys were deployed during leg 2 from St. Croix to the Bahamas to investigate the continuity of the song through this well studied area. Many whales south of Puerto Rico and north to Silver and Navidad Banks have been recorded singing a similar song to that which we recorded on the survey sonobuoys. The main differences in the song include the number of times a syllable is repeated (for humpback song element definitions see Winn and Winn, The Song of the humpback whale *Megaptera novaeangliae* in the West Indies, Marine Biology, 47:97-114, 1978.), the complexity of a particular syllable, and slight changes in the start and end frequency of a given element. Many times pieces of our familiar song were evident in other survey areas, such as off the coast of Grenada, with one or more phrases or motifs replaced by a novel element. This was most common in the vicinity of Silver and Navidad Banks, where high frequency chirps replaced much of the mid-frequency part of the song.

Further song analysis will be necessary to determine more precisely the geographical distribution of the different song types, however, it is evident that there is a change, albeit slight from the southern extreme of our survey in Venezuela, to the most northern sonobuoy deployment along the Dominican Republic banks. No song was heard on four buoy deployments in Bahamian waters.

Other acoustic signals

Thump trains-

Thump trains, illustrated in Figure 5, were common on sonobuoys around Barbados, Martinique and Guadeloupe during leg 2 of the cruise. Detections of thump trains throughout the survey and non-survey area on shown in Figure 11. We encountered a notable density of thump trains north of the survey area near Puerto Rico, Silver and Navidad banks, and to the south of the Bahamas. There were no buoy deployments that detected thump trains that did not contain humpback song. On two days during the transit north to Puerto Rico, excellent visual survey conditions allowed for many

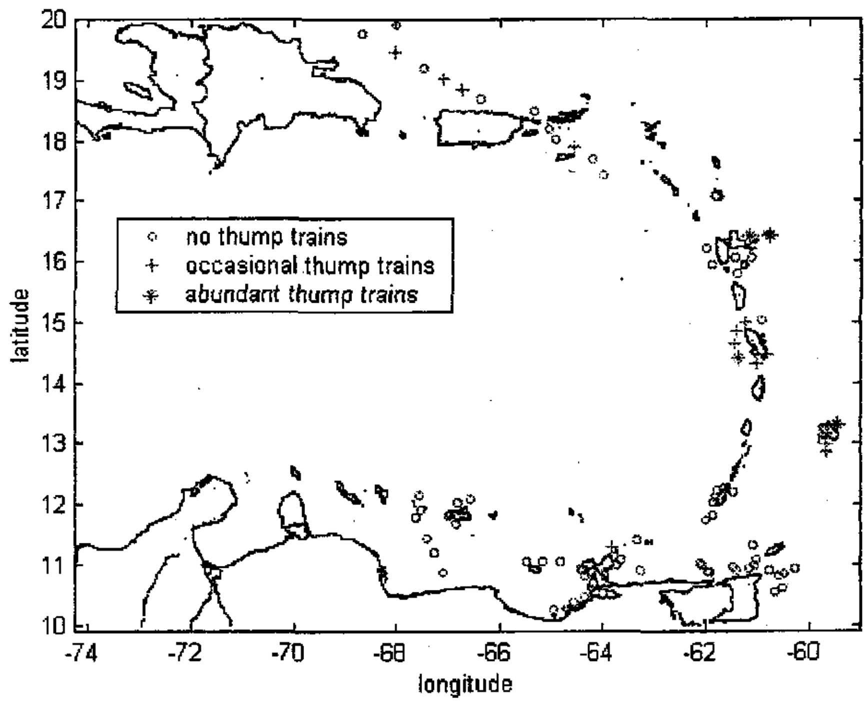


Figure 11. Thump train distribution during leg 2 of the Windward Island survey. Detections north of the survey area are also shown.

sightings of whales that had not been previously observed. On both of these days, thump trains were recorded, however, minke whales, which have been associated with the production of thump trains, were not seen.

On the east side of Guadeloupe, a pair of buoys was deployed three miles apart with the intention of localizing and identifying the source of the thump train. Unfortunately, the second buoy of the pair did not result in any detections of thump trains, and the experiment was abandoned to pursue acoustic and visual detections of humpback whales.

Sperm whales-

Sonobuoys that detected sperm whales during leg 2 are shown in Figure 12. As stated previously, DIFAR sonobuoys are not ideal for detecting sperm whales, however many were still encountered and could easily be heard through headphones attached to the laptops used to process the acoustic signals. On many occasions around Martinique sperm whales were visually observed in close proximity to the sonobuoy, providing some indication that we were truly detecting sperm whales. On other occasions where sperm whale clicks were heard, we did not have any visual confirmation of the source.

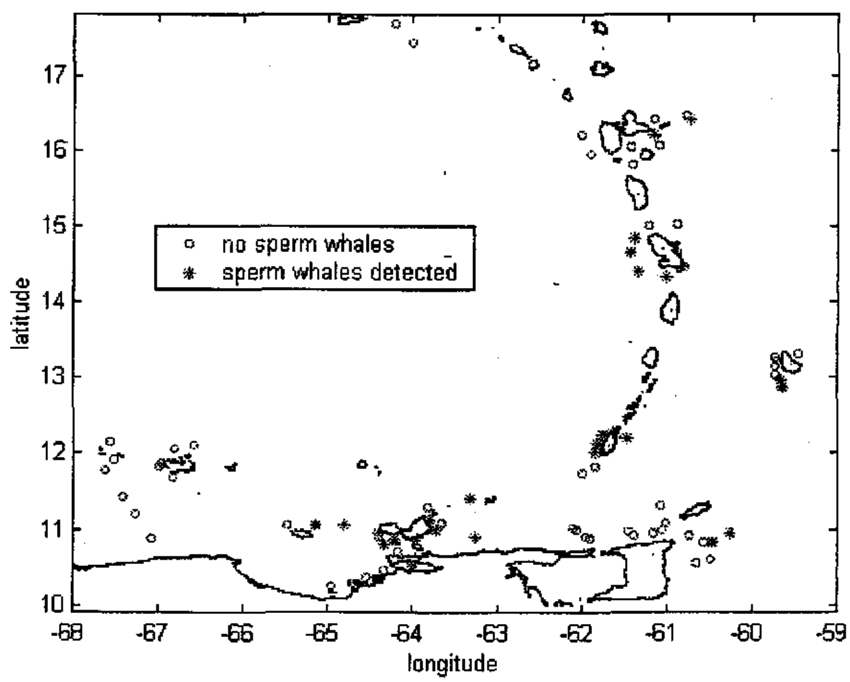


Figure 12. Sperm whale acoustic detection during leg 2.

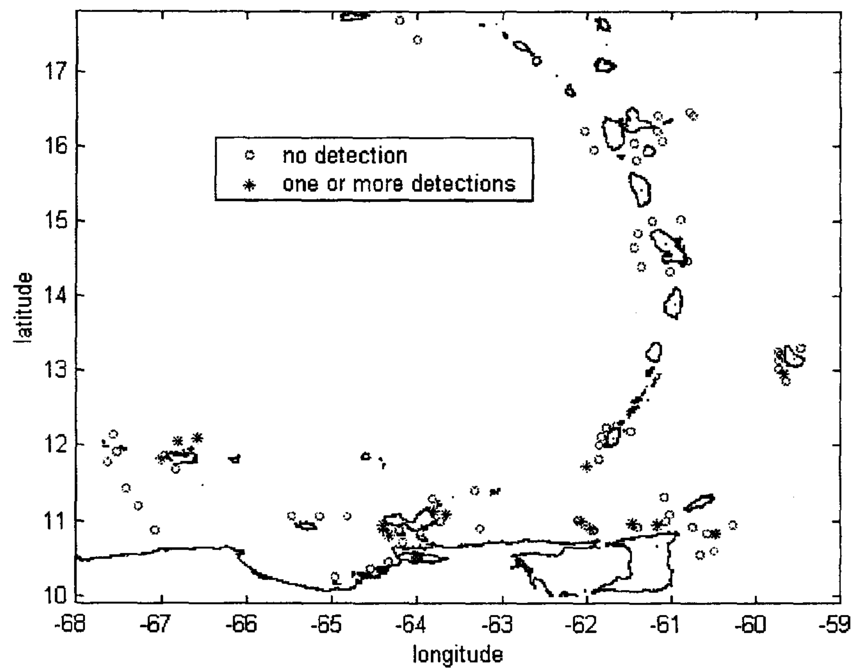


Figure 13. Low frequency tone occurrence during leg 2. The tone is hypothesized to be that of either a fin whale of Bryde's whale.

The low frequency tone

On much of the southern portion of the cruise , a low frequency sound, characterized by a fundamental frequency of approximately 17 Hz, harmonics evident up to about 100 Hz, and a duration of 1 to 3 seconds was common. The sound is not produced by a ship. This is verified by its localization well distant from any ships or small watercraft. Although the source of this tone is unknown, two potential marine mammal sources have been discussed.

The sound has characteristics very similar to that of the fin whale. Many unidentified large balaenopterids, sometimes speculated to be fin whales, were seen in the southern regions of our cruise. Although this is a viable possibility, fin whales are not thought to be common in the tropical latitudes. The frequent occurrence of these sounds, especially in Venezuelan waters, seems to make fin whales an unlikely source of this sound. The geographical location does, however, lend more validity to our second possibility that the source of this call is a Bryde's whale. Many Bryde's whales were seen in Venezuelan waters, with many of the unidentified large balaenopterids likely being Bryde's whales. Although there are few previous recordings of Bryde's whales, and their calling behavior is largely unknown, the possibility of these low frequency tones being produced by Bryde's whales can not be dismissed, and warrants further investigation. A map of the distribution of occurrence of this tone is plotted in Figure 13.

Summary

During 80 sonobuoy deployments, 44 singing male humpback whales were detected in survey areas during leg 2 of this cruise. On many occasions cross-bearings from the DIFAR sonobuoys provided locations of a singing male humpback, however, poor sighting conditions, and stealthy animals made visual detection very difficult. On more than one occasion, during excellent sighting conditions, a likely singer was observed to only appear briefly at the surface, with little or no blow, and quickly disappear without showing its flukes.

The estimate of humpback whales, in the Caribbean Island and northern Venezuela during this leg of the cruise is 413 animals. Visual sightings of humpbacks including two cow/calf pairs were obtained with and without acoustic assistance on 33 occasions during the cruise. In some instances, non-singing humpbacks were detected visually without the aid of acoustics (e.g., cow-calf pairs and non-singers), while other times whales were sighted visually while traveling to or searching for a singing whale that was detected acoustically. The overall acoustic versus visual disparity, a ratio of 30 "on effort" acoustic detections versus 7 visual sightings of whales (including one cow/calf pair) during leg 1, and 44 acoustic detections versus 15 whales seen on leg 2, illustrates the value of acoustics on a survey such as this.

About 380 hours of two-channel DAT tape has been archived from this cruise, inclusive of both legs 1 and 2. The tapes will be useful for song analysis and population comparison studies. The tapes have also been used to study ship noise from the R/V Gunter at various speeds for future towed array acoustic work (J. Barlow report in prep).

Appendix I

Table I. Sonobuoy locations during leg 1 of Windward Island survey.

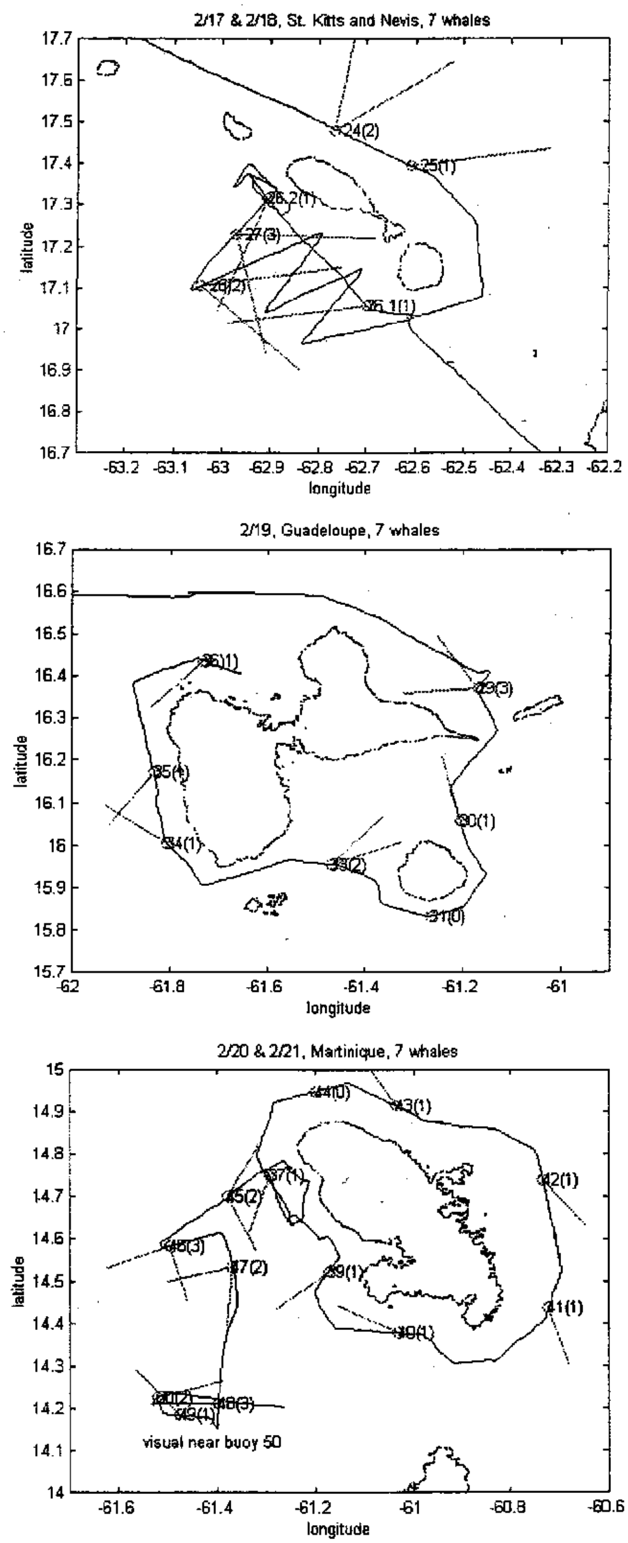
Buoy #	date	time	latitude	longitude
17	14-Feb	07:42	20.48975	-71.8765
18	14-Feb	20:01	20.09455	-70.188
19	14-Feb	20:31	20.0617	-70.1169
20	15-Feb	04:32	19.69483	-69.1297
21	15-Feb	05:18	19.65233	-69.0213
22	17-Feb	06:30	17.86917	-64.1195
24	17-Feb	15:15	17.48117	-62.7657
25	17-Feb	16:20	17.39433	-62.609
26.1	17-Feb	20:05	17.05487	-62.6973
26.2	17-Feb	22:02	17.31445	-62.9064
27	18-Feb	08:00	17.2285	-62.9733
28	18-Feb	09:06	17.10433	-63.0433
29	19-Feb	06:50	16.37183	-61.1697
30	19-Feb	09:20	16.058	-61.2055
31	19-Feb	11:17	15.83283	-61.2667
33	19-Feb	12:46	15.95483	-61.469
34	19-Feb	14:56	16.00483	-61.8063
35	19-Feb	15:50	16.17183	-61.8328
36	19-Feb	18:07	16.4375	-61.7322
37	20-Feb	06:40	14.75033	-61.2933
39	20-Feb	09:12	14.522	-61.1722
40	20-Feb	11:13	14.3775	-61.029
41	20-Feb	13:40	14.43583	-60.7233
42	20-Feb	15:30	14.74	-60.735
43	20-Feb	17:40	14.91433	-61.0348
44	20-Feb	18:46	14.94733	-61.1997
45	21-Feb	07:55	14.6995	-61.3797
46	21-Feb	09:08	14.58367	-61.4957
47	21-Feb	10:18	14.5335	-61.3687
48	21-Feb	12:09	14.21233	-61.3972
49	21-Feb	13:03	14.18367	-61.476
50	21-Feb	13:43	14.22583	-61.522
51	22-Feb	07:33	14.29917	-61.0675
52	22-Feb	08:55	14.10583	-61.077
53	22-Feb	10:40	13.88917	-61.1698
54	22-Feb	12:40	13.67783	-61.0445
55	22-Feb	15:11	13.826	-60.7743
56	22-Feb	16:25	14.02817	-60.8007
57	22-Feb	17:25	14.16383	-60.9042
58	23-Feb	05:52	12.38633	-61.5975
59	23-Feb	08:50	12.20433	-61.8103
60	23-Feb	13:30	11.83217	-61.6683
61	23-Feb	15:23	12.04467	-61.5222
62	23-Feb	19:15	12.31683	-61.3125
63	23-Feb	20:50	12.40183	-61.1153
64	24-Feb	02:48	12.694	-60.1952

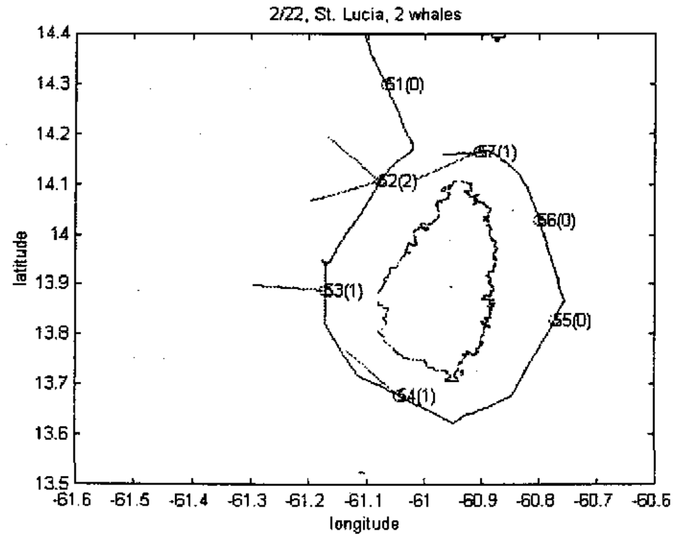
Buoy #	Date	time	latitude	longitude
65	24-Feb	07:04	12.90517	-59.5378
66	24-Feb	08:23	13.06067	-59.6957
67	24-Feb	09:49	13.3165	-59.722
68	24-Feb	10:52	13.40583	-59.5958
69	24-Feb	12:09	13.2775	-59.4678
70	24-Feb	13:28	13.131	-59.3415
71	26-Feb	10:19	12.86717	-59.7712
72	26-Feb	12:46	12.50967	-59.9393
73	26-Feb	15:03	12.13983	-60.1188
75	26-Feb	17:20	11.82033	-60.2723
76	26-Feb	19:23	11.55183	-60.477
78	26-Feb	21:36	11.33533	-60.7712
79	27-Feb	06:14	11.078	-60.9797
80	27-Feb	08:29	11.07767	-60.6893
81	27-Feb	09:45	11.18783	-60.506
82	27-Feb	10:21	11.25417	-60.4298
83	27-Feb	11:56	11.1175	-60.4658
85	27-Feb	16:11	10.96467	-60.5748
86	27-Feb	17:14	10.81567	-60.5377
87	28-Feb	06:13	10.62	-60.5848
88	28-Feb	11:12	10.54517	-60.6797
89	28-Feb	12:24	10.54233	-60.8172
90	29-Feb	05:52	10.085	-60.8962
91	29-Feb	07:44	10	-61.1638
92	29-Feb	09:46	10.00083	-61.5538
93	29-Feb	13:53	10.36933	-61.9772
94	29-Feb	15:41	10.49167	-61.7415
95	29-Feb	20:21	10.907	-61.2922
96	01-Mar	06:00	10.8305	-60.8317
97	01-Mar	07:15	10.81867	-60.658
98	01-Mar	07:53	10.82183	-60.5612
100	02-Mar	06:01	11.13717	-60.9277
101	02-Mar	11:58	10.89083	-60.8107
102	02-Mar	14:09	10.68417	-60.6693
103	02-Mar	14:59	10.54817	-60.674
104	03-Mar	06:19	10.6185	-60.6835
105	03-Mar	07:16	10.61367	-60.5682
106	04-Mar	12:03	11.243	-60.4047
107	04-Mar	14:10	10.959	-60.294
108	05-Mar	06:23	10.70633	-60.8463
109	05-Mar	08:25	10.506	-60.6825
110	05-Mar	09:16	10.50667	-60.5482
111	05-Mar	14:48	10.86667	-60.4905
112	05-Mar	15:40	10.865	-60.5673
113	06-Mar	06:35	10.8665	-60.5525

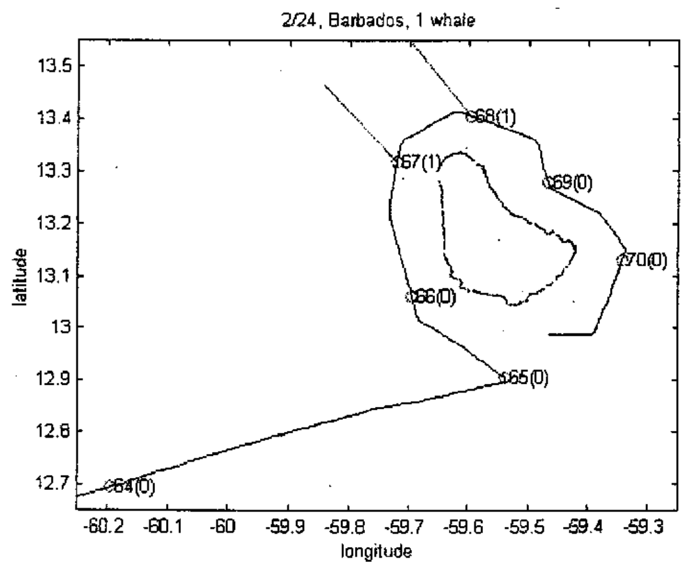
Table 2. Sonobuoy locations during leg 2 of Windward Islands survey.

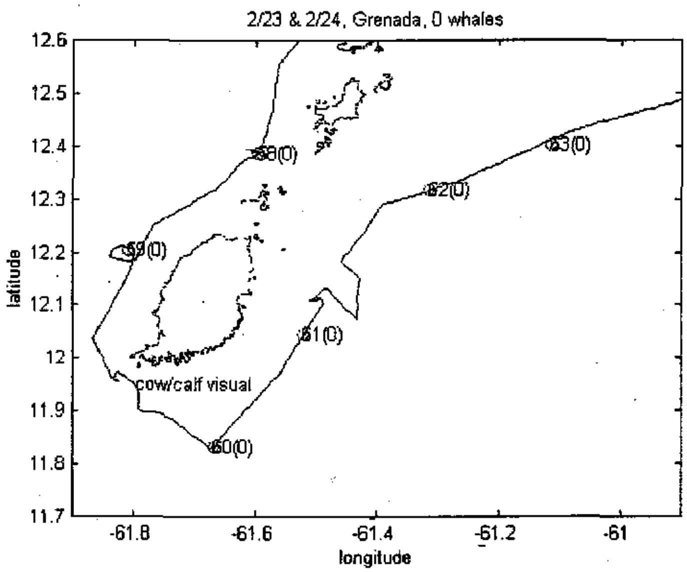
Buoy #	date	time	latitude	longitude	Buoy #	Date	time	latitude	longitude
114	11-Mar	10:20	10 52.28	67 5.41	156	19-Mar	15:46	12 16.0	61 13.98
115	11-Mar	12:25	11 11.31	67 16.72	157	19-Mar	17:09	12 12.09	61 28.67
116	11-Mar	14:07	11 25.66	67 25.0	158	20-Mar	06:48	10 56.51	60 16.22
117	11-Mar	16:32	11 47.27	67 37.32	159	20-Mar	09:10	10 50.01	60 29.12
118	11-Mar	18:18	11 54.36	67 30.86	160	20-Mar	10:47	10 49.68	60 35.13
119	11-Mar	20:20	12 8.53	67 33.38	161	20-Mar	13:37	10 36.04	60 30.02
120	12-Mar	06:40	12 5.52	66 35.0	162	20-Mar	15:24	10 33.53	60 40.12
121	12-Mar	11:41	12 2.72	66 48.8	163	20-Mar	18:27	10 54.97	60 45.27
122	12-Mar	15:17	11 49.55	67 0.1	164	20-Mar	19:55	11 4.47	61 0.56
123	12-Mar	16:20	11 51.77	66 57.42	165	21-Mar	06:43	10 59.78	61 2.88
124	12-Mar	18:14	11 41.17	66 50.23	166	21-Mar	07:57	10 56.88	61 9.1
125	13-Mar	04:11	11 3.04	65 28.89	167	21-Mar	10:40	10 57.52	61 27.3
126	13-Mar	06:19	11 3.07	65 9.42	168	21-Mar	14:56	10 54.66	61 23.55
127	13-Mar	10:10	11 3.11	64 48.72	169	21-Mar	19:47	11 18.5	61 5.02
128	13-Mar	12:51	10 55.96	64 24.69	170	22-Mar	07:25	12 48.28	58 56.93
129	13-Mar	14:36	10 53.95	64 24.06	171	22-Mar	08:14	12 51.79	59 39.19
130	13-Mar	18:05	10 48.27	64 20.44	172	22-Mar	10:11	12 58.06	59 39.97
131	14-Mar	05:02	10 30.65	64 0.08	173	22-Mar	13:40	13 1.7	59 43.52
132	14-Mar	09:45	10 32.08	64 6.06	174	22-Mar	16:12	13 8.18	59 44.21
134	14-Mar	13:06	10 26.92	64 20.57	175	22-Mar	16:54	13 15.36	59 43.35
135	14-Mar	14:39	10 21.8	64 33.43	176	23-Mar	13:24	13 12.24	59 42.5
136	14-Mar	17:33	10 15.12	64 58.14	177	23-Mar	15:14	13 24.99	55 32.27
137	15-Mar	05:30	10 42.76	64 10.05	178	23-Mar	17:04	13 18.18	59 27.79
138	15-Mar	11:52	10 51.91	64 12.97	179	24-Mar	06:57	14 27.54	60 47.96
139	15-Mar	13:30	10 51.01	63 58.31	180	24-Mar	09:00	14 19.36	61 0.86
140	15-Mar	18:08	11 5.57	63 39.58	181	24-Mar	11:04	14 23.97	61 20.73
142	15-Mar	21:04	11 24.91	63 19.86	182	24-Mar	12:43	14 38.62	61 25.36
143	16-Mar	645	11 0.67	62 6.2	183	24-Mar	14:12	14 50.74	61 23.68
144	16-Mar	720	10 59.28	62 3.66	184	24-Mar	15:31	14 59.41	61 13.68
145	16-Mar	1230	10 53.48	61 56.91	185	24-Mar	17:57	15 0.76	60 53.24
146	16-Mar	1309	10 51.91	61 54.96	186	25-Mar	06:15	16 24.7	60 44.74
147	17-Mar	705	10 54.14	63 15.23	187	25-Mar	07:59	16 26.93	60 47.02
148	17-Mar	928	10 58.93	63 43.15	188	25-Mar	10:45	16 24.88	61 9.73
149	17-Mar	15:56	11 7.89	63 47.52	189	25-Mar	12:14	16 12.15	61 9.29
150	17-Mar	18:57	11 16.88	63 49.81	190	25-Mar	13:24	16 4.03	61 6.51
151	19-Mar	07:29	11 44.08	61 59.02	191	25-Mar	14:53	16 3.0	61 26.03
152	19-Mar	08:56	11 49.74	61 50.45	192	25-Mar	15:57	15 48.0	61 24.2
153	19-Mar	10:16	12 1.08	61 51.27	193	25-Mar	20:04	15 57.09	61 54.21
154	19-Mar	11:33	12 7.74	61 49.48	194	25-Mar	21:38	16 11.77	62 0.51
155	19-Mar	13:22	12 14.32	61 46.13					

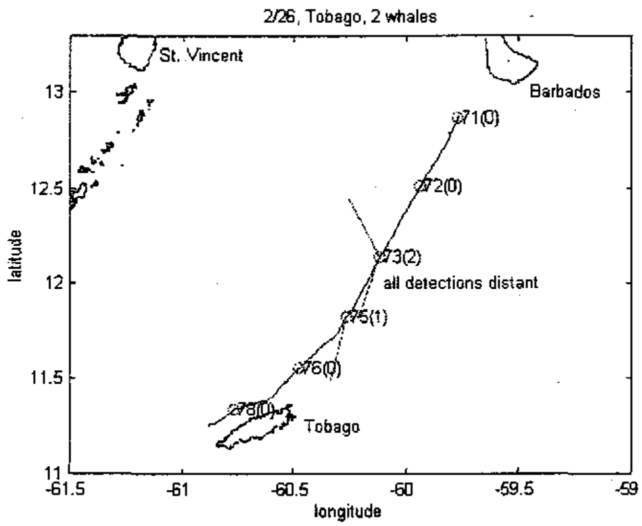
Figure 1.1-1.10. Sonobuoy locations and ship track around each island or survey region- leg 1.

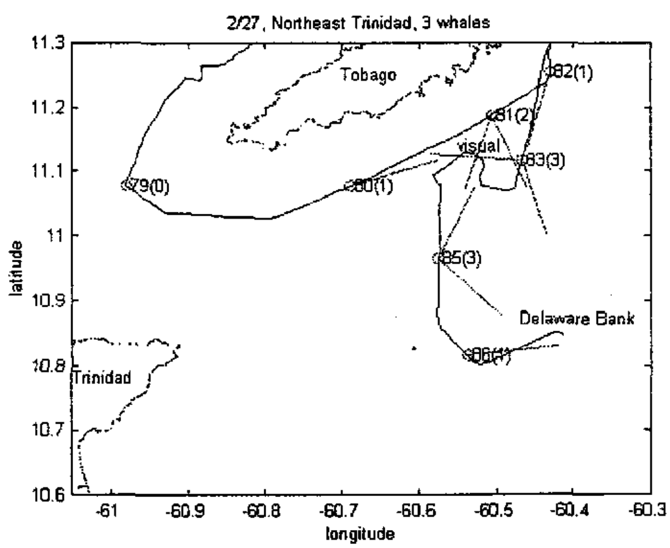



2/22, St. Lucia, 2 whales
latitude
longitude
51(0)
52(2)
53(1)
54(1)
55(0)
56(0)
57(1)

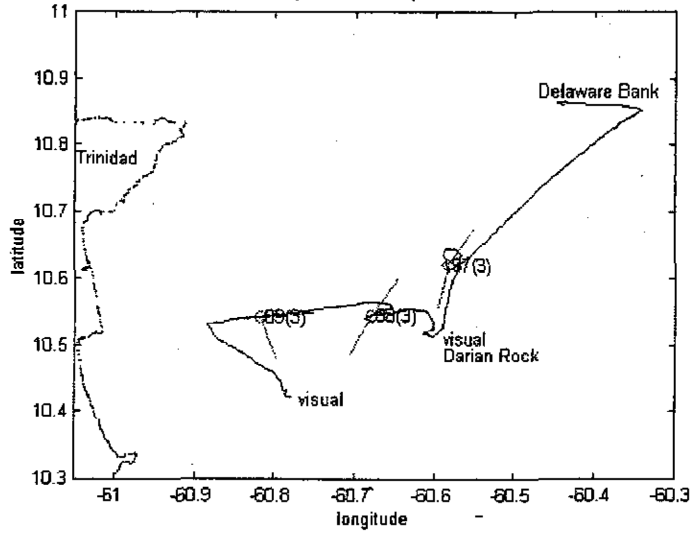

2/24, Barbados, 1 whale
latitude
longitude
64(0)
65(0)
66(0)
67(1)
68(1)
69(0)
70(0)


2/23 & 2/24, Grenada, 0 whales
58(0)
63(0)
62(0)
59(0)
61(0)
cow/calf visual
60(0)
latitude
longitude


2/26, Tobago, 2 whales
St. Vincent
Barbados
71(0)
72(0)
73(2)
all detections distant
75(1)
76(0)
78(0)
Tobago
latitude
longitude


2/27, Northeast Trinidad, 3 whales
Tobago
82(1)
81(2)
visual
83(3)
79(0)
80(1)
85(3)
Delaware Bank
86(1)
Trinidad
latitude
longitude

2/28, East Trinidad, 3 whales



Trinidad, 0 whales, 2/29

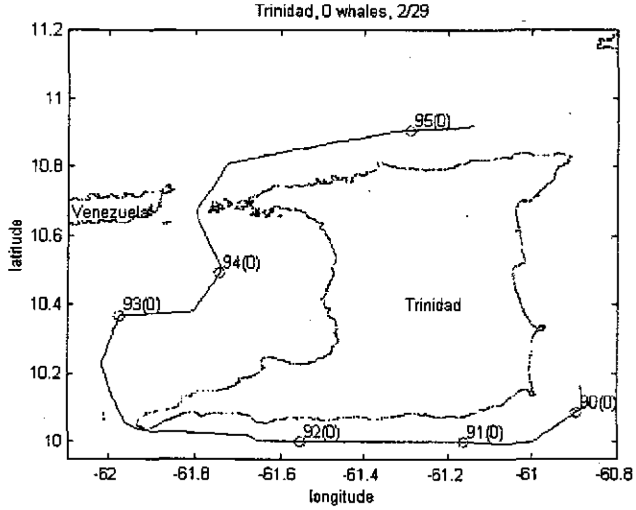
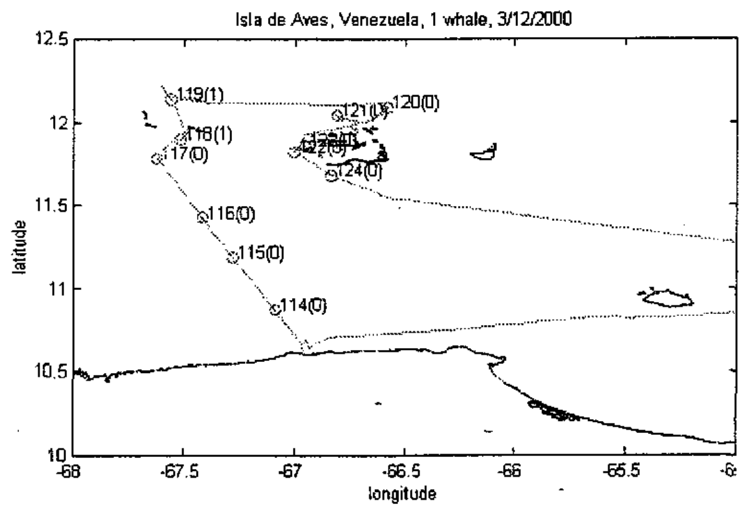
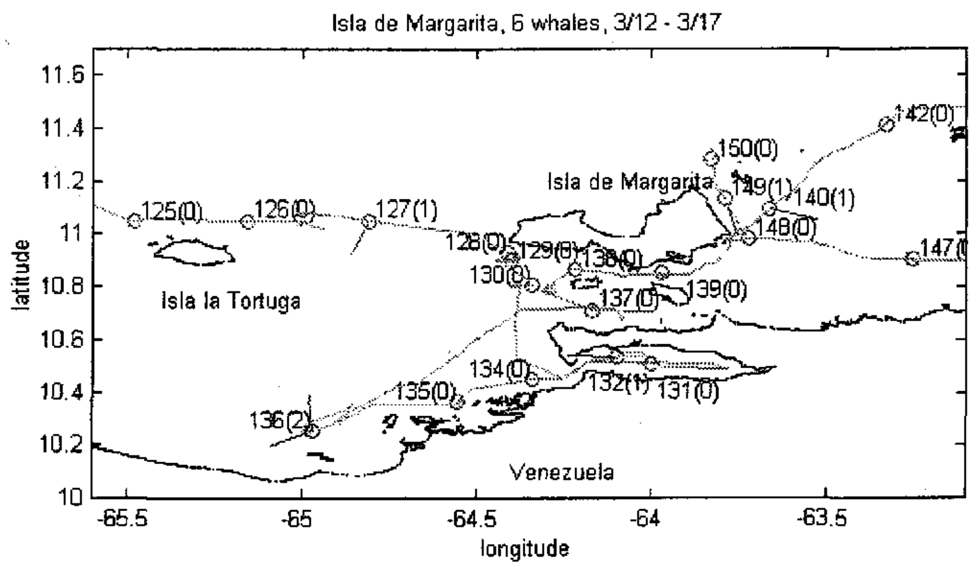
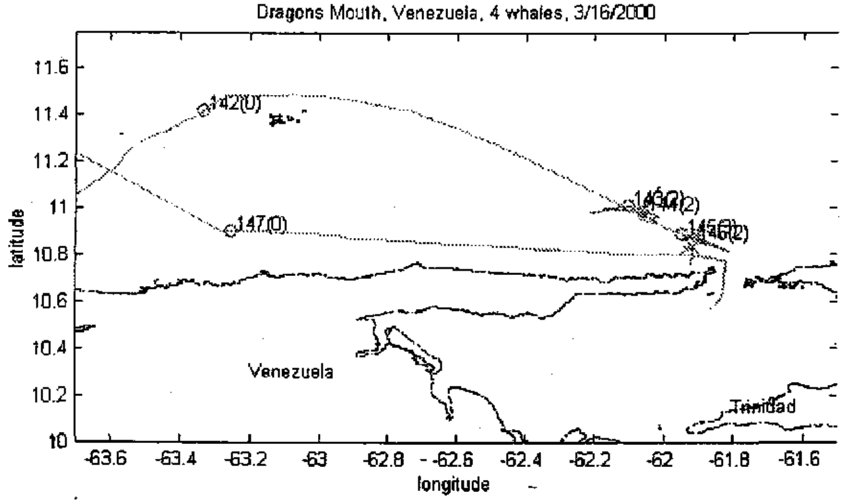


Figure 2.1-2.8. Sonobuoy locations and ship track line for each surveyed area- leg 2.

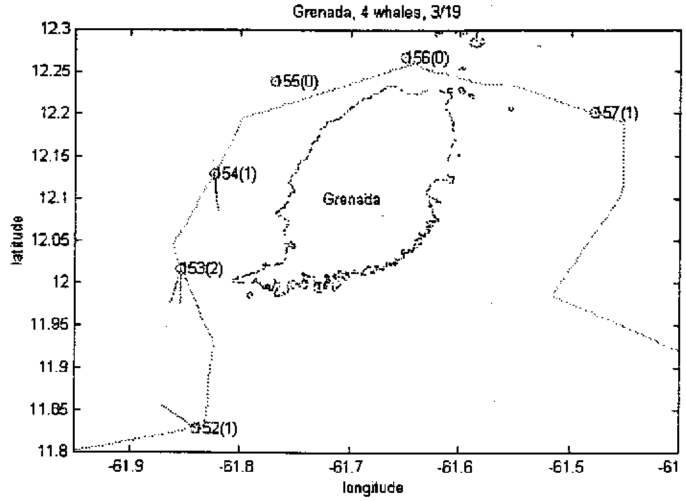




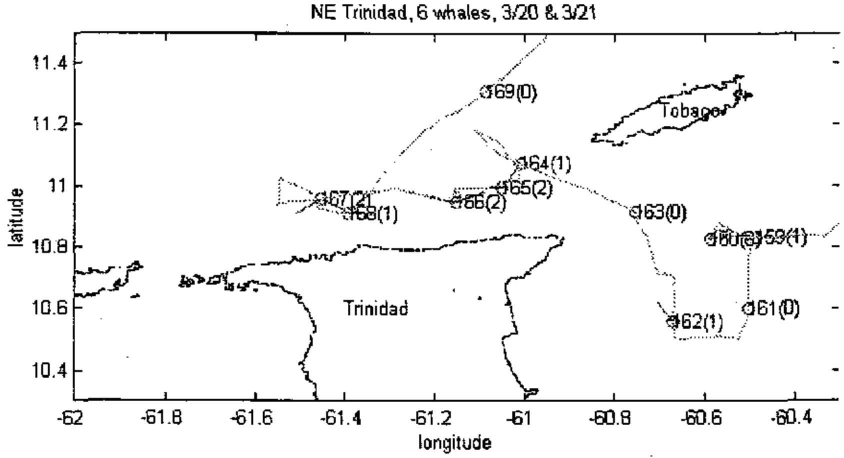
Dragons Mouth, Venezuela, 4 whales, 3/16/2000

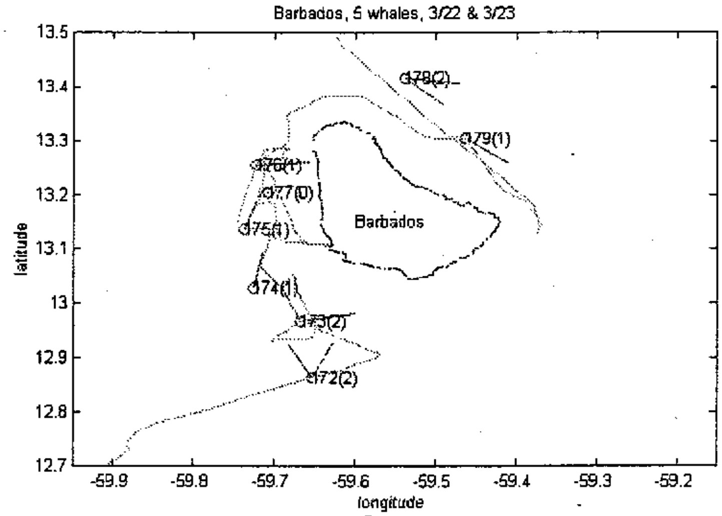


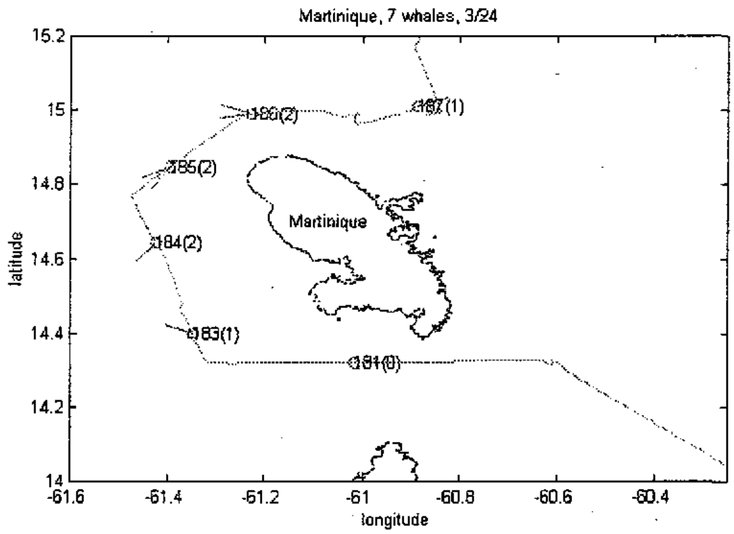
Grenada, 4 whales, 3/19



NE Trinidad, 6 whales, 3/20 & 3/21




Barbados, 5 whales, 3/22 & 3/23
Barbados
latitude
longitude
13.5
13.4
13.3
13.2
13.1
13
12.9
12.8
12.7
-59.9
-59.8
-59.7
-59.6
-59.5
-59.4
-59.3
-59.2


Martinique, 7 whales, 3/24
Martinique
latitude
longitude
15.2
15
14.8
14.6
14.4
14.2
14
-61.6
-61.4
-61.2
-61
-60.8
-60.6
-60.4

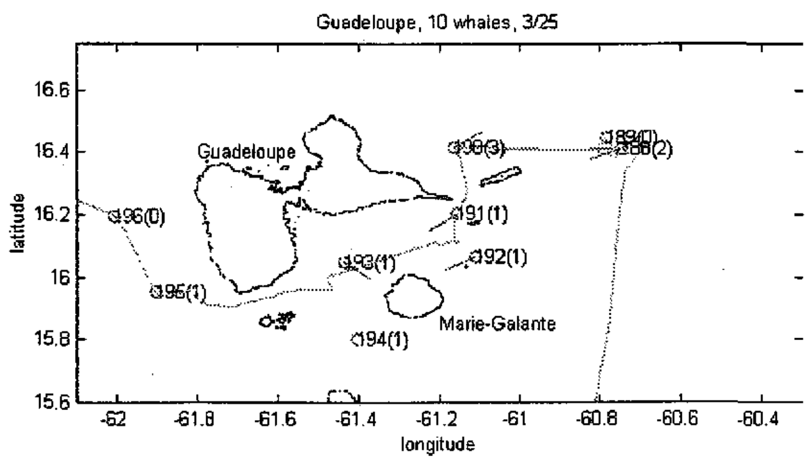
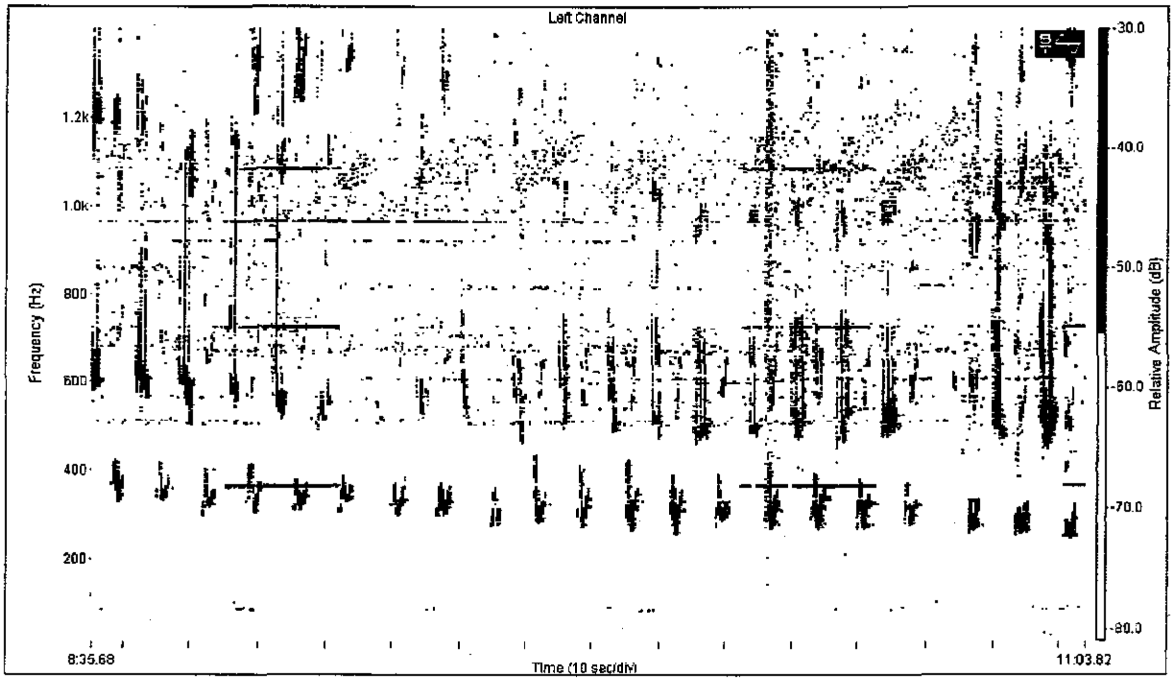
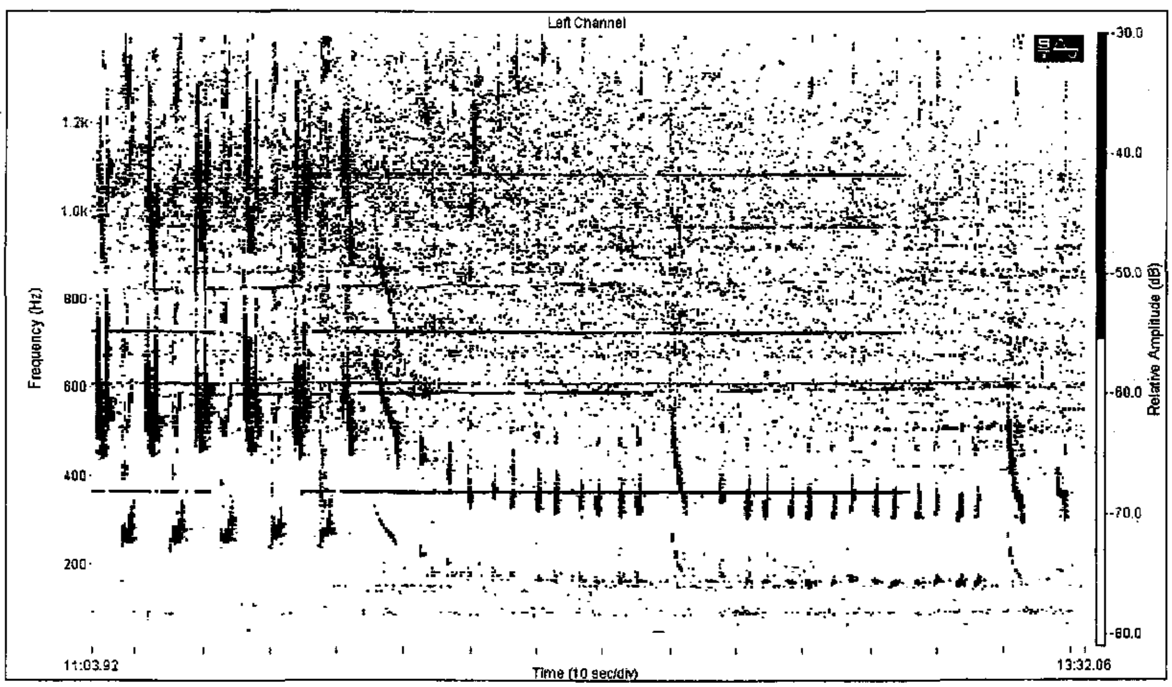
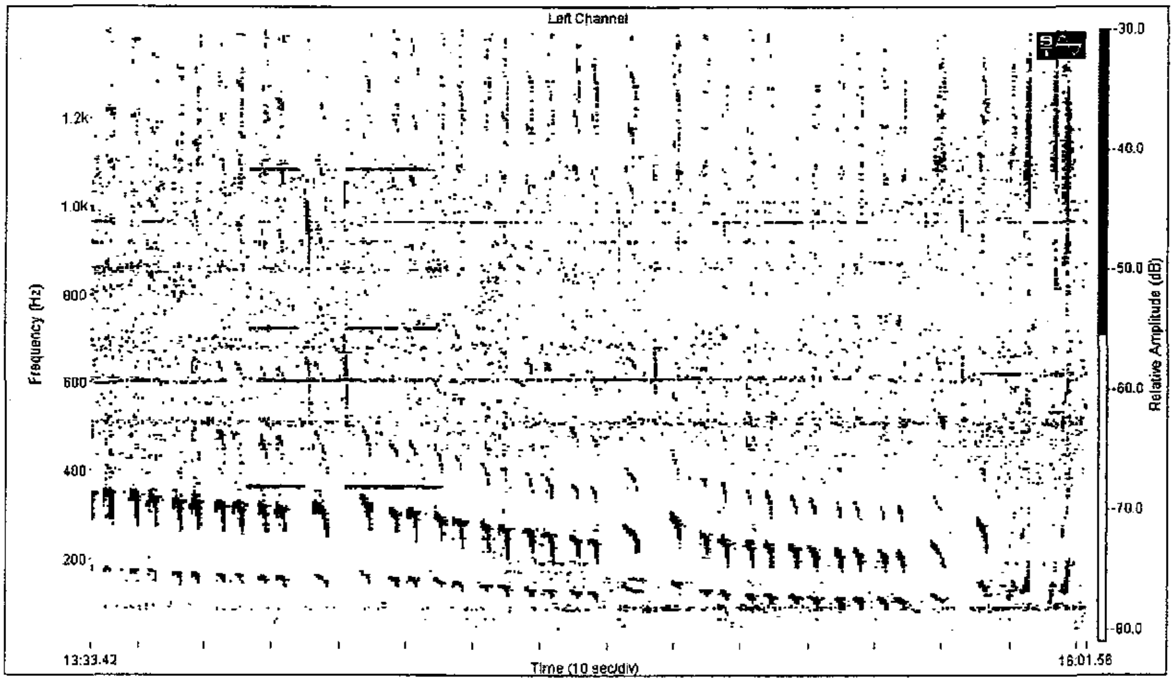
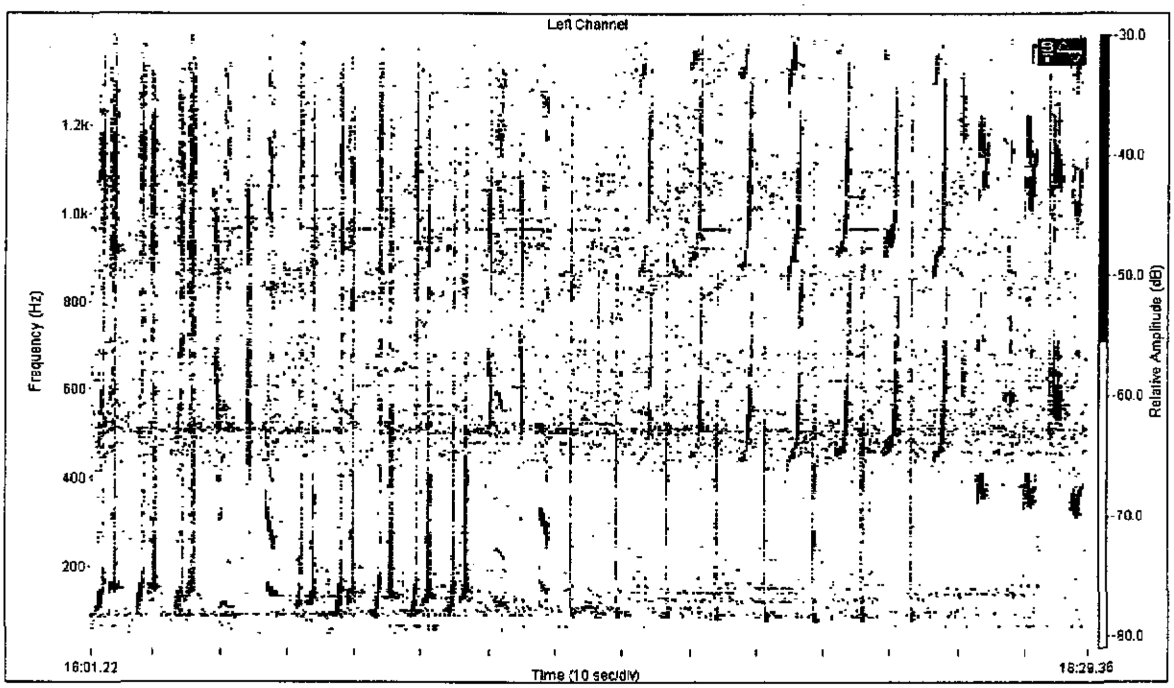

Guadeloupe, 10 whales, 3/25
Guadeloupe
Marie-Galante
latitude
longitude
16.6
16.4
16.2
16
15.8
15.6
-62
-61.8
-61.6
-61.4
-61.2
-61
-60.8
-60.6
-60.4

Figure 3 a,b,c,d. Spectrogram of frequently encountered humpback song during leg 2 of Windward Island survey. This particular song was recorded off the west coast of Barbados.






Left Channel
1.2k
1.0k
800
600
400
200
Frequency (Hz)
13:33.42
Time (10 sec/div)
16:01.56
-30.0
-40.0
-50.0
-60.0
-70.0
-80.0
Relative Amplitude (dB)


Left Channel
1.2k
1.0k
800
600
400
200
Frequency (Hz)
16:01.22
Time (10 sec/div)
18:29.36
-30.0
-40.0
-50.0
-60.0
-70.0
-80.0
Relative Amplitude (dB)