

## DIFAR HYDROPHONE USAGE IN WHALE RESEARCH

**Mark A. McDonald**

WhaleAcoustics, 11430 Rist Canyon Road, Bellvue, CO 80512, USA, [www.whaleacoustics.com](http://www.whaleacoustics.com)

### ABSTRACT

Directional Frequency Analysis and Recording (DIFAR) sonobuoys have been used by the Navy for many decades, providing magnetic bearings to low frequency (less than 4 kHz) sound sources from a single sensor. Computing advances have made this acoustic sensor technology increasingly easy to use and more powerful. The information presented here is intended to help new users determine when DIFAR sensors are or are not appropriate in whale acoustics research. Acoustic detection ranges for baleen whales average near 20 km but vary from 5 to 100 km depending on conditions. Radio reception range from DIFAR sonobuoys to a typical research vessel averages 18 km with an omni directional antenna on the ship and standard antenna on the sonobuoy. DIFAR bearing accuracy is analyzed for a set of whale calls where the track of the whale was well known. Bearings from the DIFAR sensor were found to have a standard deviation of 2.1 degrees. Systematic error and magnetic deviation can be removed using DIFAR bearings to the sound of the research vessel at a known location. A DIFAR sensor array requires fewer sensors than a conventional hydrophone array and sometimes provides more accurate source locations than the "time of arrival" hyperbolic methods used with conventional hydrophones. Continuous sounds such as ships are more easily localized with DIFAR sensors than with conventional hydrophones, because it is often difficult to find transient features upon which to estimate the time differences needed for hyperbolic fixing with a conventional hydrophone array. DIFAR hydrophone systems are well suited to right, blue, minke, fin and other baleen whale calls, as well as numerous other sound sources including ships.

### RÉSUMÉ

Les bouées acoustiques directionnelles DIFAR sont utilisées par la marine depuis plusieurs décennies, fournissant des relèvements magnétiques provenant d'un détecteur unique pour des sources sonores à basse fréquence (moins de 4 kHz). Les avancées computationnels ont fait de cette technologie un outil puissant et simple à utiliser. L'information présentée dans le présent article a pour but d'aider les nouveaux utilisateurs à déterminer quand les détecteurs DIFAR sont ou ne sont pas appropriés dans l'étude acoustique des baleines. La portée de détection acoustique pour baleines mysticètes atteint une moyenne voisine de 20 km mais varie de 5 à 100 km dépendant des conditions. La portée de la réception radio des bouées acoustiques à un navire de recherche typique atteint une moyenne d'environ 18 km avec une antenne omni directionnelle sur le bateau et une antenne standard sur la bouée acoustique. La précision du relèvement DIFAR est analysée pour un certain nombre de vocalisations de baleine où le parcours de la baleine est bien connu. Les relèvements provenant du détecteur DIFAR ont démontré une déviation standard de 2.1 degrés. Les erreurs systématiques et la déviation magnétique peuvent être corrigées en utilisant les relèvements DIFAR vers le son d'un navire de recherche qui a une position connue. Un réseau de détecteurs DIFAR a besoin de moins de détecteurs qu'un réseau d'hydrophones conventionnel et procure parfois une localisation de la source plus précise que la méthode hyperbolique des "temps d'arrivée" utilisée avec les hydrophones conventionnels. Les sons continus, comme ceux des bateaux, sont plus facile à localiser avec le détecteur DIFAR qu'avec les hydrophones conventionnels parce qu'il est souvent difficile de trouver des signaux transitoires permettant d'estimer les différences temporelles nécessaires pour le positionnement hyperbolique avec un réseau d'hydrophones conventionnel. Les systèmes d'hydrophones DIFAR conviennent aux vocalisations de baleines franches, bleues, de petits rorquals, rorquals communs et autres mysticètes, aussi bien qu'un bon nombre d'autres sons incluant les navires.

# 1. INTRODUCTION

Acoustic surveying for whales is becoming commonplace, either in conjunction with shipboard visual surveys or land based visual surveys or independently (Širović *et al.*, in press; Laurinolli *et al.*, 2003; McDonald and Moore, 2002; Noad and Cato, 2001; Clark and Ellison, 2000; Norris *et al.*, 1999). The tools for these acoustic studies include shore cabled hydrophones, autonomous hydrophone recorders, towed hydrophones, drifting sonobuoys and moored sonobuoys. Acoustic surveys can be used for line transect, relative, minimum and potentially even for absolute abundance estimation. In some cases acoustics are used to locate whales of a given species for biopsy, photo-id or tagging or to document the presence of migrating whales in locations which may not have any visual survey data.

For whale species which produce most of their acoustic calls above 200 Hz, conventional towed hydrophones work well. If a ship is also conducting a visual line transect survey with an emphasis on covering the greatest distance and the species of primary interest produce calls above about 200 Hz, the large number of sonobuoy deployments required is more expensive and less efficient than using a towed hydrophone array. For the species which call below 200 Hz, sonobuoys and fixed hydrophones have significant advantages over towed hydrophones, being more distant from the typically noisy research vessel and avoiding flow noise as it is costly to slow or stop the research vessel to better hear on towed hydrophones. A conventional hydrophone provides no directional information to localize low frequency acoustic sound sources unless it is used in an array the length of which is determined primarily by the frequency of the whale calls of interest and then the whale must call multiple times to break the left-right ambiguity inherent in direction finding with a single array.

A DIFAR sensor makes use of particle motion in the sea water due to acoustic wave propagation, allowing for a compact sensor which indicates horizontal direction to each sound source present (D'Spain, 1994; D'Spain *et al.*, 1991). DIFAR hydrophones are sensitive to overloading from motion and thus have not been suitable for use on a ship hull or in towed arrays. In fixed configurations, they typically must be shielded from current flow by some form of shroud.

The sensor portion of a DIFAR sonobuoy consists of two orthogonal horizontal directional acoustic particle velocity sensors, a magnetic compass, and an omni directional pressure sensor. Within conventional DIFAR sonobuoys the magnetic North-South (NS) and magnetic East-West (EW) components of particle motion are computed by the sensor electronics at the hydrophone, the three signals including pressure are multiplexed and transmitted by radio. In the case of autonomous recorders or dipping hydrophones the three data sets can be recorded separately without multiplexing. In a type 53 sonobuoy the frequency response begins to rolloff at about 2 KHz, but not rapidly, such that sufficient response remains to about 4 kHz if the sound source is relatively loud.

A disadvantage of a DIFAR sensor when compared to ordinary hydrophones is that it requires three times the data bandwidth, with all three of the output channels, pressure, East-West particle motion and North-South particle motion being required to compute an unambiguous bearing (D'Spain, 1994). DIFAR sonobuoys of type AN/SSQ53B, AN/SSQ53D and AN/SSQ53E were used in the work presented here, the author having deployed nearly 500 of these in the course of various whale research projects. In a type 53 sonobuoy, the useful bandwidth of about 4 kHz takes up nearly 20 kHz of bandwidth after the analog multiplexing done by the electronics built in to the sensor head.

## 2. PROCESSING AND PERFORMANCE

### 2.1. Demultiplexing and Display

Commercial software from GreeneRidge Sciences Inc. was used to process raw DIFAR sonobuoy signals into three channels, 1) east-west particle motion, 2) north-south particle motion and 3) omni-directional pressure. Direction finding theory and methods for DIFAR sonobuoy processing are discussed in the published literature (D'Spain *et al.*, 1991; D'Spain *et al.*, 1992; D'Spain *et al.*, 1994). A MATLAB program was written based on the published theory to compute bearings to sound sources.

Processing speed for demultiplexing and bearing computation is faster than real time, although applications used to date always use a human operator selecting segments of data from a spectrogram and keeping each calling animal tracked on a plot or chart. Prior to about 1992 DIFAR processing was done in hardware rather than software, making processing more expensive and less flexible.

A typical DIFAR blue whale recording is shown in Figure 1, illustrating overlapping whale calls and ship noise.

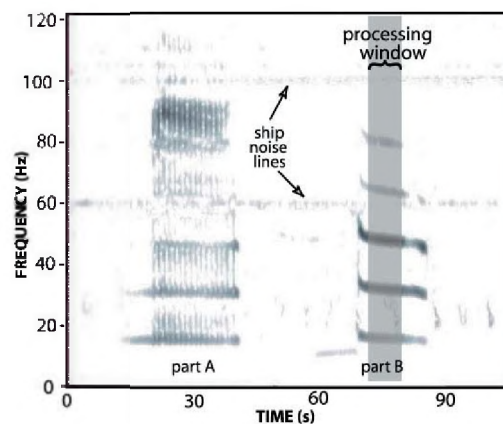


Figure 1. This spectrogram shows a Northeastern Pacific blue whale call which is used to illustrate bearing processing with multiple sound sources.

The display options for illustrating sound source bearings from sonobuoy data are nearly endless given the three independent variables, magnetic bearing, frequency and some measure of energy over time. The work presented here uses an averaged output for a given duration of data plotted as frequency versus azimuth (Figure 2). The sound source bearings are picked from the plot with a cursor.

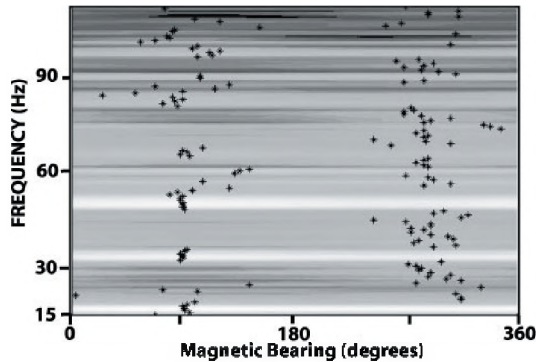


Figure 2. Bearing plot for six seconds of data containing a blue whale "B" call, as shown in Figure 1. Bearing is seen as high energy at the frequency bands of the sound source observed in the spectrogram. The asterisks mark the highest energy in each frequency bin. Lighter color indicates higher energy. This blue whale call is found at 95 degrees. The energy near 290 degrees is from the research ship.

## 2.2. Bearing Accuracy

In October of 1997 sonobuoy recordings of blue whales were collected during a whale photo-id cruise. A goal of this cruise was to acoustically record and genetically sample blue whales to examine sex bias in calling behavior, requiring localization of each acoustic call (McDonald *et al.*, 2001). A whale track was determined by recording the GPS position of the final surfacing of each surface sequence from a small boat following the whale. Whale positions at the time of each call are interpolated between surfacing's. Only one whale track was used for the analysis presented here, that being whale number one in McDonald *et al.* (2001). Overlapping calls from multiple animals always resulted in two distinct correct bearings, rather than a weighted average bearing between the two whales, which might have been supposed from theory.

DIFAR sonobuoy bearings are compared to bearings computed using GPS coordinates in Figure 3.

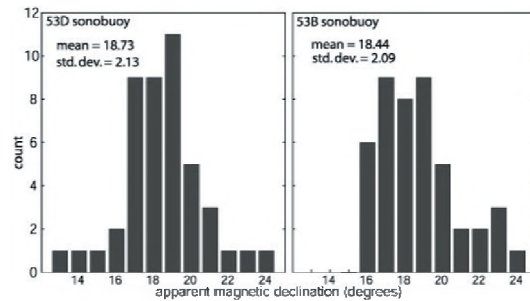


Figure 3. Difference between sonobuoy bearing and GPS bearing are plotted as histograms uncorrected for magnetic declination for two different sonobuoys, one type 53D and one type 53B. These data are for blue whale type "A" and "B" calls. The navigation chart for this area indicates the magnetic declination to be 17 degrees with significant local variability.

These calls were recorded at ranges from 3 km to 8 km. Short range calls were discarded because the whale position errors translate to increasingly large bearing errors at short ranges, these errors becoming potentially greater than the DIFAR bearing errors. One standard deviation of these data is 2.1 degrees, well within the sonobuoy specification requirement for a maximum error of 10 degrees. In this case the different model sonobuoys had very similar mean values (18.7 and 18.4) suggesting the compasses were either correct or had very nearly the same error. The two sonobuoys used were different models, manufacturers and vintages, so it is unlikely there was a common error. The standard deviation being acceptably small, methods of improved processing or bearing picking algorithms may be possible. Bias error may be related to sensor construction (i.e. compass not mounted accurately) and/or to uncertainty in the actual deviation of the earth's magnetic field from true north.

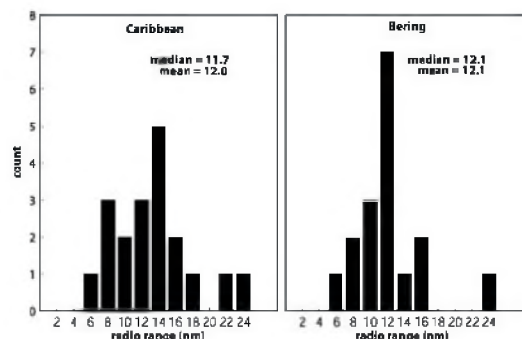
## 2.3. Sonobuoy Radio Range

Production type 53 sonobuoys use a one watt VHF radio transmitter and an antenna only about 0.5 meters above sea level at its top. Radio frequencies are selectable between 136 and 172 MHz. Commercial VHF radios intended primarily for voice communication are typically not acceptable for sonobuoy work because the frequency response of the audio sections in these are limited to the band needed for intelligible voice communication only. GrenneRidge Sciences provided modified ICOM commercial radios used for this work. Receiver sensitivity is not though to be a primary factor in determining the working radio range of these sonobuoy systems.

Experience tells us the VHF radio range from these buoys is not determined strictly by line of sight between the two antennas as even the average radio ranges for a 3 dBi antenna are well beyond line of sight. Radio ranges are plotted in Figure 4 for two different cruises. Note that in

each case there are occasional ranges out to 24 nautical miles, about twice the average.

Experience suggests the greatest factor in radio reception range is atmospheric conditions, the detection ranges typically being similar on a given day and often changing when the weather changes. This phenomenon is well known to VHF radio hobbyists. Good conditions are most often thought to be caused by tropospheric enhancement, often associated with temperature inversions (Pocock, 1992). Equally important is receiving antenna gain, although practicality often dictates using a relatively low gain (3 dBi) omni directional antenna which allows maneuvering the vessel without the need to rotate a directional antenna. These low gain antennas also stand up well to wind and icing conditions.



**Figure 4. Radio reception distances from DIFAR sonobuoys are plotted for two cruise legs, one in the southern Caribbean and one in the Bering Sea. Antenna heights were 61 ft. (18.6 m) in the Bering Sea and 85 ft. (25.9 m) in the Caribbean. The same 3 dBi gain antenna was used on both cruises and average reception range was 12 nautical miles (22 km).**

Comparison of an omni antenna with 3 dBi gain against a YAGI antenna with 12 dBi gain, typically results in more or less a doubling of effective range, assuming the YAGI is correctly pointed at the sonobuoy. The least important factor appears to be sea state or swell height as long as sea state is below 6. At or above sea state 6, it appears the sonobuoy suspension no longer functions well and buoys have a high failure rate in addition to much higher noise levels.

### 3. APPLICATIONS

#### 3.1. Detection Ranges for Baleen Whales

Detection ranges vary for many reasons including 1) ambient noise due to ships, ice or sea state, 2) acoustic propagation being relatively good or bad, good typically because of an isothermal surface layer creating a sound channel with both receiver and whale in it, or a flat bottom shallow water sound channel or bad because of irregular seafloor bathymetry or a shadowing sound speed profile and 3) the source level of the whale calls. Listed in Table 1 are observed detection ranges with corresponding estimates of ambient noise level and propagation environment for each case.

There are descriptions of detections of baleen whale calls at many hundreds of kilometers range (Charif, *et al.*, 2001; Stafford *et al.* 1998), but often these use hydrophone arrays with substantial gain and/or are in the deep sound channel and are thus not applicable comparisons for hydrophone or single sonobuoy recordings.

species	location	Range (km)	ambient noise	propagation	References
humpback	Caribbean	50 +	moderate	good, surface sound channel	Swartz <i>et al.</i> , 2003; McDonald <i>et al.</i> 2000
right	Bering	50 +	low to mod.	excellent, shallow water wave guide	McDonald and Moore, 2002; Wiggins <i>et al.</i> , this issue
right	off Cape Cod	5-10	high, shipping	poor, rugged bathymetry	IFAW, 2001; Doug Gillespie, Pers. comm.
blue	NE Pacific	20	moderate	moderate to poor, shadowing sound speed profile	McDonald <i>et al.</i> , 2001; unpublished authors data
blue,	Antarctic	60-100	low	moderate, surface trapped sound speed profile	Širović <i>et al.</i> , in press; unpublished authors data
fin,	NE Pacific	20	moderate	moderate to poor, shadowing sound speed profile	McDonald and Fox, 1999
sperm, male	N. Pacific	30-40	moderate	moderate, deep sound source	Barlow and Taylor, 1998
Sperm, female	N. Pacific	5-10	moderate	Moderate, deep sound source	Barlow and Taylor, 1998

**Table 1. Acoustic detection ranges for various whale species based on observations, noting qualitatively both noise environment and propagation. Some estimates are based on hydrophones other than DIFAR sonobuoys. Beam steering gain from DIFAR sensors was not used in generating this table, but could improve detection ranges beyond the values given here. Source levels and call frequencies are not tabulated, but play an important role.**



### 3.2. Localization

Hyperbolic fixing depends on finding the arrival time difference for a whale call between two or more hydrophones to solve for a location. To localize a whale call with hyperbolic fixing requires three sonobuoys or hydrophones in a good geometry while only two DIFAR sensors in a good geometry are required for localization. This important distinction is often critical to obtaining a good call location.

In the case of the blue whale calls presented in McDonald *et al.* (2001), both hyperbolic and DIFAR bearing localization was applied. The multi-path environment combined with the long duration of the blue whale calls resulted in average time difference errors of about one second while the time difference between array elements was only a few seconds. While these results are not necessarily typical of all arrays or all types of whale calls, it does demonstrate a significant advantage with DIFAR sensors in many baleen whale localization arrays. If even only one DIFAR sensor is employed in a two hydrophone array, a call location can be determined, given a good array geometry.

### 3.3. Sperm Whales

DIFAR sonobuoys have sufficient frequency response to about 4 kHz such that DIFAR localization works well for the lower frequency sounds of killer, and pilot whales and would appear to adequately record the lower frequency sounds of sperm whales.

Very short duration whale calls such as sperm whale clicks have never produced good bearings on DIFAR sonobuoys in the experience of the author. The reasons are unclear, but it may have to do with either the short duration of the signal or with the fact these whales are often producing their clicks at depths comparable to the horizontal ranges, resulting in a significant vertical angle to the incoming acoustic energy.

### 3.4. Directivity Index

Beam steering of DIFAR sensors is a simple matter in software and potentially provides over 4 dB of directivity index gain from the resulting cardioid beam pattern. While beam steering of sonobuoys is undoubtedly useful in some situations, it would appear to require a level of adaptive processing beyond that which has been used to date in whale research.

## 4. SUMMARY

DIFAR sonobuoys are not the ideal tool for every whale acoustics research question, but are irreplaceable in certain applications. An example of a near ideal application would be locating right whales in the Bering Sea for photo-id, biopsy or tagging studies (McDonald and Moore, 2002).

Right whale calls are mostly below 200 Hz where towed array performance suffers from flow noise and ship noise. The propagation environment in the Bering Sea allows long distance reception and mode dispersion allows range estimation from a single hydrophone (Wiggins *et al.*, this issue). Because visual searching stops for darkness and the ship stops also, a single sonobuoy stays within radio range, and it has often been possible to locate calling animals acoustically during the night such that the ship can plan to arrive in the vicinity of the whale or whales the following morning.

Bering Sea right whale calls occur infrequently and often in clusters from widely separated counter-calling animals. A single towed array would not be suitable for locating these animals because of the inherent left-right ambiguity. A double towed array would add expense and logistical difficulty.

An intermediate application might be the survey of humpback whales in the Southern Caribbean (Swartz *et al.*, 2003), where either a towed array or DIFAR sonobuoys could provide a good acoustic survey with similar logistical effort and cost. A clear advantage goes to towed arrays for sperm whale surveys.

When the goals of a whale acoustics research project are clearly defined, the information presented here should help the potential DIFAR user compare the logistical effort of using DIFAR sonobuoys versus using some other acoustic method such as a towed array system. The performance results presented here for DIFAR sonobuoys and DIFAR sensors provide guidelines for what can be accomplished with a given effort for a number of different species of whales.

## 5. REFERENCES

- Barlow, Jay and Barbara L. Taylor. Preliminary abundance of sperm whales in the northeastern temperate Pacific estimated from a combined visual and acoustic survey. International Whaling Commission, Scientific Committee document SC/50/CAWS20, 19p. 1998.
- Charif, R.A., Clapham, P.J. and C.W. Clark. Acoustic detections of singing humpback whales in deep waters off the British Isles. *Mar. Mamm. Sci.* **17**(4):751-768. 2001.
- Clark, C.W. and W.T. Ellison. Calibration and comparison of the acoustic location methods used during the spring migration of the bowhead whale, *Balaena mysticetus*, off Pt. Barrow, Alaska, 1984-1993. *J. Acoust. Soc. Am.*, **107**(6), 2000, p.3509-3517. 2000.
- Stafford, K.M., C.G. Fox, and D.S. Clark. Long-range detection and localization of blue whale calls in the northeast Pacific Ocean. *J. Acoust. Soc. Am.*, **104**(6), 3616-3625, 1998.
- D'Spain, G.L., Relationship of Underwater Acoustic Intensity Measurements to Beamforming, *Canadian Acoustics*, **22** (3), 157-158, 1994.
- D'Spain, G.L., W.S. Hodgkiss, and G.L. Edmonds, Energetics of the deep ocean's infrasonic sound field, *J. Acoust. Soc. Am.*, **89**(3), 1134-1158, 1991.

D'Spain, G.L., W.S. Hodgkiss, G.L. Edmunds, J.C. Nickles, F.H. Fisher, and R.A. Harris, Initial Analysis of the data from the Vertical DIFAR Array, in *Mastering the Oceans through Technology (OCEANS 92)*, pp. 346-351, I.E.E.E., Newport, Rhode Island, 1992.

IFAW, Report of the Workshop on Right Whale Acoustics: Practical Applications in Conservation. (eds. Gillespie, D., and Leaper, R.) International Fund for Animal Welfare, Yarmouth Port, MA. 27pp., 2001.

Pocock, E., The weather that brings VHF DX, pp. 21-26 in "Beyond Line of Sight: A history of VHF Propagation from the pages of QST", American Radio Relay League, Newington, CT., 1992

Swartz, S.L., Cole, T., McDonald, M.A., Hildebrand, J.A., Oleson, E.M., Martinez, A., Clapham, P.J., Barlow, J. and Jones, M.L., Acoustic and Visual Survey of Humpback Whale (*Megaptera Novaengliae*) Distribution in the eastern and Southeastern Caribbean Sea. *Caribbean Journal of Science*, **39**(2), pp. 195-208, 2003.

Laurinolli, M. H., A. E. Hay, et al.. Localization of North Atlantic right whale sounds in the Bay of Fundy using a sonobuoy array. *Mar. Mammal Sci.* **19**(4): 708-723, 2003.

McDonald, M. A. and S. E. Moore, Calls recorded from North Pacific right whales (*Eubalaena japonica*) in the eastern Bering Sea, *J. Cetacean Res. Manage.* **4**(3): 261-266, 2002.

McDonald, M. A., Calambokidis, J., Teranishi, A. M. and Hildebrand, J.A. The Acoustic Calls of Blue Whales off California with Gender Data, *J. Acous. Soc. Am.*, **109**(4), pp. 1728-1735, 2001.

McDonald, M.A., Oleson, E. M., and Hildebrand, J.A., Windwards 2000 Acoustic Cruise Report, NOAA Technical Memorandum NMFS-SEFSC-441, 32 pp., U.S. Dept. of Commerce, May 2000.

Norris, T. F., Mc Donald M. and Barlow J., Acoustic detections of singing humpback whales (*Megaptera novaeangliae*) in the eastern North Pacific during their northbound migration. *J. Acoust. Soc. Am.* **106**(1): 506-514, 1998.

Noad, M.J., and Cato, A combined acoustic and visual survey of humpbacks off southeast Queensland, *Memoirs of the Queensland Museum* **47**(2):145-161. 2001.

Širović, A., Hildebrand J. A., Wiggins, S.M., McDonald M.A., Moore S.E., and Thiele, D. Seasonality of blue and fin whale calls west of the Antarctic Peninsula, Deep Sea Research II, in press.

Wiggins, S.M., McDonald, M.A., Munger, L.A., Hildebrand, J.A. and Moore, S.E. Waveguide propagation allows range-dependent estimates for North Pacific right whales in the Bering Sea, *Canadian Acoustics*, **32** (2), 2004.

reviewers. The author thanks the National Marine Fisheries Service for financial support and specifically Jay Barlow, Sue Moore and Steve Swartz for their encouragement throughout this work.

## ACKNOWLEDGEMENTS

Thanks to Charles Greene and Gerald D'Spain for help in understanding DIFAR processing, to John Hildebrand for supporting the sonobuoy field work and to two anonymous