

# **Bioacoustic Absorption Spectroscopy**

Dr. Orest Diachok  
Acoustics Division, Code 7120  
Naval Research Laboratory  
Washington, D.C., 20375

phone: 202 404 4650 fax: 202 404 7813 e-mail: [orest@wave.nrl.navy.mil](mailto:orest@wave.nrl.navy.mil)

Document numbers: N0001403WX20457 (Biology), N0001403WX20780 (Acoustics)

## **LONG TERM GOAL**

Demonstrate the potential of bioacoustic absorption spectroscopy for tomographic mapping of the bioacoustic parameters of fish with swim bladders in shallow water.

## **OBJECTIVES**

Develop a propagation model that accounts for the effects of bioacoustic absorptivity on transmission loss in shallow water at frequencies between 0.2 and 10.0 kHz. Develop a bioacoustic model that accounts for the resonance frequencies of absorption lines, which are due to dispersed pelagic fish, and schools of pelagic fish with swim bladders. Develop a model of the seasonal variability of resonance frequencies. Demonstrate consistency between absorptivity and echo sounder based estimates of number densities.

## **APPROACH**

Design, construct and employ ultra-broadband (0.2 – 10 kHz), lightweight, long term, autonomous source and receiving arrays that permit inversion of bio-acoustic parameters from transmission loss (TL) measurements. Conduct a series of bio-acoustic absorptivity experiments in the Santa Barbara Channel (BAS I and II) in littoral seas in co-operation with fisheries biologists from the Southwest Fisheries Science Center. Develop a TL model that includes multiple bio-acoustic absorbing layers. Apply model to new and previously published bio-acoustic absorptivity measurements, and derive bio-acoustic parameters of sardines and anchovies and other fish. Formulate methods for classification of absorption lines due to fish with swim bladders, including frequency downshifted lines due to schools. Demonstrate consistency of estimated bio-acoustic parameters with trawling and echo sounder data recorded during BAS I and II, and geo-acoustic parameters, which were made with a “chirp” sonar during BAS III.

## **WORK COMPLETED**

The second bio-acoustic absorption spectroscopy experiment, BAS II, which employed the recently developed ultra-broadband source and receiving array, was conducted in the Santa Barbara Channel in August 2002. The array was 45 m long and consisted of 16 elements with an inter-element spacing of 3 m. Hydrophones were deployed at depths between 8 and 53 m. The source depth was 9 m. The separation between the source and array was 3.8 km, and the water depth was 63 m. Trawls provided estimates of the modal lengths of year classes of sardines and anchovies. A scientific echo sounder

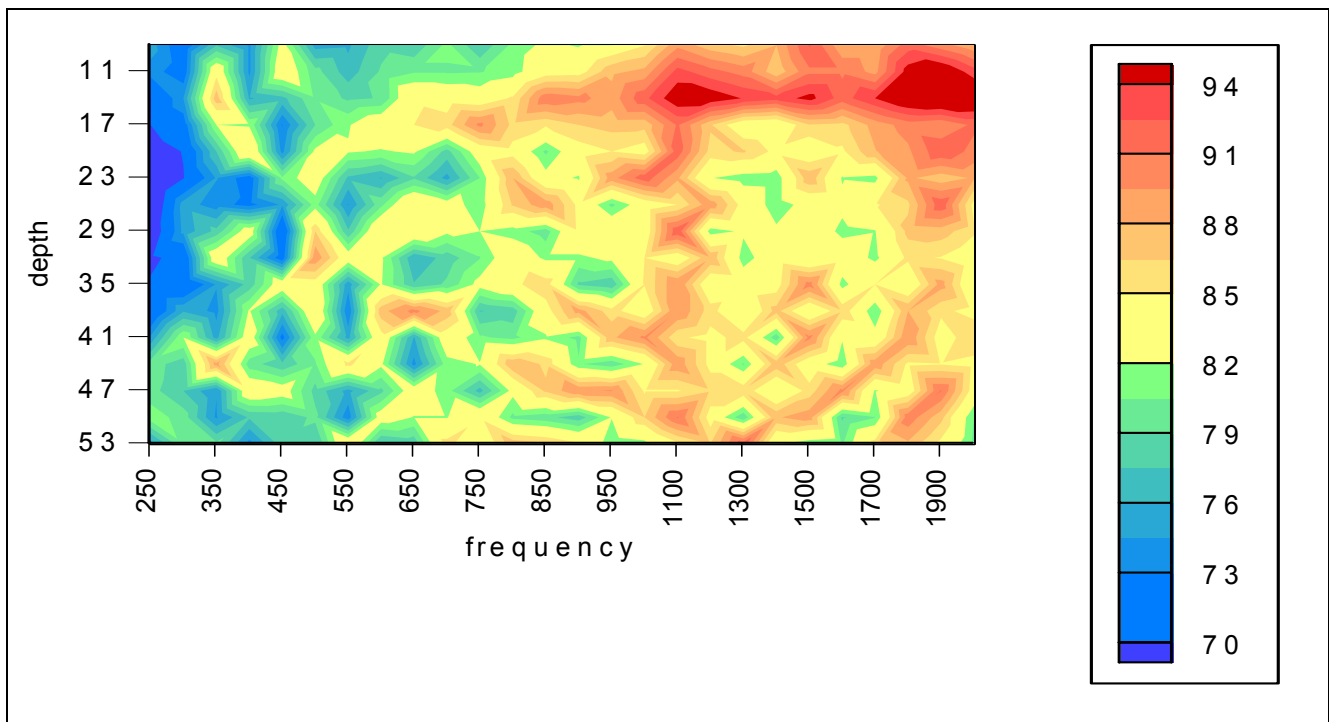
## Report Documentation Page

*Form Approved*  
*OMB No. 0704-0188*

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE <b>30 SEP 2003</b>	2. REPORT TYPE	3. DATES COVERED <b>00-00-2003 to 00-00-2003</b>			
4. TITLE AND SUBTITLE <b>Bioacoustic Absorption Spectroscopy</b>		5a. CONTRACT NUMBER			
		5b. GRANT NUMBER			
		5c. PROGRAM ELEMENT NUMBER			
6. AUTHOR(S)		5d. PROJECT NUMBER			
		5e. TASK NUMBER			
		5f. WORK UNIT NUMBER			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>Acoustics Division, Code 7120,,Naval Research Laboratory,,Washington,,DC,20375</b>		8. PERFORMING ORGANIZATION REPORT NUMBER			
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)			
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)			
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT <b>Demonstrate the potential of bioacoustic absorption spectroscopy for tomographic mapping of the bioacoustic parameters of fish with swim bladders in shallow water.</b>					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>	<b>Same as Report (SAR)</b>	<b>9</b>	

provided information on depth distributions of biological scattering layers. Figure 1 shows TL vs. depth and frequency at night. The frequencies of absorption lines at 1.1, 1.5 and 1.9 kHz at 14 m were consistent with the presence of 15 cm long sardines and 12 and 10 cm long anchovies respectively. This interpretation was based on theoretical calculations, which indicated that transmission loss is maximum at the depth of the absorbing layer. The inferred depth was consistent with modal depth of biological scattering layers, which was determined from echo sounder measurements. Absorption lines at frequencies below the resonance frequencies of individual sardines, viz., at 0.85 kHz at 14 m and 0.75 kHz at 17 m, were consistent with the presence of schools of sardines, as shown in Figure 2.



**Figure 1. Transmission loss vs. frequency and depth at 3.8 km averaged over 2 hrs at night during BAS II. Frequencies of absorption lines at 1.1, 1.5 and 1.9 kHz at 14 m are consistent with resonance frequencies of 15 cm sardines and 12 and 10 cm anchovies respectively. Low frequency lines at 0.85 and 0.75 kHz are consistent with schools of 15 cm sardines (Diachok, 1999). Calculations suggest that lower level maxima at other depths are associated with the vertical distributions of the amplitudes of normal modes.**

BAS II included time series temperature measurements on 3 orthogonal, vertical temperature strings (the spacing between strings was 2 km), which permitted monitoring the intensity and direction of tidally induced changes in sound speed profiles. Tidally generated solibores propagated normal to the acoustic propagation path; consequently mode coupling may be disregarded in theoretical calculations of acoustic fields. Measurements at 250 Hz, which were not affected by bio-absorptivity, reflected solibore-induced changes in the depth of the mixed layer. Measurements at higher frequencies reflected changes in the depth of the mixed layer and changes in the depths of sardines.

Absorption lines associated with anchovies did not change with time, which indicates that anchovies did not undergo vertical migration during this experiment. This is consistent with Mais' (1974)

observation that anchovies do not undergo vertical migrations in the Santa Barbara Channel. Differences in the vertical migration patterns of sardines and anchovies at this site may be due to differences in the migration patterns of their prey.

A third experiment, BAS III, which was designed to measure the geo-acoustic parameters of the bottom at the BAS II site with “chirp” sonar and cores, was conducted in July 2003. The resultant geo-acoustic parameters will serve as inputs for calculation of replica fields for derivation of bio-acoustic parameters.

## RESULTS

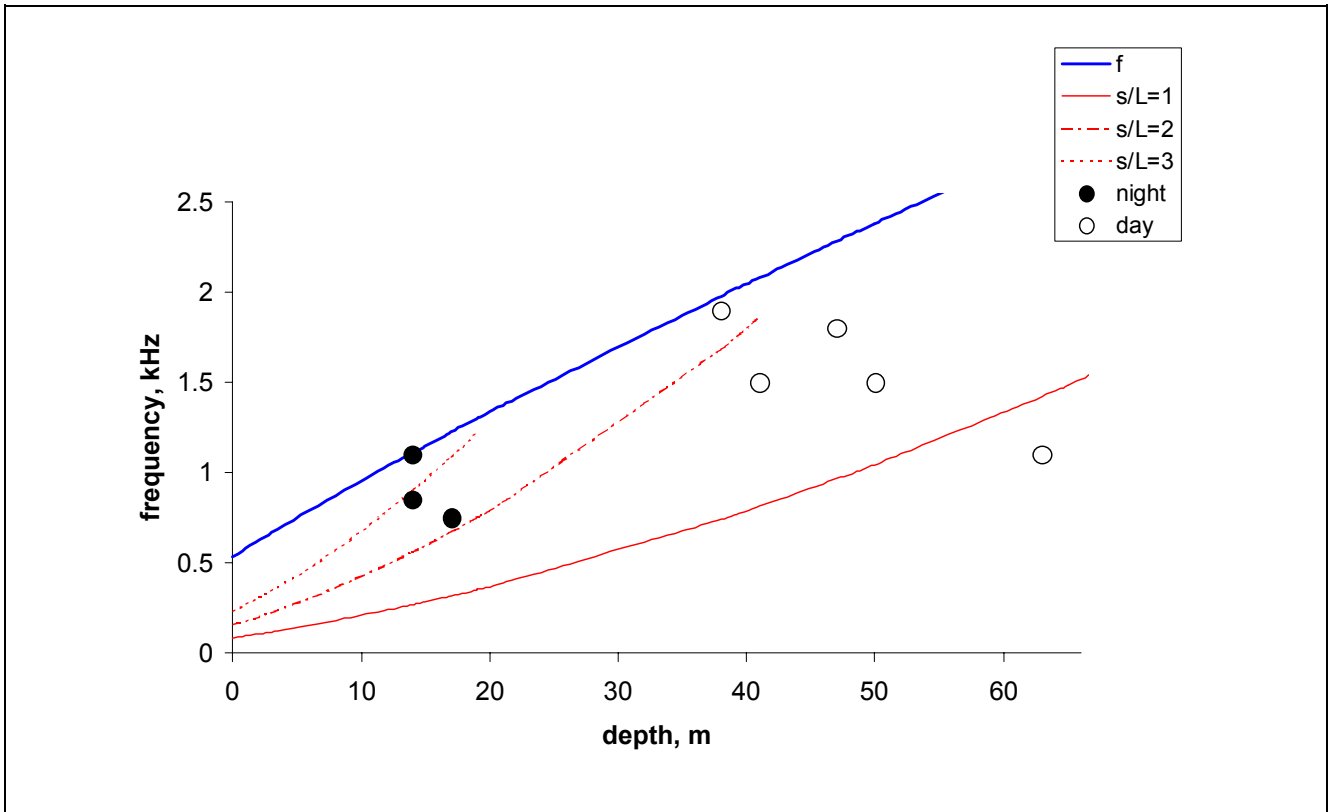
An inversion algorithm has been developed that permits concurrent estimation of bio-acoustic parameters of fish with swim bladders and geo-acoustic parameters of the bottom from TL measurements made between multiple source and receiver depths. The inversion is based on minimizing the rms difference,  $\Delta$ , between measured and calculated values of TL at all ranges and depths, and involves a simultaneous search for biological layer depth, layer thickness and bio-absorption coefficient, and geo-sound speed and geo-alpha. This new method for isolation of the causes of attenuation, and classification of absorption lines is more robust than “classification by observation of frequency shifts at twilight”, since the latter is not suitable for fish, which do not undergo vertical migration.

This algorithm was first applied to measurements made by Qiu et al. (1999) in the Yellow Sea. Inverted bio and geo-acoustic parameters were consistent with historical measurements of in this region. In particular, inferred lengths of anchovies and number densities were shown to be comparable to previously reported trawling and echo sounder measurements of anchovies (Ohshimo, 1996; and Iverson et al., 1993); and the inferred sound speed in the bottom and geo-alpha were shown to be comparable to previously reported measurements of these parameters in the Yellow Sea (Dahl et al., 1998; and Rogers et al., 2000). These results have been documented in a manuscript, which has been accepted for publication in the Journal of the Acoustical Society of America.

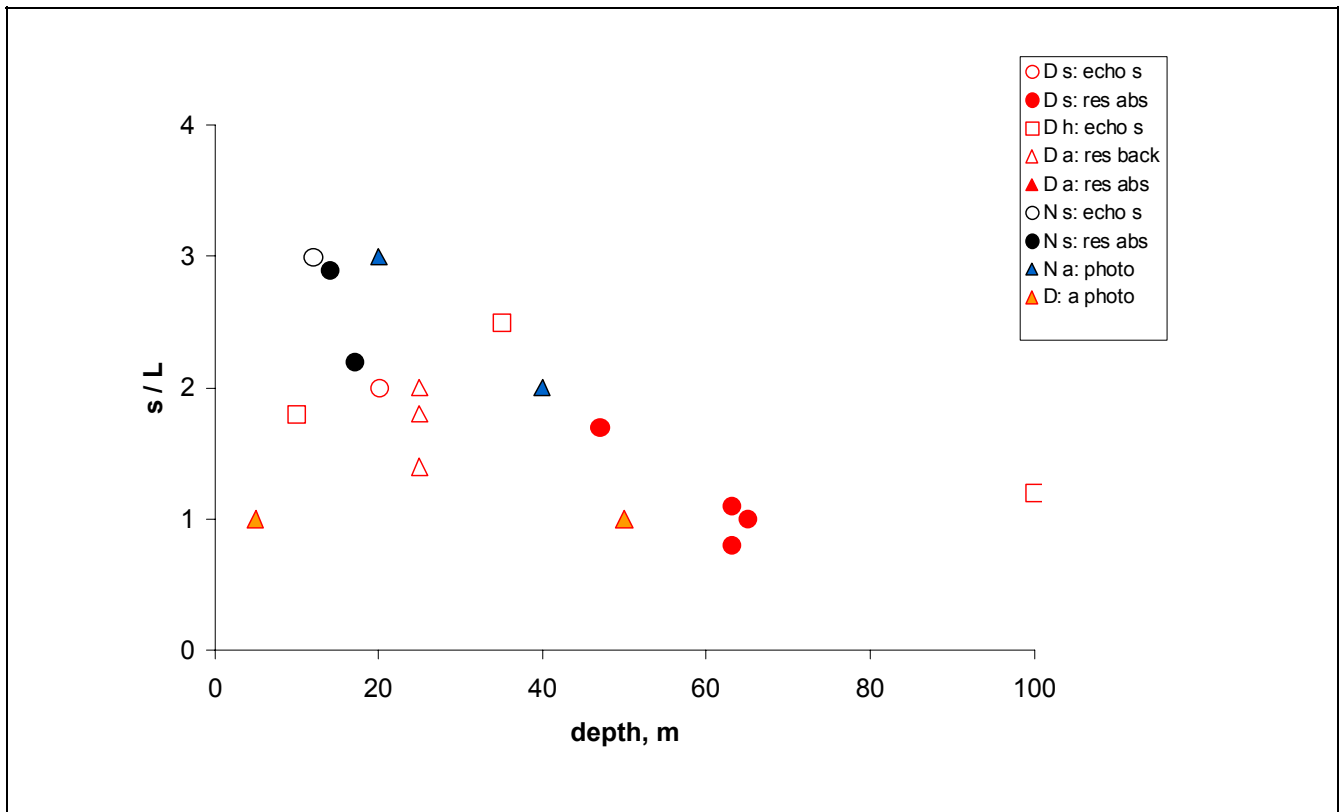
Estimation of bio-acoustic parameters from BAS II data has been initiated. Measured frequencies of the dominant absorption lines are consistent with the resonance frequencies of trawled sardines and anchovies and echo sounder data. Fig. 2 shows measurements of measured frequency lines attributed to individual 15 cm long sardines and sardines in schools during night and day, and theoretical calculations, based on a model developed by Diachok (1999). Measurements at 1.1 kHz at 14 m at night and 2 kHz at 38 m during day were consistent with echo sounder data, which revealed the presence of persistent biological layers at 12 m at night and 38 m during day. Lower frequency absorption lines at 0.85 and 0.75 kHz during night and  $f \leq 1.8$  kHz during day were consistent with theoretical calculations of the resonance frequencies of schools of sardines with the average number of fish per school,  $N$ , equal to  $10^4$ , and separation to length ( $s/L$ ) ratios equal to 1, 2 and 3 (Diachok, 1999). This interpretation of the source of the low frequency lines is consistent with echo sounder data, which indicated the presence of a large number of schools at depths shallower than 21 m with a modal depth of 12 m at night, and deeper than 35 m during the day. The inferred values of  $s/L$  are comparable to previously reported measurements of  $s/L$ , which were derived from photographs and echo sounder data at other sites, as illustrated in Figure 3. These results are qualitatively similar to measurements of diurnal changes in resonance frequencies associated with the vertical migration of sardines in the Gulf

of Lion (Diachok, 1999). Initial results of BAS II were presented at the IEEE Oceans 2003 Conference.

It is possible that larger fish, such as jack mackerel or hake, may have contributed to bio-alpha at frequencies below the resonance frequencies of individual sardines. Identification of a robust discriminator of absorption lines, which are associated with individuals and schools, remains an important research challenge.



**Figure 2. Frequencies and depths of absorption lines during night and day inferred from BAS II TL data, and theoretical resonance frequencies of individual sardines ( $f$ ), and schools with  $N = 10^4$  and  $s/L = 1, 2$  and  $3$  (Diachok, 1999). Echo sounder based depths of persistent biological layers were 12 m at night and 38 m during day. Echo sounder data indicated that the depths of schools were  $< 21$  m at night and  $> 35$  m during day.**



**Figure 3.** Separation / length of sardines (s), anchovies (a) and herring (h) during day (D) and night (N) derived from echo sounder, resonance backscatter, resonance absorptivity and photo data. Measurements at depths > 60 m were made near the bottom. This compilation is consistent with Misund's (1991) observation that  $s/L \approx 1$  near boundaries.

## IMPACT / APPLICATIONS

**Naval applications:** This research suggests that the detection range of tactical sonars operating at/near the resonance frequencies of pelagic fish may be significantly reduced when operating in littoral environments, where concentrations of pelagic fish with swim bladders are large, such as the shallow seas off the coasts of the United States, China and the Arabian Sea. Combatants in littoral environments, where fish concentrations are high, may find themselves in situations where the detection range of one combatant's sonar, operating at the resonance frequency of a pelagic species, may be very short, whereas the opponent's sonar, operating at a different frequency, may be very long *at the same time and place*. This research also indicates that operational codes, which are designed to invert geo-acoustic parameters from TL data, *must* consider the effects of bio-absorptivity in littoral regions where fish concentrations are high.

**Fisheries applications:** These results suggest that bio-acoustic absorptivity can be used to estimate number density vs. length (and possibly species) of pelagic fish with swim bladders in littoral environments. Possible applications include discrimination between juveniles and adults during fishing operations, and long term observatories for monitoring the arrival and departure times of migrating species.

## TRANSITIONS

The Naval Research Laboratory (NRL) supported a four year 6.2 research program of experimental and theoretical investigations on the effects of bio-acoustic absorptivity on transmission loss, and is considering supporting a follow-on 6.2 research program to develop rapid, robust algorithms for inversion of geo-acoustic parameters in the presence of bio-absorptivity. As a direct result of the research described here and my briefings for Naval Oceanographic Office (NOO) scientists, NOO management has decided that “development of algorithms for inversion of geo-acoustic parameters in the presence of bio-absorptivity” is a *requirement*.

## RELATED PROJECTS

Southwest Fisheries Science Center: biological sampling and fisheries sonar programs.

## REFERENCES

- Dahl, P.H., C.J. Eggen, D.J. Tang and R.C. Spindel, “Low frequency sound propagation in the Yellow Sea Results from the 1996 China U.S. experiment”, APL UW Technical Report 9804, Applied Physics Laboratory, Seattle, Washington, 1998.
- Iverson, S. et al., “Stock size, distribution and biology of anchovy in the Yellow Sea and East China Sea”, *Fisheries Research*, **16**, 147-163, 1993.
- Mais, K. Pelagic fish surveys in the California Current, *Fisheries Bulletin* 162, Dept. Fish and Game, State of California, 1974.
- Misund, O., “Dynamics of moving masses; variability in packing density, shape and size among pelagic schools, in *Swimming Behaviour of Schools Related to Fish Capture and Acoustic Abundance Estimation*, Ph. D. Thesis, Bergen, Norway, 1991.
- Ohshimo, S., “Acoustic estimation of biomass and school character of anchovy *Engraulis japonicus* in the East China Sea and the Yellow Sea, *Fisheries Science*, **62**, 344-349, 1996.
- Qiu, X. et al., “Frequency selective attenuation of sound propagation and reverberation in shallow water”, *J. Sound and Vibration*, **220**, 331-342, 1999.
- Rogers, P.H., J.X. Zhou, X.Z. Zhang and F. Li, “Sea-bottom acoustic parameters from inversion of Yellow Sea experimental data” in *Experimental Acoustic Inversion Methods for Exploration of the Shallow Water Environment*, A. Caiti, J.P. Hermand, S.M. Jesus and M.B. Porter, Editors, Kluwer, Dordrecht., 2000.

## PUBLICATIONS

### Papers in refereed journals

- Orest Diachok and Stephen Wales, “Effects of bioacoustic absorptivity on transmission loss in the Yellow Sea”, *US Navy Journal of Underwater Acoustics (Invited)*, July 2003.
- Orest Diachok and Stephen Wales, “Concurrent inversion of bio and geo-acoustic parameters from transmission loss measurements in the Yellow Sea”, accepted for publication, *J. Acoust Soc. Am.*

Orest Diachok, Paul Smith, George Cavanagh, William Hodgkiss, Stephen Wales and David Demer, "The potential of bioacoustic absorption spectroscopy for estimation of number densities vs. fish size and depth", submitted to ICES J. Mar. Sci.

Orest Diachok, Bernard Liorzou and Carla Scalabrin, "Estimation of the number density of fish from resonance absorptivity and echo sounder data", ICES J. Mar. Sci., 58, 137-153, 2001.

Orest Diachok, "Bioacoustic absorption spectroscopy: estimation of the biomass of fish with swim bladders", Bioacoustics, 12, 271-274, 2002, and an *Invited* talk presented at the International Conference on Fish Bioacoustics, Chicago, Ill., 2001.

Orest Diachok, "Interpretation of the spectra of energy scattered by dispersed anchovies", J. Acoust. Soc. Am., 110, 2917-2923, 2001.

Orest Diachok, "Absorption spectroscopy: a new approach to estimation of biomass" (*Invited*), Fisheries Research, 47, 231-244, 2000.

Orest Diachok, "Effects of absorptivity due to fish on transmission loss in shallow water", J. Acoust. Soc. Am., 105, 2107-2128, 1999.

### **Chapter in book**

Orest Diachok, "Bioacoustic Absorption Spectroscopy: a new approach to estimation of the number and lengths of fish in the ocean", *Invited* Chapter 14 in *Sounds in the Sea: from Ocean Acoustics to Acoustical Oceanography*, H. Medwin, Editor, Cambridge University Press, 2003.

### **Proceedings of conferences / abstracts (2002-2003)**

Orest Diachok, Stephen Wales, George Cavanagh and Paul Smith, "Bioacoustic absorption spectroscopy (BAS): instruments, measurement strategies and results of experiments", Proceedings of the IEEE Oceans 2003 Conference.

Orest Diachok, "Sound absorption due to fish: from David Weston's discoveries to recent developments", *Invited* abstract, Fall 2002 Meeting of the Acoustical Society of America.

Orest Diachok, "Observations of frequency shift associated with schooling fish", Spring 2003 Meeting of the Acoustical Society of America.

Jeff Dunne, Orest Diachok and Stephen Wales, "Observations of solitons in the Santa Barbara Channel", Spring 2003 Meeting of the Acoustical Society of America.

Orest Diachok and Stephen Wales, "Simultaneous inversion of geo and bio-acoustic parameters from transmission loss measurements in the Yellow Sea", Spring 2003 Meeting of the Acoustical Society of America.



Orest Diachok and Paul Smith, “Preliminary results of concurrent bioacoustic absorption spectroscopy (BAS) and trawling measurements of anchovies in the Santa Barbara Channel”, CalCOFI Meeting, November 2002.

## **PATENTS**

I have been awarded a patent for the “bioacoustic absorption spectroscopy” method.