

**REPORT DOCUMENTATION PAGE**

Form Approved  
OMB No. 0704-0188

The public reporting burden for this 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 the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 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 any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

**PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**

1. REPORT DATE (DD-MM-YYYY)      2. REPORT TYPE  
Conference Proceeding      3. DATES COVERED (From - To)  
18-22 November 2002

4. TITLE AND SUBTITLE  
Evaluating Forward Light Scattering Measurements

5a. CONTRACT NUMBER  
5b. GRANT NUMBER  
5c. PROGRAM ELEMENT NUMBER  
602435N

6. AUTHOR(S)  
Amanda Briggs, W. Pegau, Alan D. Weidemann and Jennifer Prentice

5d. PROJECT NUMBER  
5e. TASK NUMBER  
5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)  
Naval Research Laboratory  
Oceanography Division  
Stennis Space Center, MS 39529-5004

8. PERFORMING ORGANIZATION REPORT NUMBER  
NRL/PP/7330/02/0072

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)  
Office of Naval Research  
800 N. Quincy St.  
Arlington, VA 22217-5660

10. SPONSOR/MONITOR'S ACRONYM(S)  
ONR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT  
Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES

20040203 124

14. ABSTRACT  
Forward light scattering can be used for rapid determination of in situ particle size distributions (PSD) based on an inversion of the volume scattering function (VSF). One advantage of this technique is that it can capture continuous in situ data rather than discrete depth bottle measurements, which are more common and more laborious. To evaluate our ability to measure the VSF, a multi-institution effort was conducted to test the performance of several instruments that measure scattering. This presentation focuses on the performance of two instruments, the VABAM (Variable Aperture Beam Attenuation Meter, WetLabs, Inc.) and the LISST-IOO (Laser In-Situ Scattering and Transmissiometry, Sequoia Scientific), that measure forward scatter at small angles. This study compares the results from Mie theory with controlled lab experiments. Phytoplankton monocultures and polystyrene beads ranging in size from 0.6 to 160um were used in various concentrations in laboratory tank tests. Here we compare the measured VSF's to theoretical results.

15. SUBJECT TERMS  
volume scattering function, VABAM, particle size distributions

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT  SAR	18. NUMBER OF PAGES  6	19a. NAME OF RESPONSIBLE PERSON Alan Weidemann
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (Include area code) 228-688-5253

**PUBLICATION OR PRESENTATION RELEASE REQUEST**

Pubkey: 3544

NRLINST 5600.2

1. REFERENCES AND ENCLOSURES	2. TYPE OF PUBLICATION OR PRESENTATION	3. ADMINISTRATIVE INFORMATION
Ref: (a) NRL Instruction 5600.2 (b) NRL Instruction 5510.40D  Encl: (1) Two copies of subject paper (or abstract)	<input type="checkbox"/> Abstract only, published <input type="checkbox"/> Book <input type="checkbox"/> Conference Proceedings (refereed) <input type="checkbox"/> Invited speaker <input type="checkbox"/> Journal article (refereed) <input type="checkbox"/> Oral Presentation, published <input type="checkbox"/> Other, explain	<input type="checkbox"/> Abstract only, not published <input type="checkbox"/> Book chapter <input checked="" type="checkbox"/> Conference Proceedings (not refereed) <input type="checkbox"/> Multimedia report <input type="checkbox"/> Journal article (not refereed) <input type="checkbox"/> Oral Presentation, not published
		STRN <u>NRL/PP/7330-02-72</u> Route Sheet No. <u>7330/</u> Job Order No. _____ Classification <u>X</u> U _____ C Sponsor _____ approval obtained <u>X</u> yes _____ no

**4. AUTHOR**

Title of Paper or Presentation  
**Evaluating Forward Light Scattering Measurements**

Author(s) Name(s) (First, MI, Last), Code, Affiliation if not NRL  
Amanda Briggs  
W. Pegau, Alan D. Weidemann, Jennifer Prentice

It is intended to offer this paper to the Ocean Optics XVI  
 (Name of Conference)

**18-NOV - 22-NOV-2002, Santa Fe, New Mexico, Unclassified**  
 (Date, Place and Classification of Conference)

and/or for publication in Ocean Optics XVI, Unclassified  
 (Name and Classification of Publication) (Name of Publisher)

After presentation or publication, pertinent publication/presentation data will be entered in the publications data base, in accordance with reference (a).  
 It is the opinion of the author that the subject paper (is \_\_\_\_\_) (is not X) classified, in accordance with reference (b).  
 This paper does not violate any disclosure of trade secrets or suggestions of outside individuals or concerns which have been communicated to the Laboratory in confidence. This paper (does \_\_\_\_\_) (does not X) contain any militarily critical technology.  
 This subject paper (has \_\_\_\_\_) (has never X) been incorporated in an official NRL Report.

Alan D. Weidemann, 7333  
 Name and Code (Principal Author)

*Alan D. Weidemann*  
 (Signature)

5. ROUTING/APPROVAL			
CODE	SIGNATURE	DATE	COMMENTS
Author(s) Weidemann	<i>Alan D. Weidemann</i>	21 Jan 03	after H-2 fact
Section Head Richard W. Gould, 7333	<i>Richard W. Gould</i>	1/21/03	
Branch Head Robert A Arnone, 7333	<i>R Arnone</i>	1/21/03	
Division Head <i>Payne, acting</i>	<i>FW Payne</i>	1/22/03	1. Release of this paper is approved. 2. To the best knowledge of this Division, the subject matter of this paper (has _____) (has never <u>X</u> ) been classified.
Security, Code 7030.1	<i>[Signature]</i>	1/24/03	1. Paper or abstract was released. 2. A copy is filed in this office. <u>OSSC - C37-3</u>
Office of Counsel, Code 1008.3	<i>[Signature]</i>	1/27/03	
ADOR/Director NCST E.O. Hartwig, 7000	<i>[Signature]</i>		
Public Affairs (Unclassified/ Unlimited Only), Code 7030.4	<i>[Signature]</i>	1/27/03	Need acknowledgment
Division, Code			
Author, Code			

**6. DISTRIBUTION STATEMENTS (Author/Contractor/Proprietary Information - ID# 1000000 - Required)**

**A - Approved for public release, distribution is unlimited.**

**B - Distribution authorized to U.S. Government agencies only (check reason below):**

<input type="checkbox"/> Foreign Government Information	<input type="checkbox"/> Contractor Performance Evaluation	<input type="checkbox"/> Critical Technology
<input type="checkbox"/> Proprietary Information	<input type="checkbox"/> Administrative/Operational Use	<input type="checkbox"/> Premature Dissemination
<input type="checkbox"/> Test and Evaluation	<input type="checkbox"/> Software Documentation	<input type="checkbox"/> Cite "Specific Authority" _____

Date statement applied \_\_\_\_\_ (Identification of valid documented authority)

Other requests for this document shall be referred to \_\_\_\_\_  
(Insert Controlling DOD Office\*)

**C - Distribution authorized to U.S. Government agencies and their contractors (check reason below):**

<input type="checkbox"/> Foreign Government Information	<input type="checkbox"/> Software Documentation	<input type="checkbox"/> Cite "Specific Authority" _____
<input type="checkbox"/> Administrative/Operational Use	<input type="checkbox"/> Critical Technology	(Identification of valid documented authority)

Date statement applied \_\_\_\_\_

Other requests for this document shall be referred to \_\_\_\_\_  
(Insert Controlling DOD Office\*)

**D - Distribution authorized to DOD and DOD contractors only (check reason below):**

<input type="checkbox"/> Foreign Government Information	<input type="checkbox"/> Critical Technology	<input type="checkbox"/> Cite "Specific Authority" _____
<input type="checkbox"/> Software Documentation	<input type="checkbox"/> Administrative/Operational Use	(Identification of valid documented authority)

Date statement applied \_\_\_\_\_

Other requests for this document shall be referred to \_\_\_\_\_  
(Insert Controlling DOD Office\*)

**E - Distribution authorized to DOD components only (check reason below):**

<input type="checkbox"/> Proprietary Information	<input type="checkbox"/> Premature Dissemination	<input type="checkbox"/> Critical Technology
<input type="checkbox"/> Foreign Government Information	<input type="checkbox"/> Software Documentation	<input type="checkbox"/> Direct Military Support
<input type="checkbox"/> Administrative/Operational Use	<input type="checkbox"/> Contractor Performance Evaluation	<input type="checkbox"/> Test and Evaluation

Date statement applied \_\_\_\_\_

Other requests for this document shall be referred to \_\_\_\_\_  
(Insert Controlling DOD Office\*)

**F - Further dissemination only as directed by \_\_\_\_\_**  
(Insert Controlling DOD Office\*)

Date statement applied \_\_\_\_\_ or higher DOD authority \_\_\_\_\_

**G - Distribution authorized to U.S. Government agencies and private individuals or enterprises eligible to obtain export-controlled technical data in accordance with regulations implementing 10 U.S.C. 140c.**

Date statement applied \_\_\_\_\_

Other requests for this document shall be referred to \_\_\_\_\_  
(Insert Controlling DOD Office\*)

\*For NRL publications, this is usually the Commanding Officer, Naval Research Laboratory, Washington, DC 20375-5320

**7. OTHER LIMITATION**

<input type="checkbox"/> Classification	<input type="checkbox"/> NOFORN	<input type="checkbox"/> DTIC exempt (explain) _____
---	---------------------------------	--

Classification Review (initial/Date) Substantive changes made in this document after approval by Classification Review and Public Release invalidate these reviews. Therefore, if any substantive changes are made by the author, Technical Information, or anyone else, the document must be returned for another Classification Review and Publication Release.

**8. INSTRUCTIONS**

Author completes and submits this form with the manuscript via line channels to the division head for review and approval according to the routing in Section 4.

- NRL Reports.....Submit the diskette (if available), manuscript, typed double-spaced, complete with tables, illustrations, references, draft SF 298, and proposed distribution list.
- NRL Memorandum Reports.....Submit a copy of the original, typed manuscript complete with tables, illustrations, references, draft SF 298, and proposed distribution list.
- NRL Publications or other books, brochures, pamphlets, proceedings, or any other printed publications.....Handled on a per case basis by Site Technical Information Office.

## EVALUATING FORWARD LIGHT SCATTERING MEASUREMENTS

*Amanda L. Briggs, Oregon State University, College of Oceanic and Atmospheric Sciences, 104 Ocean Admin Building, Corvallis, OR 97331-5503*

*W. Scott Pegau, Katchemak Bay Research Reserve,  
2181 Katchemak Drive, Homer, AK 99603*

*Alan Weidemann, NRLSSC Code 7331, Bldg. 1009, SSC, MS, 39529*

*Jennifer Prentice, NAVAIR Code 456, Bldg. 2185 Suite 1100, 22347 Cedar Point Rd.,  
Unit 6, Patuxent River, MD, 20670-1161*

### INTRODUCTION

Forward light scattering can be used for rapid determination of *in situ* particle size distributions (PSD) based on an inversion of the volume scattering function (VSF). One advantage of this technique is that it can capture continuous *in situ* data rather than discrete depth bottle measurements, which are more common and more laborious. To evaluate our ability to measure the VSF, a multi-institution effort was conducted to test the performance of several instruments that measure scattering. This presentation focuses on the performance of two instruments, the VABAM (Variable Aperture Beam Attenuation Meter, WetLabs, Inc.) and the LISST-100 (Laser In-Situ Scattering and Transmissiometry, Sequoia Scientific), that measure forward scatter at small angles. This study compares the results from Mie theory with controlled lab experiments. Phytoplankton monocultures and polystyrene beads ranging in size from 0.6 to 160 $\mu$ m were used in various concentrations in laboratory tank tests. Here we compare the measured VSF's to theoretical results.

### INSTRUMENTS

The VABAM measures forward scattered light between 0.11 and 3.2°. The instrument utilizes a collimated light source consisting of three light-emitting diodes (LED's) with wavelengths of 455, 532, and 650nm. Forward scattered light is collected on a ring detector after it has passed through a mechanical iris with a known aperture. Scattering at specific solid angles is determined by the difference of sequential measurements of the light scattered in the circular detector area. A single scan takes approximately 4 seconds. Beam attenuation (acceptance angle 0.1°) is also measured in each scan.

The LISST-100 measures the angular scattering distribution between 0.1-18° at 670nm. The LISST employs a collimated laser diode light source, has a 5 cm pathlength, and a silicon ring detector with 32 log-spaced rings. It does not have a mechanical aperture, so it collects 32 solid angle measurements of forward scattering simultaneously. The LISST also measures optical transmission at an acceptance angle of 0.6°. For a more detailed description of the LISST-100 and its operating principle, see Agrawal, 2000.

The Mie code used in this analysis is a Matlab translation of Bohren and Huffman's FORTRAN code (1983).

## THE EXPERIMENT

Multiple instrument inter-calibration experiments were performed at the Patuxent River Naval Air Station in Lexington, Maryland in May and June of 2002. The LISST and the VABAM were mounted in line, along with an *ac-9* (WetLabs, Inc.) to provide an independent measure of beam attenuation. Polystyrene spheres (Duke Scientific Corporation) and then, phytoplankton monocultures were added to optically pure water to produce a range of known concentrations of particles. The setup was flushed with and then filled with a sample, and measurements were taken simultaneously.

## RESULTS

The VSF's obtained from the LISST more closely resemble the theoretical results than the VABAM measurements (Figure 1). In most cases the VABAM underestimates the theoretical VSF by up to two orders of magnitude. The 5 $\mu\text{m}$  bead VSF measured by the LISST captures the magnitude and shape of the theoretical VSF, although the strong theoretical resonances are somewhat damped in the real data by the variability in the size of the beads. The LISST also performed well in capturing the VSF of the nearly spherical phytoplankton *Dunaliella tertiolecta* (Figure 1b). Values for the Mie code phytoplankton input parameters of  $r$ , the radius,  $n$ , the relative index of refraction, and  $n'$ , the imaginary part of the index of refraction, were 3.16 $\mu\text{m}$ , 1.027, and 0.0018 respectively (MacCallum). The 5 $\mu\text{m}$  bead input parameters were  $r = 2.5\mu\text{m}$ ,  $n = 1.195$ , and  $n' = 0$ . The Mie parameters were not adjusted to fit the measured data.

The VSF is inherently affected by the magnitude of total scattering in the medium. To assess how the instruments perform over a range of particle concentrations, one has to compare the particle volume scattering phase function,  $\tilde{\beta}$  of various dilutions of the same particle size. This is possible because the volume scattering function  $\beta$  can be rewritten as the product of the particle phase function  $\tilde{\beta}$  and the scattering coefficient  $b$ . This separates the volume scattering function into a factor that indicates the strength of the scattering,  $b$ , and a factor that describes the angular distribution of the scattering,  $\tilde{\beta}$  (Mobley, 1994). So, to remove the effect of particle concentration on the magnitude of the VSF while preserving its shape, one can simply normalize by the scattering coefficient,  $b$ . The phase function is a useful parameter in this experiment because if the instruments are measuring the volume scattering function properly, then the phase functions for all concentrations of particles should be equivalent.

We performed a dilution series using 3 $\mu\text{m}$  spheres, and normalized the VSF's from the LISST and the VABAM by the scattering coefficient for each concentration. In this case the phase functions all fell closely together for both instruments, except at the lowest concentration where  $c = 0.138\text{m}^{-1}$  (Figure 2). The highest beam attenuation

reached in this dilution series was only  $1.0124\text{m}^{-1}$ , but in a dilution series with Maalox we reached values of over  $3\text{m}^{-1}$ . In that case the LISST still performed well, with low variability between concentrations ( $c = 0.064 - 3.27\text{m}^{-1}$ ). The VABAM performed poorly in the Maalox dilution series, varying by two orders of magnitude in the calculated phase functions (data not shown).

## DISCUSSION

The LISST showed the least variability at angles greater than 1 degree, whereas the VABAM showed the opposite trend (Figure 3). The increased error for the LISST at small angles can be attributed to the variability of the presence of large particles, which disproportionately affect the signal at the smaller rings. The variability in the VABAM measurement may be the result of inconsistent aperture alignment between different scans.

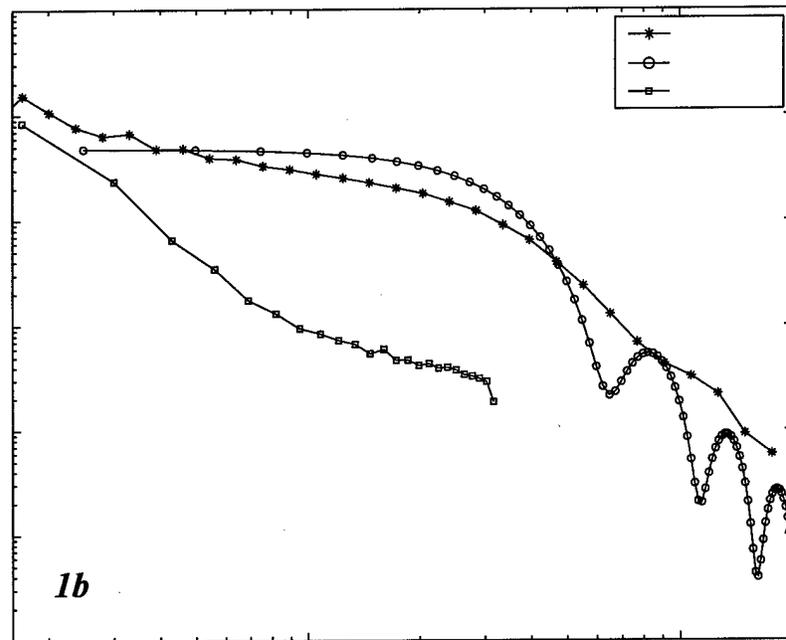
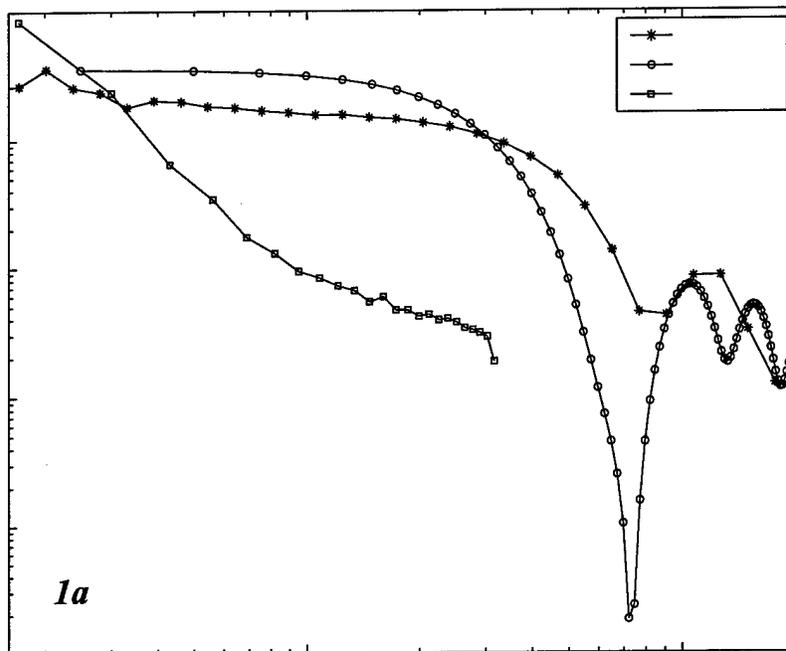
The magnitudes of the VSF's measured by the VABAM are over an order of magnitude less than the theoretical results in most cases (Figure 1). Though it does have higher angular resolution than the LISST between some angles ( $0.2 - 3.16^\circ$ ), the VABAM's narrow angular range limits its functionality in inversion models for estimating a particle size distribution. The VABAM appears to have the advantage of being a spectral instrument, but we were never able to reliably acquire meaningful data with wavelengths other than 650nm. The 532nm channel and especially the 455 channel often produced negative values for the VSF. All data shown are from the 650nm output.

## CONCLUSION

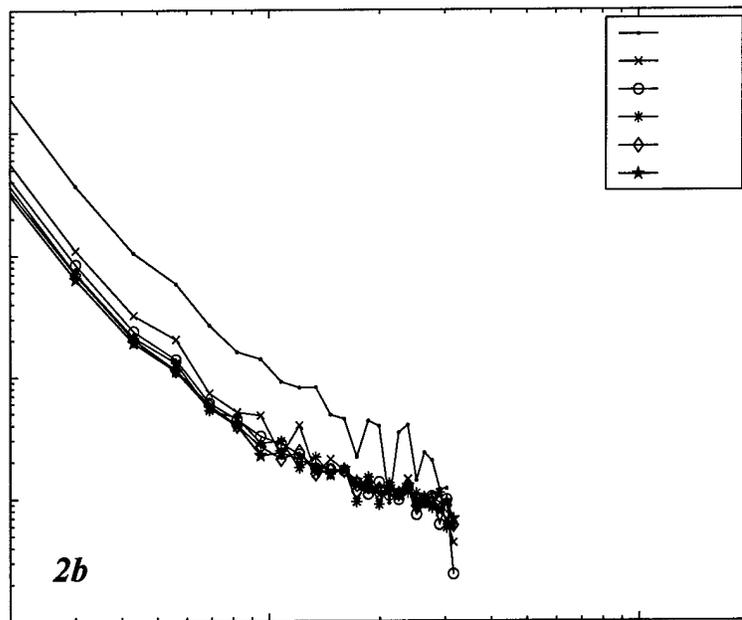
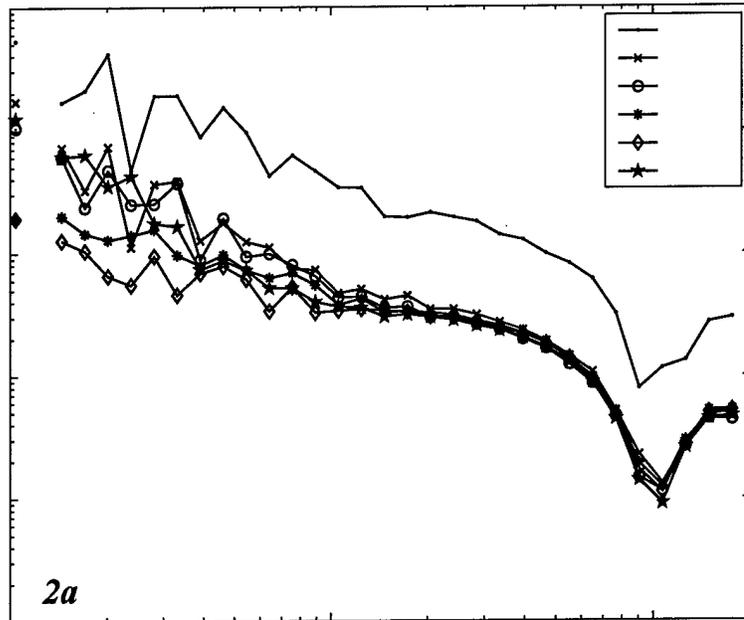
We evaluated the performance of two instruments that measure forward scattering at small angles. Various polystyrene spheres and phytoplankton cultures were prepared in optically pure water and were sampled simultaneously by the LISST-100 and the VABAM. The LISST showed closer agreement with Mie theory for both the beads and the phytoplankton. Although the magnitudes of the VABAM measurements were off, both instruments performed well in capturing a consistent phase function over a range of bead concentrations.

## REFERENCES

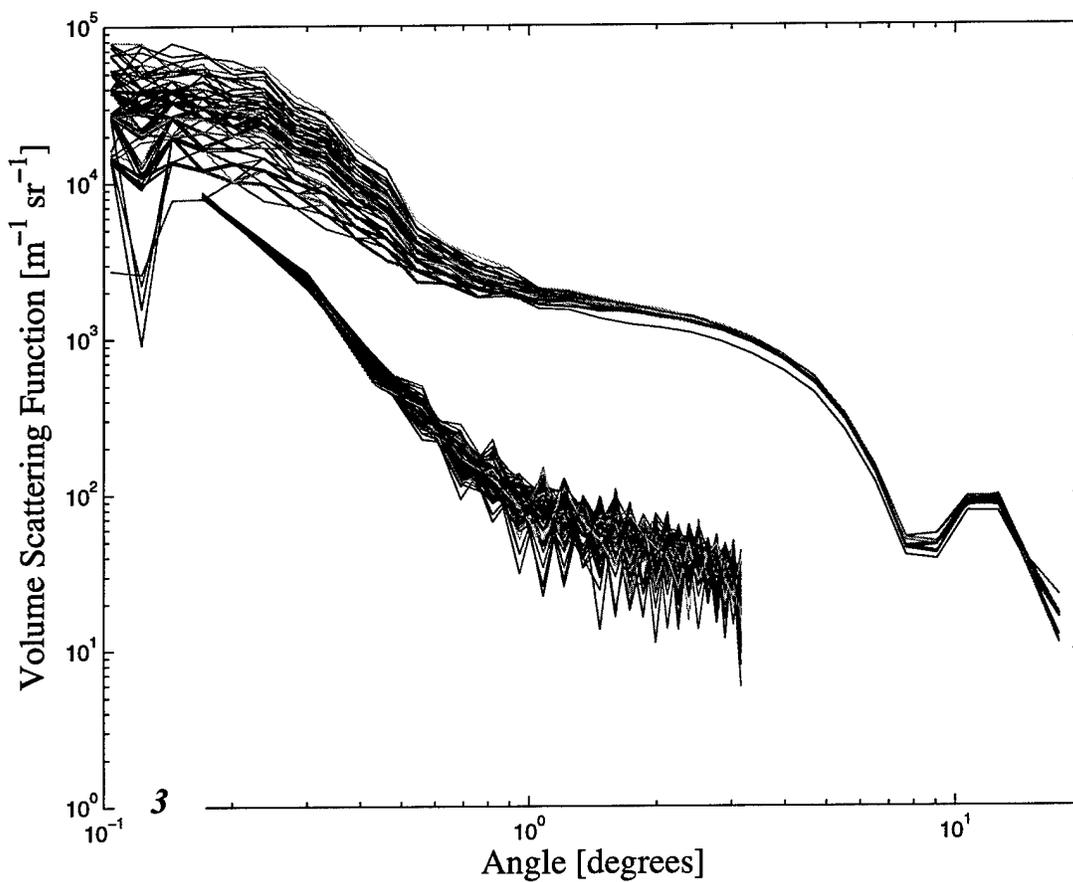
- Agrawal, Y.C. and H.C. Pottsmith, 2000. *Instruments for particle size and settling velocity observations in sediment transport*. Mar. Geol. 168, 89-114.
- Bohren, C.F., and D.R. Huffman, 1983. *Absorption and Scattering of Light by Small Particles*, J. Wiley and Sons, New York, 530 pp.
- MacCallum, Iain, 2000. *Measurement and Modeling of Phytoplankton Light Scattering*, Ph.D. Thesis, University of Strathclyde, Glasgow, 228 pp.
- Mobley, Curtis D., 1994. *Light and Water: Radiative Transfer in Natural Waters*, Academic Press, Inc., San Diego, 592 pp.



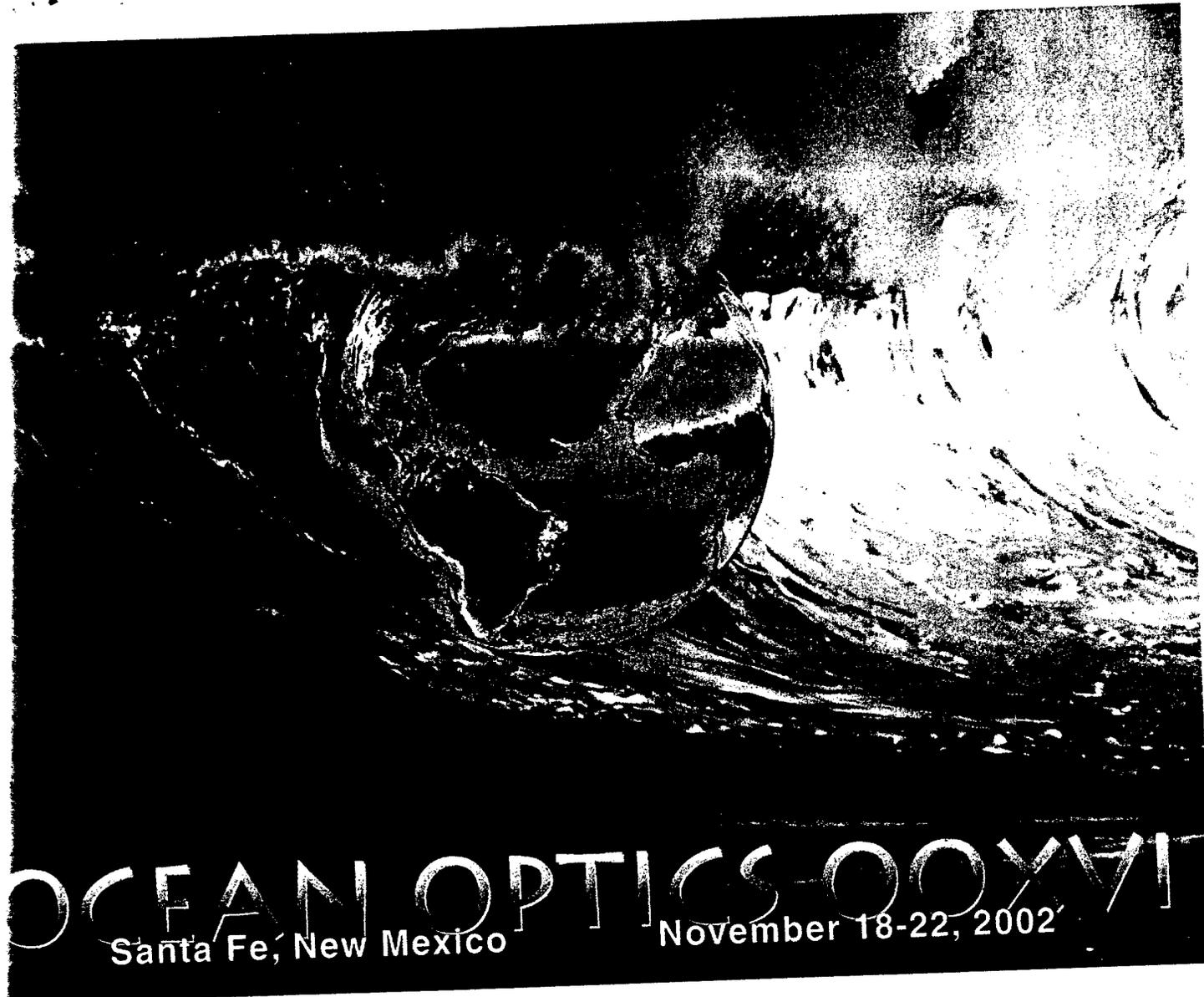
**Figure 1. Volume scattering functions from 0.10 – 20° for (a) 5µm polystyrene beads and for (b) *Dunaliella tertiolecta* as measured by the LISST-100 and the VABAM, and as predicted by Mie theory. Inputs for the Mie calculations were:  $r=2.5\mu\text{m}$ ,  $n=1.195$ , and  $n'=0$  for the beads, and  $r=3.16\mu\text{m}$ ,  $n=1.027$ ,  $n'=0.0018$  for *D. tertiolecta*.**



**Figure 2. Phase functions measured by (a) the LISST-100 and (b) the VABAM. 'b' values for normalization were taken from the LISST measurement of beam attenuation, assuming that for the beads there was no absorption so  $b = c$ . The legend shows the beam attenuation for each concentration.**



**Figure 3. Variability in VSF measurements from the LISST (upper curves,  $N=100$ ) and the VABAM (lower curves,  $N=72$ ) for  $5\mu\text{m}$  beads.**



OCEAN OPTICS OOVVI  
Santa Fe, New Mexico November 18-22, 2002

## ***Program and Abstracts***

**COVERING A DIVERSITY OF TOPICS PERTAINING TO:**

- Radiative Transfer Theory
- In Situ and Remote Sensor and Measurement System Design
  - Applications of Quantitative Remote Sensing
- Interdisciplinary Processes Pertaining to the Ocean Surface, Volume, and Floor
  - Marine Environment Management Strategies

***Sponsored by:***

*Office of Naval Research  
National Aeronautic and Space Administration*