PROCEEDINGS OF THE ACOUSTIC CURRENT PROFILING SYMPOSIUM

NOVEMBER 2 AND 3, 1983

WASHINGTON, D.C.

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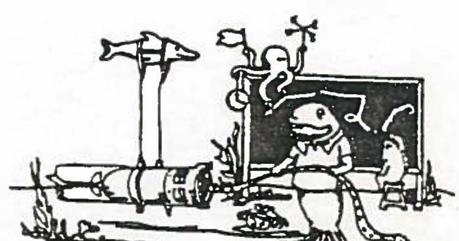

IEEE
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SUMMARY

In the past few years, the interest of the oceanic community in the use of acoustic techniques for measuring profiles of ocean currents has expanded considerably. Although the acoustic Doppler method has been exploited for many years to measure ship's speed through the water, only recently have current measurement systems based on this same principle become commercially available. As is typical with the introduction of new measurement techniques, a broad and varied perception of the utility and capability of acoustic Doppler systems has developed within the community. In an effort to focus specific attention on this aera of ocean technology and collectively provide a review of the status of the techniques, the "Acoustic Current Profiling Symposium" was convened in Washington, D.C., on November 2 and 3, 1983, under the joint auspices of NOAA and the Current Measurement Technology Committee of the IEEE Oceanic Engineering Society. The meeting objectives were to review the development of and community experience with remote acoustic current profiling methods, to identify critical areas of the technology that require further development, and to provide guidance and direction for continued short and long-term development and application.

The community was well represented at the Symposium with an attendance of 75. The speakers were divided into four categories: (1) program managers who reviewed the involvement, motivation and possible future direction of their agencies in this area of ocean technology; (2) investigators who have purchased and are using commercial systems; (3) researchers who are exploring acoustic techniques other than those presently commercially available for making measurements of ocean currents; and (4) commercial interests represented by manufacturers and other supporting activities.

Program Managers

In this category representatives from NOAA, NASA, ONR, and NSF reviewed their programs. Although in each case the principal motivation for interest in acoustic current profiling has been the measurement of upper ocean and river/estuarine currents, the nature and emphasis of the funded efforts have differed somewhat.

In order to insure the availability of upper layer ocean current measurements to complement and groundtruth spaceborne techniques, NASA since 1978 has invested directly in the development of acoustic Doppler techniques. Now in the final year of NASA-sponsored development, the specific efforts have included shipborne and bottom-mounted applications and, most recently, self-contained units for moorings and/or drifting buoys.

Support for and interest in acoustic current profiling from ONR lies principally in the physical and coastal oceanography programs in the Environmental Science Directorate. The Navy is interested in the entire spectrum of ocean circulation scales and ONR sponsors research in these areas. Although they have not invested heavily in the development phase, ONR considers the acoustic techniques to be useful tools and welcomes research proposals that include studying ocean process applications of high priority to the Navy.

During the last ten years, NOAA has had a number of projects involving current measurement by acoustic techniques. Motivation for these efforts can be divided into three program areas: Climate Research, National Ocean Service (NOS) Products, and Acoustic Research. The NOAA work involves both the purchase of commercial hardware and basic research on alternative acoustic measurement approaches.

The National Science Foundation, much like ONR, has a prime interest in applying this technology to their ocean science research objectives. In addition to this, a new program was started in 1982 to provide funds aimed specifically at ocean technology development.

Investigators Using Commercial Systems

Experiences with current profiling systems manufactured by AMETEK-STRAZA and RD Instruments, Inc., were reported on by speakers from the U.S. Geological Survey, Scripps Institution of Oceanography, NOAA, University of New Hampshire, University of Miami, Woods Hole Oceanographic Institution, U.S. Naval Research Lab, Bedford Institute of Oceanography and the Rijkswaterstaat in the Netherlands. Although bottom-mounted applications were discussed by Appell (NOAA) and Pettigrew (UNH) the emphasis was on shipboard measurements at both 115 kHz and 300 kHz. Because the need for some method of verifying the representativeness of the acoustic measurements is recognized, all but two presentations described some type of comparison with measurements made independently by, for example, current meter moorings and/or acoustically tracked dropsondes. Results from these "sea truth" efforts ranged from very good to very poor agreement.

Researchers Examining Alternative Acoustic Approaches

In an effort to improve upon suspected shortcomings of commercially available acoustic current profiling systems, a small group of investigators are engaged in exploratory efforts to investigate fundamental acoustic issues and develop alternative methods as well as other system geometries and signal processing techniques.

Alternate sonar systems include the transverse Doppler system of Clark and Proni (AOML), the pulse coherent Doppler sonar of L'hermitte (U of Miami), the correlation sonar presented by Edwards (GE), and a single-beam Doppler probe by Farmer and Zedel (IOS).

Methods for analyzing the signal return were also presented, for example, the auto regressive methods of Hodgkiss and Hansen (SIO). Fundamental acoustic research of attenuation, ambient noise, etc., was also discussed by Syck (NUSC).

Manufacturers and Other Commercial Interests

Manufacturers of commercial acoustic Doppler current profiling instruments were represented by Jim Christensen of AMETEK-STRAZA and Fran Rowe of RD Instruments. They presented their views on the capability of their products, direction of product developments, and some of the problems they face in satisfying consumer demand. Richard Williams of General Electric Company described activities relating to the development and use of correlation sonar for the measurement of current profiles. Scott Daubin of Daubin Systems, Inc. and Ken Theriault of Bolt Beranek and Newman, Inc. talked of support activities by these companies that respectively provided ship motion analysis and statistical analysis of expected accuracy for velocity and shear profiles.

Interactions and Concerns

The Symposium format was designed to allow ample time for interaction among attendees in an informal manner during breaks and lunch, and also formally at the close of each day's presentations. The following summarizes some of the topics discussed and reflects the major areas of concern.

One of the greatest concerns reflected by attendees was the lack of understanding of the acoustic beam backscattering process. Discussions revolved around historical and present research on the backscattering phenomenon and suggested methods for continued investigation, such as a global atlas of sonar scatterers. Experiences were expressed relating complete loss of return signal as a function of plankton in the water column. It was suggested that a method for systematically calibrating sonars and of defining reflective strength should be developed so that intercomparison between different units could be made.

Another discussion centered on the penetration of the acoustic beam in the water column and several investigators mentioned that they could not achieve the advertised range on their commercial systems. A general discussion on transducer design ensued with comments on efficiency, power requirements, and side lobe reduction. Transducer side lobes were of major concern because of their effect on the return signal interpretation. Manufacturers discussed their approaches to the problem including array shading techniques and parametric sonars.

Other important topics addressed included the use of scanning sonars for a three-dimensional picture of the flow velocity and of probing water turbulence by use of "coherent" Doppler sonars.

CONCLUSIONS

The Symposium was highly acclaimed by attendees as the type of forum necessary to advance the understanding of acoustic current profiling techniques. Interest was expressed in convening a similar symposium sometime in the future as the state of the art progresses.

Investigators have demonstrated through controlled intercomparison experiments that the acoustic Doppler technique is a viable method for the measurement of currents. Commercial systems are available that may satisfy a wide range of applications; however, it is necessary to have a thorough understanding of their operating principles and limitations. Continued research is necessary on the scattering process as well as further development of superior transducers and improved methods and further evaluation of the present technology. Caution should prevail for routine use of these systems until a firm understanding and clear definition of their performance is obtained.

ACKNOWLEDGEMENTS

As with any conference there are workers behind the scenes without whose diligent help nothing would be accomplished. A grateful thanks must, therefore, go to Barbara Roush, Gail Lozupone and Carolyn Putnam for all they did in making the Symposium successful.

INTRODUCTION

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This meeting is being hosted jointly by NOAA and the IEEE Oceanic Engineering Society, specifically the Current Measurement Technology Committee of that Society. As an introduction to the meeting, let me review some of the background of acoustic current profilers and some of the philosophy that has motivated us to come together here and then finally review specifically what the objectives of the meeting are.

It has been over 140 years ago that Christian Johann Doppler in 1842 while he was a professor of elementary mathematics at the State Technical Academy in Prague initiated his famous principle that the observed frequency of a wave depends on the velocity of the source relative to the observer. And it was a year later that the first experimental verification of the acoustic doppler effect took place in the Netherlands. It was done by a fellow by the name of Christoph Ballot, who used a locomotive to pull a group of trumpeters past another set of musicians who were standing still and who provided notes at perfect pitch. You can imagine how hard that was to get funded. I think not only was that significant in its being the first experimental verification of the principle, but I have been led to believe that was also the first recorded evidence of the use of a wave train in acoustic experiments. I am sure that Doppler had no idea of the significance of his discovery and that his principle would go on to form the basis of most of the so-called remote sensing techniques for ocean and atmospheric measurements on this planet. And although that was certainly a landmark discovery, it was 140 years ago and I think that a question that is today worthy of reflection is "Just what kind of stewards have we been of that scientific discovery?" and "How successful have we been in applying it to today's science?"

The situation as I perceive it is that we have quite a broad representation of investigators, program managers and commercial people involved in various aspects of the use, evaluation, and fabrication of devices that measure ocean currents via acoustic backscattering techniques. Since this community and the resources behind it are relatively small, I would think it reasonable to wish all of these efforts be sufficiently coordinated to assure that the goals and objectives of each program supporting this work are achieved with reasonable efficiency. As a step towards effecting this coordination, we have invited representatives from each segment of the community: the program managers to tell us why; the investigators to tell us how; and the commercial people to tell us how much. I think that we should take note that we have expanded from our original objective of a so-called straight Doppler meeting, for we are including other technqiues that may not be classified as straight Doppler but certainly are fundamentally based on the Doppler principle. I am referring to the correlation approach for example. So our principle objectives, therefore, are to review where we are in the development of this technology, and to identify particular areas of the technology that are critical, that require further work and most importantly to provide some appropriate guidance and direction for the continued long and short-term development and application of these principles. This can only happen if everybody is ready and willing to be an active participant here as well as an honest participant to "tell it like it is."

NOAA's Review

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The NOAA activity in terms of acoustic Doppler is broken into three program areas: Climate Research, National Ocean Service (NOS) Products, and another category called acoustic research. This gives you an idea of why we get into it - what motivates us. In the area of climate research, we have two activities going on - research ships and ships of opportunity. The objective in the research ship area is to establish the uncertainty in the underway ship measurement of upper ocean velocities. We are seeking to determine whether or not the acoustic Doppler profiling technique - shipboard in this case - is in fact a useful tool for making upper ocean heat transport measurements. Our engineering program is separated into three areas - ship motion, sea truth and spectral technique evaluation. Each one of these will be reviewed by people here today. Scott Daubin will speak tomorrow about his work - understanding the effects of the motion on the shipboard measurement. Jerry Appell will describe some of the sea truth work. Bill Hodgkiss will talk about spectral technique evaluation. Dave Bitterman will discuss the profiler on the NOAA Ship RESEARCHER.

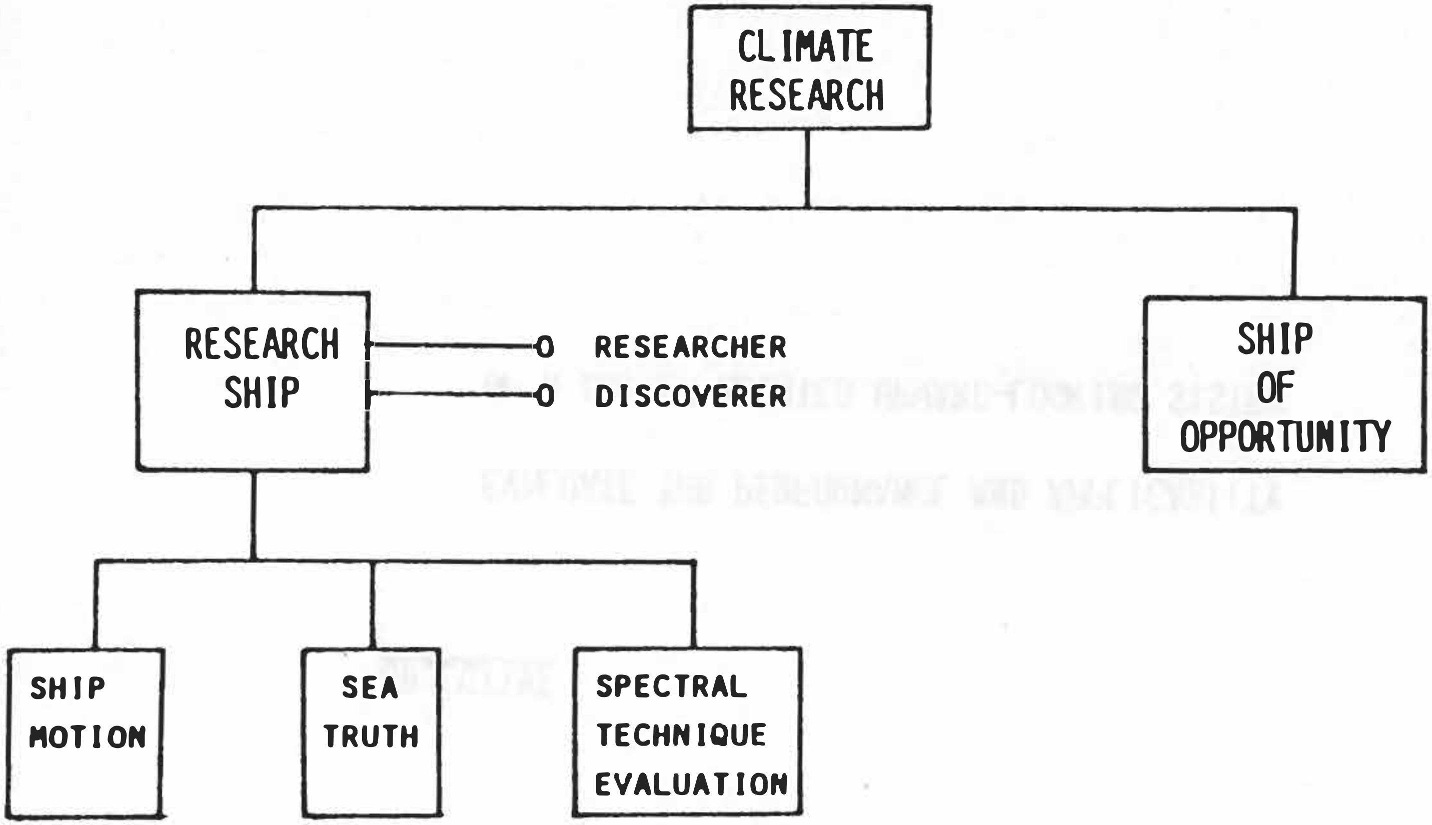
In the other category - ships of opportunity - we have a small project underway. This project objective is to determine the feasibility of deploying a commercially available Doppler acoustic current profiler aboard a commercial ship of opportunity. We seek to measure vertical profiles of upper ocean velocity by combining off the shelf current profiling electronics with the existing transducer and cable assembly of a conventional shipboard acoustic speed log.

NOS products - the objective here is to evaluate performance and applicability of a bottom-mounted system. Jerry Appell will go into detail on the applications for the device.

Lastly, we have a research activity at the NOAA lab in Miami (Atlantic Oceanographic and Meteorological Lab) and Tom Clarke will talk about that. Their principal emphasis is to investigate various transducer geometies and signal processing approaches for bottom-mounted systems applications.

NOAA

CLIMATE RESEARCH	NOS PRODUCTS	ACOUSTIC RESEARCH
MOTIVATION:	**MOTIVATION:**	**MOTIVATION:**
O UPPER OCEAN HEAT TRANSPORT MEASUREMENTS	O TIDAL CURRENT TABLES CHARTS, ETC. O CIRCULATION SURVEY RPTS O REAL TIME NAVIGATION AID	O RESEARCH INTO IMPROVED METHODS



OBJECTIVE

ESTABLISH UNCERTAINTY IN UNDERWAY SHIP MEASUREMENT

OBJECTIVE

DETERMINE FEASIBILITY OF DEPLOYING A COMMERCIALLY AVAILABLE PROFILER ABOARD A COMMERCIAL "SHIP OF OPPORTUNITY"

NOS
PRODUCTS

OBJECTIVE

EVALUATE THE PERFORMANCE AND APPLICABIITY

OF A BOTTOM-MOUNTED UPWARD-LOOKING SYSTEM

ACOUSTIC RESEARCH

OBJECTIVE

INVESTIGATE DIFFERENT APPROACHES TO IMPROVE MEASUREMENT CAPABILITY

Doppler Acoustic Current Profiler System Aboard The NOAA Ship Researcher

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Abstract: An Ametek-Straza DCP4400-115 Doppler Acoustic Backscatter Current Profiler was purchased by NOAA-AOML and installed aboard the NOAA Ship RESEARCHER. An associated data acquisition system consisting of an LSI 11-23 Minicomputer and nine track tape drives is used to log the data. The 11-23 Minicomputer was selected because there are a large number of interfaces and peripheral devices available and the software, including high level languages and operating system, are well supported by the manufacturer. A high speed digitizer was also built and installed with the data acquisition system to digitize the return signal from each beam at the output of the transducer and record it on tape.

Sea trials began in September, 1982 in the Straits of Florida near Miami to determine transducer misalignment, check-out the data acquisition system, and get data to evaluate profiler performance. The system was then used extensively in the Eastern Equatorial Pacific Ocean.

Depth penetration was approximately 200 meters and intercomparisons with a ship lowered current meter and an acoustically tracked dropsonde were very good under most situations.

Use of the profiler at present is severely limited by the lack of high quality, continuous navigation coverage over wide areas of the world's oceans. A prototype NAVSTAR Global Positioning System (GPS) receiver was used with the system on occasion and it is expected that translation of the ship can be determined to within a few cm/sec from the GPS position information.

The profiler has proven to be a very reliable system and has yielded much useful data on upper ocean dynamics and is expected to be one of the more important shipboard research tools in the coming years.

REMOTE ACOUSTIC DOPPLER SENSING

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Remote acoustic doppler sensing technology is being explored within NOAA to determine its application to a variety of measurement programs. The Ocean Systems Division of the National Ocean Service is investigating the technique and characterizing the performance of an experimental system developed during the past several years.

The experimental system was developed to demonstrate the usefulness of continuous real time measurements of vertical current profiles for safe navigation within ports and harbors. The system is based on an AMETEK STRAZA DCP 4400/300 doppler current profiler configured into a bottom mounted upward-looking system. The design goal was to operate continuously for a period of 1 year transmitting data to a remote station in real time. Tests were conducted on the bottom mounted current profiler in the summer of 1982 (Mero, Appell, Porter, 1983), and comparisons were made against conventional current meter moorings. Results over a 5-day period were encouraging with the system operating flawlessly and measurement comparison obtained well within the experimental uncertainty, estimated at 12 cm/s.

In August of 1983, the completed real time current monitoring system was installed approximately 100 meters south of Ambrose Light Tower, New York. The acoustic transducer and junction box are housed in the underwater platform and are connected via cable to the processing electronics on Ambrose Light Tower. Data is telemetered to the NOAA lab at Sandy Hook, New Jersey, via a Motorola UHF repeater. A dedicated phone line from Sandy Hook to NOAA in Rockville, Maryland, completes the real time data link. Table 1 shows the system specifications for the hardware used to control and operate the DCP 4400/300 and transmit data in real time.

TABLE 1

SYSTEM HARDWARE SPECIFICATIONS

SYSTEM CONTROLLER:	Hewlett Packard HP-85 Computer with 32K RAM, HPIB and GPIO Interfaces
REAL TIME REFERENCE:	Kinemetrics True Time GOES Satellite Receiver FREQ 468 MHZ
TELEMETRY TO SANDY HOOK:	Motorola UHF Repeater FREQ - 410 MHZ Power - 12 Watts
TELEMETRY TO ROCKVILLE:	Racal Vadic Modems Dedicated Phone Lines - 1200 Baud
ROCKVILLE CONTROLLER:	Hewlett Packard HP-85 Computer with 32K RAM, HPIB and RS232 Interfaces
Data Recording:	Columbia Model 3000 Tape Recorder, Hewlett-Packard, Dual Disk Drive
Display:	LSI Graphics Terminal

This system is unique in two aspects: One is the periodic monitoring of the backscattered acoustic signal strength and the second is an acoustic beam side lobe deflector installed above the transducer. The backscattered acoustic signal provides an indication of the health of the system and is also being explored as a means of monitoring pollution properties of the water with time and depth. The side lobe deflector is an experimental attempt to remove side lobe contamination from the near surface measurement bins. Table 2 shows the operating specifications of the system, and Figure 1 shows the system information flow and recording characteristics.

TABLE 2

SYSTEM OPERATING SPECIFICATIONS

LOCATION:	100 Meters Southwest of Ambrose Light Tower, New York	
	Latitude (N) 40° 27.5'	
	Longitude (W) 73° 49.9'	
DEPTH:	23 Meters	
PROFILER:	AMETEK DCP 4400	
	Operating Frequency	300 KHZ
	Number of Beams	4
	Beam Width	3°
	Transmit Pulse Width	2.4 ms
	Process Time Window	2.4 ms
	Depth Resolution (Bin Width)	1.6 meters
	Ping Rate	30/minute
	BACKSCATTER MODE	
	Transmit Pulse Width	2.4 ms
	Process Time Window	1.6 ms
	Depth Resolution (Bin Width)	1.0 meters

At the present time, several current meter moorings are deployed in the vicinity of the underwater platform to verify the system operation and obtain correlation with the measurement accuracy of conventional systems. Several other experiments are being planned during the course of the 1-year operation. A near surface experiment will define the system's capability to make near surface measurements with our side lobe deflector and water sample collection and analysis would allow correlation of water properties to backscatter data. Continued collection and analysis of current profiles will provide an excellent data base for the determination of the scientific value of high vertical resolution data over daily and seasonal environmental conditions.

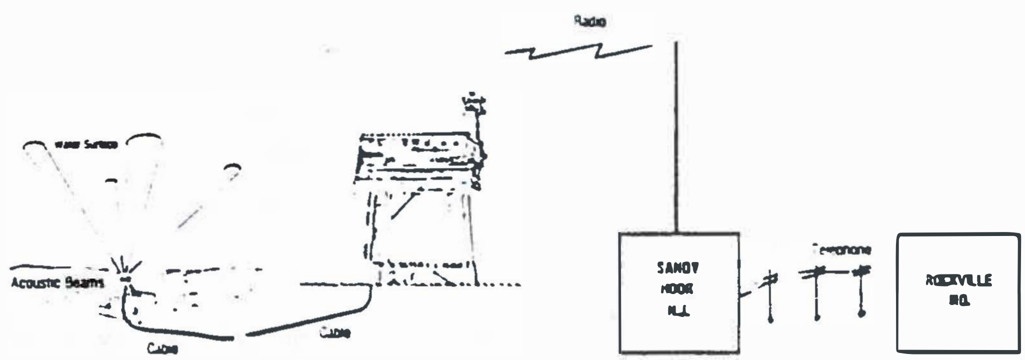
Remote acoustic doppler systems provide promise as a useful measurement tool. However, until all of their performance and operating characteristics have been fully explored and defined, caution should be exercised in using such systems for operational programs.

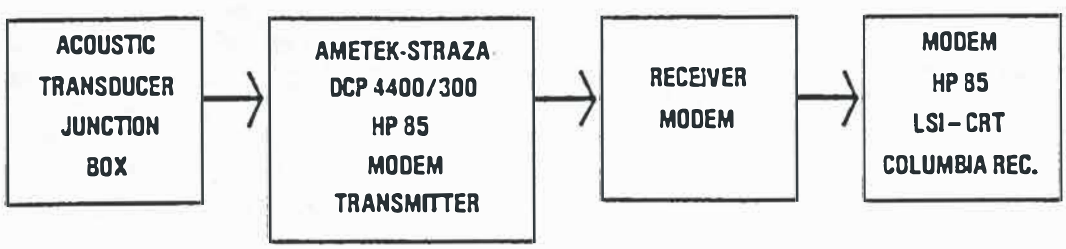
Mero, T.N., Appell, G.F., Porter, D.L., "Sea-Truth Experiments on Acoustic Doppler Current Profiling Systems," Oceans '83 Conference, San Francisco, CA, September 1983.

REAL – TIME HARBOR CURRENT MONITORING SYSTEM

NOAA – National Ocean Service
Ocean Systems Division

AMBROSE LIGHT TOWER, N.Y. HARBOR





EVERY 6 MINUTES:	**DISPLAY**	AVERAGE SPEED PROFILE AVERAGE DIRECTION PROFILE
	RECORD	1- AVERAGE VELOCITY & STD. DEV. FOR EACH BEAM IN 63 BINS 2- NUMBER OF PINGS 3- DEPTH, TEMP., DATE, TIME
EVERY HOUR:	**DISPLAY**	PROFILE OF BACKSCATTER SIGNAL STRENGTH FOR EACH BEAM
	RECORD	1- BACKSCATTER SIGNAL STRENGTH & STD. DEV. FOR EACH BEAM IN 63 BINS 2- TEMP., DATE, TIME

THE DEVELOPMENT OF THE TRANSVERSE DOPPLER CURRENT PROFILER

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Two years ago the Ocean Acoustics Group of AOML/NOAA became involved in the design of a proposed system for acoustically monitoring the flux of particulates through an estuarine transect. Available doppler profilers, both commercial and experimental units, were examined, but none was found to have the combination of range resolution, measurement accuracy and time resolution needed for flux measurement in an estuarine environment. A solution was found by adopting a geometry commonly used in LASER velocimetry to acoustic doppler profiling. Figure 1 shows how a central main transducer emits a colimated pulse of sound which defines a single sampling volume. The acoustic backscatter from this insonified volume is detected by the transversely mounted auxilliary doppler sensors. The direction lines from the transverse sensors to the insonified volume define two independent directions at angle Θ so that the components of velocity can be determined. This configuration thus measures the velocity from a single well-defined sampling volume. Profiler configurations that use the Janus geometry use multiple insonified volumes so that flow homogeneity must be assumed. This geometry can, of course, also be used in a downward looking mode as the tripod mounted system in Figure 2 suggests.

Two main types of signal processing are in use for the pulse train signals produced by doppler profilers. In single pulse processing a sample of the signal is range gated out for analysis to yield the doppler shift. The signal is viewed through the narrow time window of the range gate and this introduces uncertainities in the velocity estimate. There is no limitation on the time between

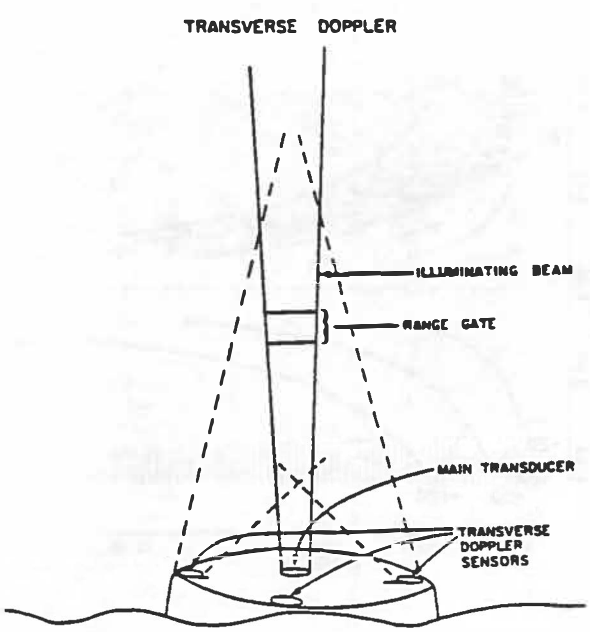

Figure 1. Upward looking transverse doppler profiler.

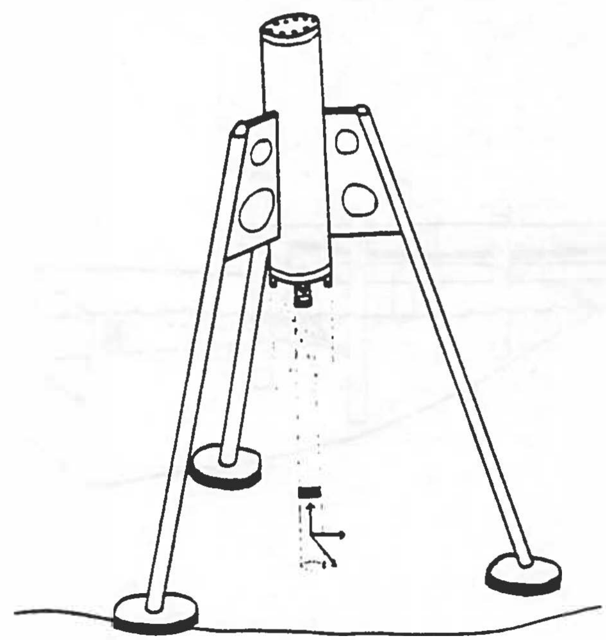

Figure 2. Tripod mounted transverse doppler boundary layer probe.

pulses, so that single pulse processing is appropriate for deep water where the time between pulses must be large, and where the range gate length can be many meters.

Pulse to pulse coherent processing samples the signal at a fixed delay after each pulse and then uses this series of samples as the input to the doppler analysis. The doppler shift and hence velocity must be small enough to avoid aliasing by the sampling rate which is limited by the maximum range. There is no limitation on the length of the sampled series so that accuracy of the estimates is limited only by the coherence of the signal itself. Pulse to pulse coherent processing is thus appropriate for very accurate measurement of slow flows in shallow water.

Typical estuaries are too shallow for single pulse and too deep and fast for pulse to pulse systems. Transverse doppler geometry alleviates the problem of pulse to pulse processing. The differential doppler shift between the two auxilliary transducers is reduced by the factor sinθ from the individual doppler shifts. The angle θ is determined solely by the range and the distance between the transverse sensors, so θ is well determined independently of transducer beam pattern so that θ can be a degree or so, extending the aliasing limit of pulse to pulse processing by an order of magnitude or more.

A test of the transverse doppler idea was conducted in the Bear cut channel in Miami near AOML off the end of a pier at the NMFS facility. As Figure 3 shows, a directional EDO-Western 200 kHz transducer and two broader beam Raytheon transducers spaced 60 cm were mounted at mid-depth in three meters of water, looking out, and were cabled to the recording system on shore.

The system was pulsed at 12.5 Hz so that the unambiguous range was 60 meters, and suprisingly good spectra were obtained out to

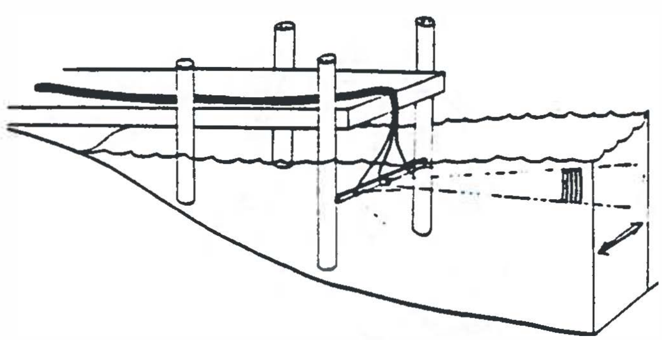

Figure 3. Bear cut transverse doppler test configuration.

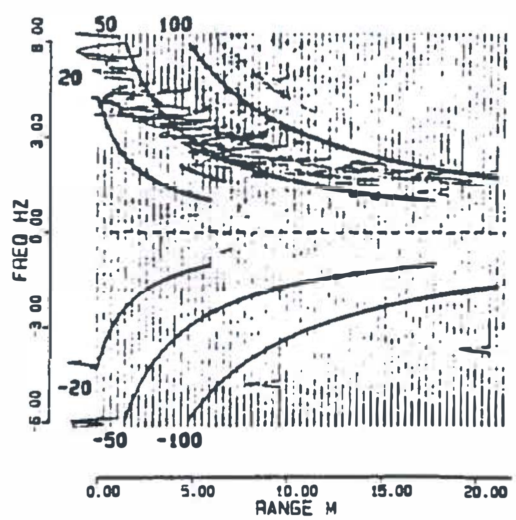

Figure 4. Profile of doppler spectra from Bear cut.

beyond 20 meters despite the unfavorable side-looking geometry. Figure 4 shows spectra from each 37 cm range gate stacked to the right. Spectral energy increases to the left and noise below a threshold has been suppressed. Each spectra covers +/- 6.25 Hz, but the velocity range varies with range as shown by the heavy lines of constant velocity.

The mean velocity as indicated by the spectrum peak, increases from about 30 cm/sec near the pier to nearly 100 cm/sec 20 meters away. This is expected and agrees with measurements taken of the end with a General Oceanics current meter. Note the peak at negative frequency in the first few spectra caused by aliasing. This profile was produced from 80 seconds of data so that these profiles incorporate only a fraction of the data recorded.

The suprising success of the transverse doppler configuration in a side looking mode has expanded the possible applications of doppler profilers. Figure 5 shows how doppler profilers might be mounted on the bottom or on the sides of a shipping channel to provide measurements of the flow in the channel. Conventional current meters cannot, of course, operate in the center of a shipping channel, so that the use of profilers would be a valuable adjunct to conventional current surveys. In the near future we hope to be able to test this concept in the government cut at the port of Miami.

There are many potential research applications of the transverse doppler idea. A tripod mounted system as shown in Figure 2 using sound in the megaHertz range produces profiles of water velocity, suspended sediment and turbulence in the marine boundary layer. By properly processing the signals, all 6 components of the Reynold's stress tensor can be estimated from a single insonified sampling volume. The system, of course, has minimal flow obstruction.

In summary, transverse doppler profilers should find use whenever energetic or inhomogeneous flows must be measured to high precision.

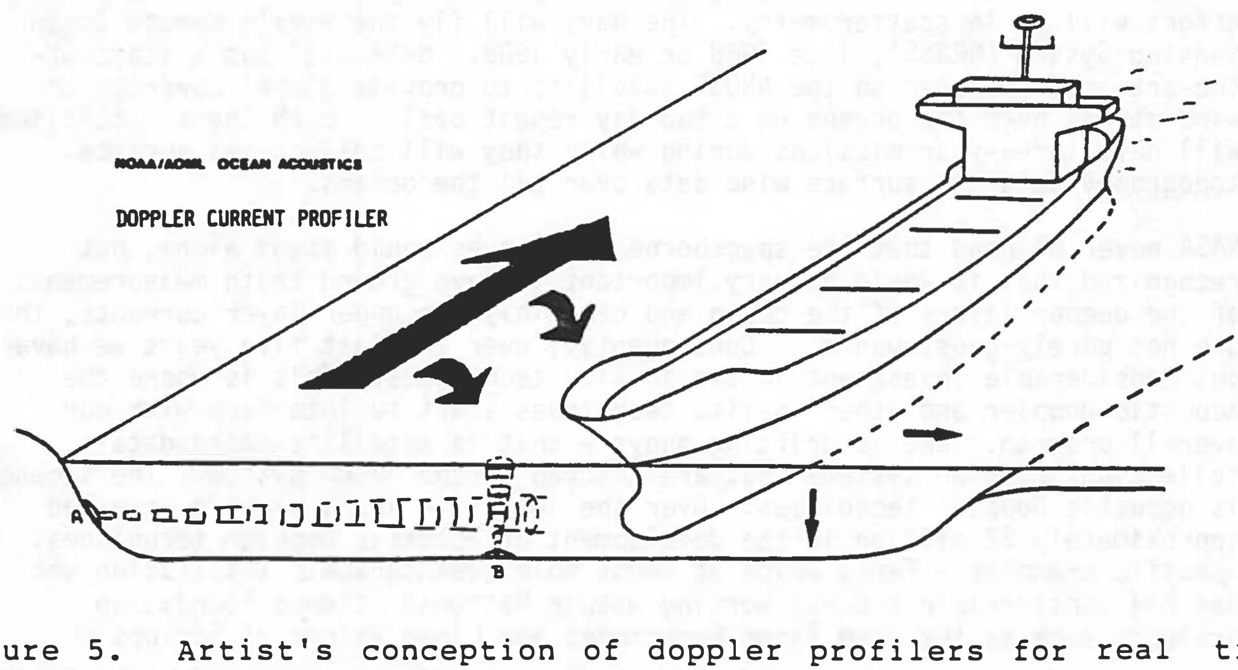

Figure 5. Artist's conception of doppler profilers for real time current monitoring within a shipping channel.

NASA'S REVIEW

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Washington, DC 20546

During the past five years NASA made a large investment in acoustic Doppler techniques. It might be useful for me to review our programs, what our intent was, and what NASA's future commitment might be to the various acoustic Doppler techniques. In NASA's Oceanic Processes Branch there are two physical oceanography programs; Ocean Circulation and Air-Sea Interaction. These programs have ambitious goals. For the first, it is to determine the general circulation of the oceans, its heat content and its horizontal heat flux. For the second, it is to assess the capabilities of spaceborne techniques to provide globe surface wind measurements and estimate air-sea fluxes. Specific objectives are to determine sea surface topography and estimates of surface winds. Altimetry measures the topography of sea surface from which you can compute the geostrophic current and scatterometry measures, over a very large area, the surface wind velocity or the surface wind stress.

NASA plans to provide these spaceborne observations in support of the large-scale experiments that will be occurring over the next decade. The World Ocean Circulation Experiment (WOCE), planned for the late 1980's going into the 1990's, will be coordinated primarily by the National Science Foundation. The effort involved here will be something of the order of what we saw with the Global Weather Experiment which focused on the atmospheric general circulation. The second large experiment planned is TOGA (Tropical Oceans/Global Atmosphere) - the lead agency for this effort is NOAA. NASA's particular contribution will be in the form of altimetry in TOPEX - a high precision altimeter which is proposed to fly in early 1989. The second NASA effort will be in scatterometry. The Navy will fly the Navy's Remote Ocean Sensing System (NROSS), late 1988 or early 1989. NASA will put a state-of-the-art scatterometer on the NROSS satellite to provide global coverage of wind stress over the oceans on a two-day repeat basis. Both these satellites will have three-year missions during which they will collect sea surface topography data and surface wind data over all the oceans.

NASA never planned that the spaceborne techniques would stand alone, but recognized that it would be very important to have ground truth measurements of the deeper layers of the ocean and certainly the upper layer currents, that are not purely geostrophic. Consequently, over the last five years we have put considerable investment in two in-situ techniques. This is where the acoustic Doppler and other in-situ techniques start to interface with our overall program. One is drifting buoys - that is satellite-based data collection/location systems that are tracked by the ARGOS system. The second is acoustic Doppler techniques. Over the last five years we have invested approximately $2 million in the development of acoustic Doppler techniques. Specific examples - Terry Joyce at Woods Hole Oceanographic Institution who has had considerable success working within National Science Foundation projects such as the Warm Rings Experiment and Lloyd Reiger at Scripps

Institution of Oceanography who has worked within the Polymode Experiment. These scientists were the pioneers in the shipborne acoustic Doppler development work. Later, we sponsored a bottom-mounted, self-contained Doppler unit that was developed by Neal Pettigrew and James Irish at the University of New Hampshire, working in conjunction with Rowe-Deines Instruments. This will be our last year of funding the development of these techniques. Our intent was development and now that they are commercially available, we are looking to NOAA, NSF and ONR to fund their use in the traditional research mode. The final application, an interesting one, will be similar to the Pettigrew-Irish effort except this will be a self-contained Doppler unit that can be used on either current meter moorings or on drifting buoys (developed by Russ Davis at Scripps Institution of Oceanography with Rowe-Deines Instruments). This is an exciting idea and we hope to see this tested in the next two years.

Looking at 1985 and 1986, TOPEX and NROSS are nearing approval and, consequently, we will be focusing more of our science and research monies on scatterometry and altimetry. Nonetheless, we will work closely with oceanographers in planning surface layer experiments that will incorporate the use of acoustic Doppler techniques and drifting buoy technology as components of WOCE and TOGA. I emphasize again - I think that acoustic Doppler techniques are unique in that ships go almost everywhere. Thus, the surface layer current information provided by acoustic Doppler instruments can provide unique spatial and temporal global coverage. When we invested in these programs, we intended that over the next few decades they would accumulate large amounts of statistical information to aid our understanding upper ocean current variability. These data will be crucial for validating the data from NASA's satellite missions planned for the next decade.

FIELD TESTS OF A SEA-FLOOR MOUNTED ACOUSTIC DOPPLER PROFILER

by

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A 308 kHz acoustic Doppler current profiler manufactured by RD instruments has been field-tested in a bottom-mounted, upward-looking configuration. The four-beam profiler has been deployed in several coastal regions as part of a battery-powered bottom instrumentation package which also includes temperature and pressure sensors and a data-logger. This Doppler Acoustic Profiling Current Meter (DAPCM) is deployed by simply allowing it to free-fall to the sea floor. Information from internal tilt and heading sensors provides the acoustic beam orientations which are required to accurately determine velocity profiles from the Doppler frequency data. The DAPCM is retrieved by command to an acoustic release which detaches an anchor and permits the instrument to float to the surface for recovery.

The DAPCM was first field-tested on the northern California continental shelf during the summer of 1982 in conjunction with the Coastal Ocean Dynamics Experiment. The profiler was deployed for 90 days in 133 m of water at a location approximately 300 m from current meter moorings which carried VMCMs at 20, 35, 55, 70, 90, and 110 m depths and VACMs at 10 and 120 m depths. During most of the experiment, hourly averaged Doppler frequency data with 4 m vertical resolution were recorded.

Analysis of the intercomparison data has shown striking agreement between the acoustic Doppler and mechanical current measuring techniques. Vector correlation coefficients were 0.97 or greater for the lower 100 m, and mean and rms speed differences were less than 1.0 and 3.0 cm/sec, respectively. In the near-surface region (10 m) the correlation coefficient decreased to 0.94 and mean and rms speed differences increased to 3.7 and 8.1 cm/sec. These increased differences are believed to reflect wave induced contamination of the VACM and acoustic contamination of the DAPCM.

The usefulness of the high degree of vertical resolution provided by the Doppler profiler is emphasized in Figure 1 which shows an hour-averaged profile of a complex flow structure observed in the Coastal Ocean Dynamics Experiment. While the comparison at corresponding depths is excellent, the conventional current-meter mooring was unable to resolve the vertical structure of the cross-shore flow.

After some modification, the DAPCM was deployed for a short test in the Gulf of Maine in August, 1983. Preliminary analysis of these data indicates that the vertical range of the profiler exceeded the 188 m water depth. Vertical profiles of backscattered signal amplitude show a clear temporal variation which is consistent with the diurnal migration of zooplankton observed in simultaneous plankton samples. Detailed correlation between scattering levels and plankton abundance has not yet been shown.

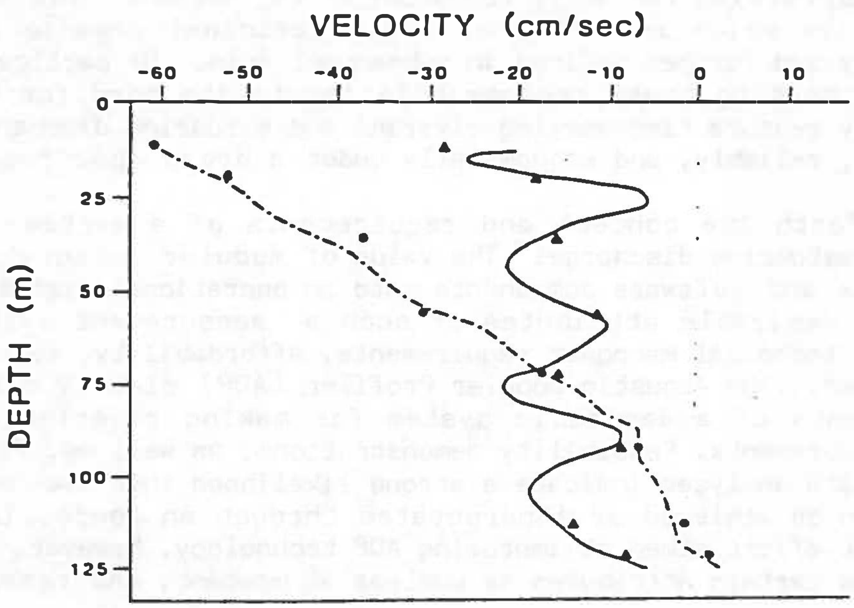

Figure 1. Hour-averaged alongshore (dashed) and onshore (solid) Doppler velocity profiles with 4 m resolution. Symbols represent comparison with current meter mooring.

MEASUREMENT OF RIVERINE AND ESTUARINE DISCHARGE

by Robert A. Baltzer[1]

ABSTRACT

The Water Resources Division of the U. S. Geological Survey (USGS) has the principal responsibility within the Federal Government for providing hydrologic information and for appraising the water resources of the Nation. This is a statutory responsibility which is contained in the original organic act establishing the agency and further defined in subsequent acts. Of particular concern to the USGS in meeting these responsibilities is its need for the capability to directly measure time-varying riverine and estuarine discharge, and to do so accurately, reliably, and economically under a broad spectrum of field conditions.

This paper sets forth the concept and requirements of a system for measuring riverine and estuarine discharge. The value of modular integration of modern-day hardware and software components into an operational system is underscored. Specific, desirable attributes of such a measurement system --portability, minimal technical manpower requirements, affordability, to name but a few--are identified. The Acoustic Doppler Profiler (ADP) clearly meets many of the requirements of a desirable system for making riverine and estuarine discharge measurements. Feasibility demonstrations, as well as, field tests and comparative data analyses indicate a strong likelihood that even more desirable attributes can be achieved or incorporated through an appropriate research and development effort aimed at improving ADP technology. However, the feasibility of achieving certain attributes is unclear at present, and remains to be demonstrated.

An Ametek/Straza 4400/300 ADP[2] is undergoing operational evaluation by USGS. This ADP system, delivered in June 1982 by the manufacturer was first tested in the Mississippi River at Baton Rouge, Louisiana. It is currently undergoing evaluation in the Lower Potomac Estuary. For the latter study the system was installed on the R/V Orion with the acoustic transducer mounted on a strut over the port side of the vessel. Directional, earth-coordinate data were supplied by a Sperry Mark 37 gyrocompass. Comparative channel cross-sectional velocities were obtained using a combination of point data from moored current-meters interspersed with vertical velocity profile data obtained at five fixed locations in the channel cross section. Preliminary results indicate that both good and poor data comparisons were obtained. As a result of these evaluation efforts several modifications and enhancements have been identified as necessary improvements to this system.

The Ametek/Straza 4400/300 is a working prototype ADP. It affords an excellent basis upon which to test and evaluate hardware, microprocessor, and software improvements and enhancements. For the longer range, research and development efforts need to be directed toward improving acoustic transducers, improving acoustic signal discrimination and processing, and to exploring alternative acoustic beam configurations. The advantages and difficulties of using higher acoustic frequencies to obtain better resolution in shallow waters clearly needs to be explored. New ADP systems should strive for lower power consumption, portability, and modular design of both hardware and software components.

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[2] Any use of trade names and trademarks in this publication is for descriptive purpose only and does not constitute endorsement by the USGS.

Small Scale Velocity Fluctuations and Doppler Sonars

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Remote acoustic sensing with Doppler sonars provides a technological option for discerning the relative temporal and spatial nature of turbulence or small scale velocity fluctuations in the open ocean. Active turbulence or small scale random motion is thought to be confined to isolated patches which occur intermittently in space and time, decay rapidly, and occupy a small volume fraction of the water column at any one time. Remote sensing is a promising approach to observing and studying this intermittent process since these systems are capable of observing phenomena over a relatively large range interval (compared to towed or dropped instrument packages) with reasonable spatial resolution at one instant of time.

Several objectives, however, must be satisfied before remote sensing of open ocean small scale velocity processes is possible. The most basic of these objectives is the design and development of accurate and reliable Doppler sonar hardware. Benchtop or laboratory calibration procedures need to be developed to verify instrumentation performance prior to field deployment. These calibration procedures ideally should exercise the sonar system over its expected operational dynamic and velocity range. Experiments need to be done to verify instrument performance in the open ocean.

Valid methods must be developed to analyze the data obtained with these remote sensing systems. This oceanic sonar data is nonstationary in space and time and little consensus exists on optimal data processing schemes. Careful studies applying alternative processing schemes to common sets of well documented data taken in a variety of experimental scenarios ranging from extremely simple to moderately complex should serve to illustrate the relative advantages and disadvantages of various analysis algorithms. Care must be taken to state under which assumptions the experimental results and conclusions are expected to be valid.

Here, initial efforts to satisfy a few of these objectives are reported. Laboratory calibration procedures have been carried out prior to field deployment on several different sonar systems. Experimental techniques have been developed and implemented to measure directly the errors associated with velocity estimation in the open ocean. These techniques have lead to an experimental determination of a value for the standard deviation constant which parameterizes velocity estimation errors for pulse-to-pulse incoherent sonars. This constant and its functional form were derived by Theriault on theoretical considerations alone. Various alternative formulations of a widely employed Doppler sonar data analysis algorithm have been applied to a common data set and the velocity estimation performance behavior of these alternative formulations tabulated. In addition, a new data analysis procedure appropriate for Doppler sonar data has been developed. This procedure is an adaptation of an AutoRegressive (AR) spectral matching technique which is capable of modeling the Doppler spectra at closely spaced range gates. One of the main advantages of this technique is its ability to locate regions of data where the Doppler spectrum has an asymmetric or multipeaked structure. When such a region is encountered one of the assumptions under which the velocity field is often inferred is strongly violated. Detection of these regions prior to data interpretation avoids drawing erroneous conclusions about the corresponding velocity field.

TIME-EVOLVING SPECTRAL ANALYSIS AND THE ACOUSTIC REMOTE SENSING OF OCEAN CURRENT VELOCITY

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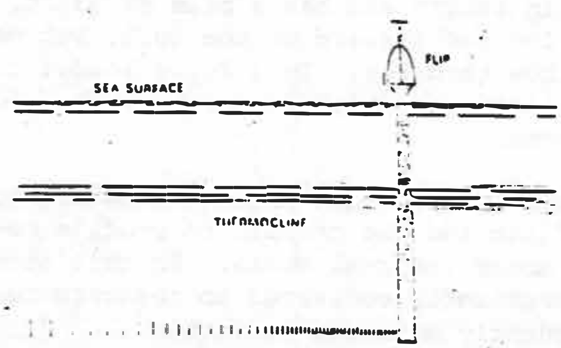
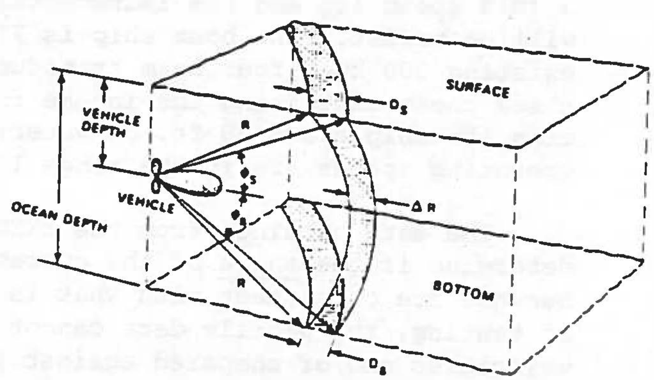
In the Doppler sonar problem, following the time-evolving (corresponding to range) spectral characteristics of a returning echo is of interest. A simplistic model of the corresponding range-Doppler map (a three-dimensional surface) consists of a single symmetrical hump whose track as a function of time is indicative of the radial velocity of scatterers in successive range cells. A more careful consideration of both the acoustic backscattering process and the sonar transducer's spatial response characteristics suggests, however, that a more complex model of the time-frequency surface is required.

A simplified graphic representation of the volume being probed by a Doppler sonar mounted on the bottom of FLIP is shown below. In the case of the 70 kHz Doppler sonar designed and fabricated by Rob Pinkel (MPL), the main beamwidth of the transducer is $\sim 1^{o}$ and the range of the sonar is $\sim$ 1.5 km A more detailed description of how a practical sonar actually views the ocean needs to consider both the transducer's sidelobes and the boundaries (surface and bottom) of the volume being probed. These considerations are taken into account in the reverberation model geometry also shown below.

The spatial transfer function characteristics of a transducer have a significant influence on the time (range) - evolving shape of the reverberation power spectrum. The distinctly different sources of backscatter (e.g., surface, bottom, plankton in the volume, and discrete scatterers such as fish) viewed through that spatial transfer function yield a spectrum which is complex and highly variable. Thus, in general, the use of a single, symmetrical hump model of the reverberation power spectrum for Doppler shift estimation purposes simply is inadequate. Modeling the reverberation time series as an autoregressive (AR) process is one promising approach for implementing multiple-hump power spectral estimation.





DOPPLER ACOUSTIC CURRENT PROFILERS ABOARD COMMERCIAL "SHIPS OF OPPORTUNITY"

D.L. Cutchin
Scripps Institution of Oceanography

Together with Ametek-Straza we are in the process of developing and testing a system which will allow for the use of a 300 kHz DCP 4400 in parallel with a standard Ametek 4015 acoustic Doppler speed log. We are thinking in terms of being able to add this system, "piggyback" fashion, to 4015 equipment already present and in use on host "ships of opportunity." For this reason we are attempting to design a system which will not interfere in any significant way with the use of the 4015 for navigating the host ship. We are also trying to make operation of the piggybacking equipment simple enough so that it can be easily serviced by ships' officers and will not require the full-time presence of an oceanographic technician.

Beyond developing the piggybacking system and a standard mode of operation, our short-term objectives are to: 1) identify any special problems associated with the use of commercial ships, which are characteristically larger and faster than research vessels, and 2) to demonstrate to the shipping industry that our profiling equipment and our activities are basically compatible with the smooth running of a ship.

The use of volunteer commercial ships for acoustic current profiling is a possibility worth exploring because installation plus operations costs are very modest. This is especially true when the host ship already has an Ametek 4015, or equivalent, but it also applies to volunteer ships which require the complete installation of transducers, wiring, etc. The major cost advantage comes in the form of free ship time. The data collecting potential of commercial ships is enormous. Their ability to monitor large-scale upper ocean variability lies somewhere between research vessels and satellites. There are over twenty thousand large commercial ships plying the trade routes of the world. Of special interest is the fact that several hundred of these already are outfitted with Ametek 4015 speed logs.

As part of testing the piggyback system we will soon install the prototype unit on a 41,000 Dwt EXXON tanker which sails regularly between Southern California and Texas via the Panama Canal. This ship is presently equipped with a 4015 speed log and the incremental costs to install a profiling capability will be modest. The host ship is 718 ft. in length and has a beam of 93 ft. The existing 300 kHz, four beam transducer is located forward on the hull, but behind a sea chest containing the intake for the bow thruster. In a fully loaded condition the ship draws 38 ft. of water; in ballast condition it draws 23 ft. Normal operating speeds are in the range 15-18 knots.

The data obtained from the EXXON tanker installation will be examined to determine if the <u>shape</u> of the current profiles and the profile to profile coherence are consistent with what is known about the real ocean. At this stage of testing, the profile data cannot be conveniently converted to absolute current velocities and/or compared against independently measured currents.

It is our expectation that this work on the development of a commercial ship installation capability for the Doppler profiler will proceed in parallel with the further development of the DCP 4400 hardware, the development of scientifically based data analysis procedures and the realization of a highly precise global navigation system. If these all come together in the next two years, as we believe they will, they will provide the basis for a very powerful and cost-effective technique for monitoring the upper ocean.

ONR'S REVIEW

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I am in the Environmental Science Directorate of ONR and support physical oceanography there. There are a number of other branches in the Directorate that do acoustics of all sorts and also some people interested in coastal oceanography who are also quite interested in some of the techniques you have talked about today. Let me summarize our program: basically the Navy's interest in physical oceanography spans the entire spectrum from basin-wide circulations down to ocean turbulence. We characteristically divide the program into three parts: a) General Circulation - or the steady state ocean flow. We concentrate on strong current regimes, e.g., Gulf Stream system, Kuroshio currents and that sort. And also the thermocline and water mass properties; the establishment of the basic structure of the ocean. The thing this generally provides, is the ocean environment with respect to the overall acoustic propagation velocity, b) The Mesoscale Variability - something on the order of maybe 100km - 200 km, typically the intense ocean eddies, warm core rings, cold core rings, ocean fronts - thing of that type. That is an area of emphasis primarily because of the Navy's operations. Resolution on these scales is typically on orders of weeks and are commensurate with some Navy predictability needs, c) Further down in size we come to the small-scale part of the problem. There we emphasize the development of the mixed layer, the inertial/internal wave oscillations, establishment of the internal wave climate and on dowm to fine structure.

The program is essentially divided for bureaucratic purposes into a core and a special focus program. These upper three entries are supported via the normal funding provided by our bosses for us to support what we think is the basic core part of the discipline. Then, from time to time, we identify certain areas that we think are right for a particular focused approach. We call these special focus programs (SFP's). Currently now we have two of them. One is remote sensing, which is primarily the development of techniques to implement satellite products to solve physical oceanographic questions and the second is upper ocean variability, which is primarily a large program. It is operating what we call LOTUS, (LOng Term Upper ocean Study), a two-year upper ocean mooring to look at internal waves and MILDEX (MIxed Layer Dynamics Experiment) is now on a six-week experiment to observe the development of the mixed layer west of California. We have two new SFP's that are coming on line next year. One is an air-sea interaction program which will focus on some processes controlling fluxes across the air-sea boundary. This is not the air-sea interaction in a global sense perhaps that Dr. Patzert talked about, but rather an assessment of what the physical processes really are like. We are looking more at what happens on an area perhaps 100km on a side. Certainly we are planning a couple of field experiments there. We will probably use some moored instrumentation and drifting buoys and also perhaps the application of acoustic current profiling techniques. The second is the Southern Ocean Study which is an anomaly for us. It is a large-scale/mesoscale field program in the Southern hemisphere, a place where the Navy has not supported much work lately, but we have some areas where we would like to do some assessments. We are concentrating primarily, in that program, on the south Atlantic and western Indian Oceans.

That is the overall view of the program and I hesitate to try and fit in the various sorts of pieces that really pertain to the techniques we are talking about today. I guess what I would rather do is to suggest to you that our philosophy is to support this work described above. The profiler has not been heavily invested in during its development, but now that the acoustic processes seem to be coming on line, we really will accept the challenge that Bill Woodward has given us and consider the application of it to those processes or particular phenomena which we think will be of high priority to the Navy.

ACOUSTIC CURRENT PROFILING IN THE FLORIDA CURRENT

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Sections across the Florida Current with Ametek Straza acoustic Doppler log model DCP 4400, i.e. 3 beam, 115 kHz, installed in R/V CAPE FLORIDA, were carried out during several surveys in the frame of the Subtropical Atlantic Climate Studies (STACS) project. Intercomparisons were made with current profiles obtained by the PEGASUS system - operated by Drs. K. Leaman (RSMAS) and R. Molinari (NOAA/AOML) along positions 1-8 marked in Fig. 1; and also with moored current meters deployed in an array of 5 moorings (Fig. 1). Ametek data logging was through HP85 and on 5" or 8" floppy disks.

Navigation was by LORAN (model North Star 7000) logged on tape through SAIL system. A spline fit was put through the LORAN positions to reduce the scatter on the ship velocities. Typical r.m.s. fluctuations of ship speed derived from LORAN were ± 5 cm/s for 8 min. time segments.

One possible check of Ametek velocity measurements is comparison of bottom tracking with LORAN. A regression between both kinds of ship speed for 15 min. (380 pings) data segments yields a r.m.s. deviation of ±14 cm/s between both methods. As pointed out above, a significant part of that is due to LORAN positioning itself.

An intercomparison of Ametek profiles (bin width 6.4 m) with PEGASUS profiles was carried out at station 3 (Fig. 1). Fig. 2a shows one such intercomparison for the northward (downstream) velocities indicating reasonable agreement in the top 180 m; below that rapid increase in std. deviations of the Ametek occurs and the downward shear seen in the PEGASUS profile is no longer followed by the Ametek profile. Analysis of the return energy showed that at about the 180 m level the backscatter return signal was lost in the noise. This depth limit did not vary much across the Florida Straits, nor between day and night.

In Fig. 2b, another intercomparison at an earlier time is shown from that same measurement series; bin width again 6.4 m. Profiles are least squares fitted over the top 150 m. R.m.s. deviations between the Ametek and PEGASUS velocities are 4.2 cm/s for Fig. 3a (best fit for top 150 m only) and 2.7 cm/s for Fig. 3b, respectively. The average of 6 PEGASUS profiles taken over an 11 hour period for which the fits were carried out resulted in a total r.m.s. difference of ±4.6 cm/s for the relative profiles over the upper 150 m. Some fraction of <u>this</u> deviation will again be due to temporal and/or spatial separations between the Ametek bins and the PEGASUS, because the PEGASUS cast from R/C CALANUS was commenced about 100 m or so downstream from the R/V CAPE FLORIDA doing the Ametek profiles and then the PEGASUS drifted further downstream while descending.

Other intercomparisons were done with moored current meters which recorded in 100 - 200 m depth range at the 5 positions in Fig. 1, again using averages over 380 pings. The overall r.m.s. differences in this case were $\pm$ 26 cm/s, i.e. a significantly higher, but much of that difference must be attributed to small scale physical variability due to the fact that the Ametek sample could not be taken at the exact current meter position but only as close as LORAN positioning would put the ship, i.e. within several 100 m up to several km..

In June 1983, zonal sections across the left side of the Current, between 26°40'N and 27°10'N were carried out jointly by the Ametek ship log and the GEK system operated by Drs. P. Koske/J. Wittstock (Kiel University, West Germany) but this analysis is still in progress.

Acknowledgements:

I thank Geoff Samuels for help in the data processing, financial support by the Office of Naval Research under contract N00014-80-C-0042 is gratefully acknowledged.

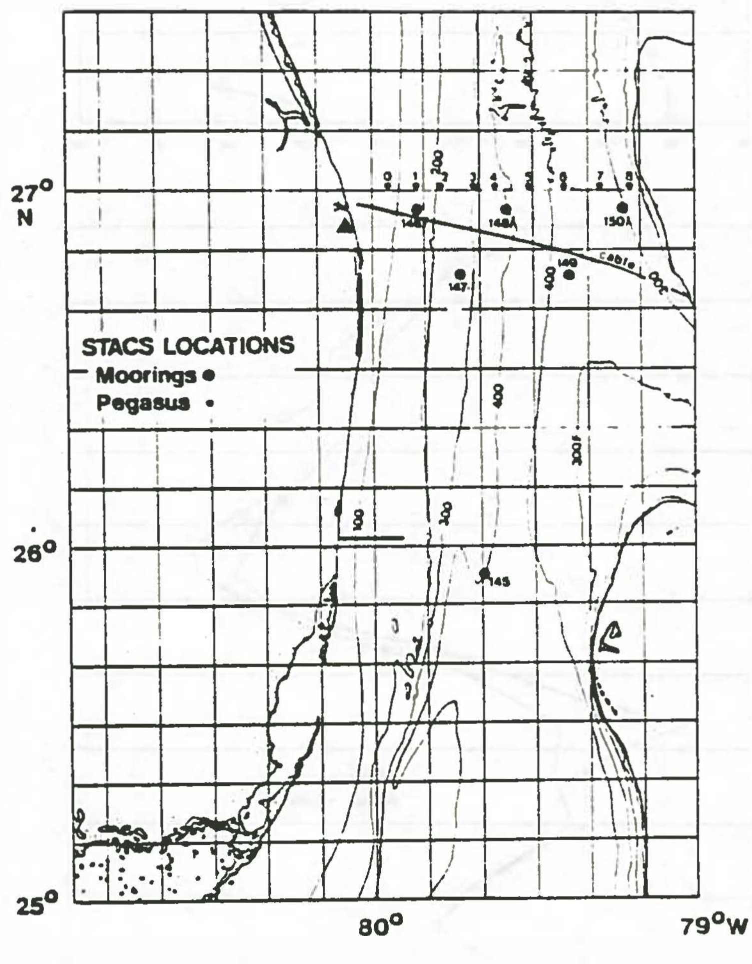

Fig. 1 Location of moorings and PEGASUS stations in Florida Current during subtrotopical Atlantic Climate Studies (STACS). Intercomparisons of PEGASUS with Ametek (Fig. 2) were taken at Station 3.

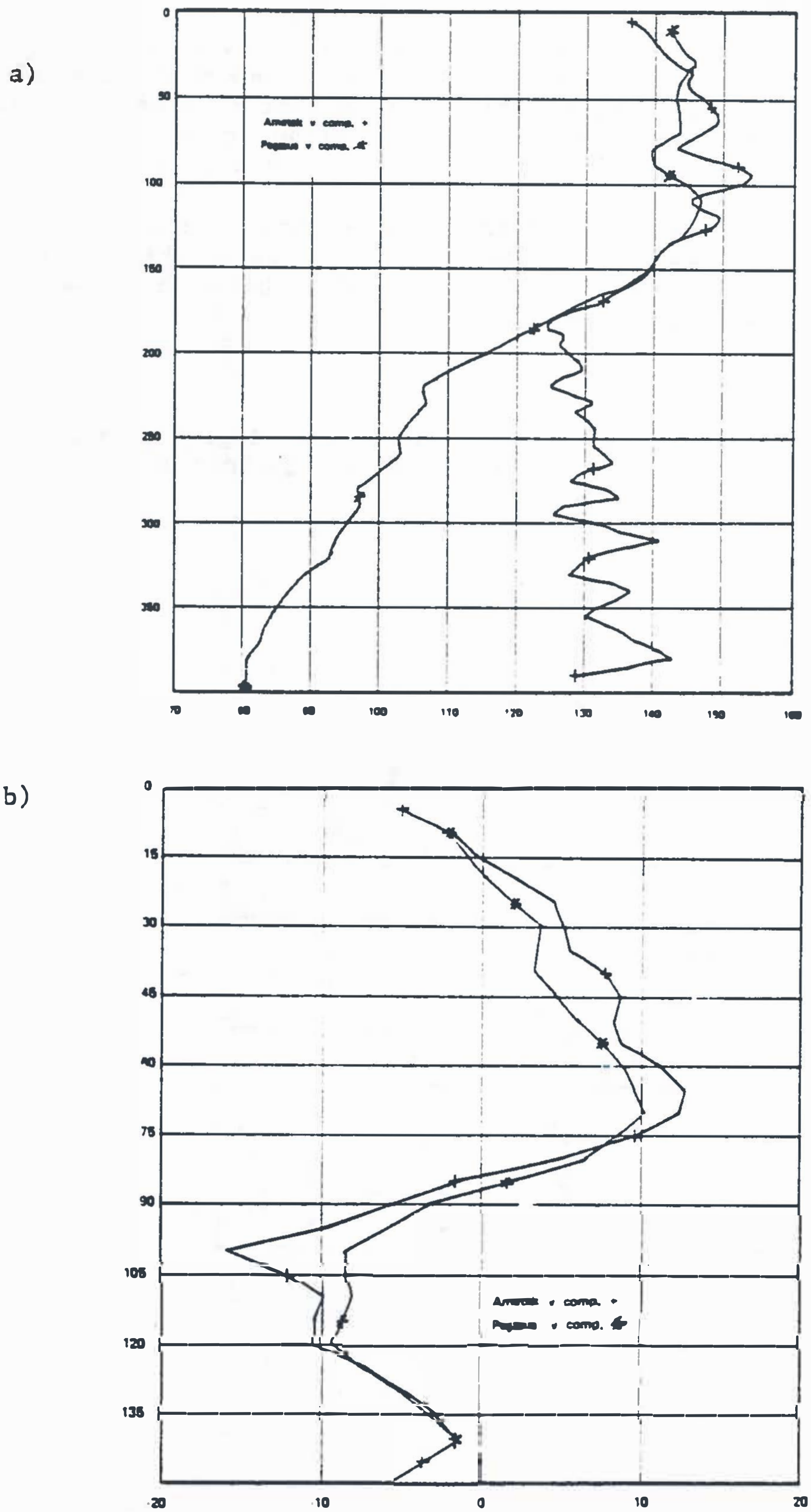

Fig. 2 PEGASUS (*) and Ametek-Straza (+) profiles (bin width 6.4 m) on 16 September, 1982:
a) depth range 0-400 m during 23:00 - 23:30
b) depth range 0-150 m at 18:00-18:30

ACOUSTIC-DOPPLER VELOCITY MEASUREMENTS IN WARM CORE RINGS

M. Kennelly and T. Joyce

Abstract

Acoustic-Doppler velocity measurements were made during three periods in the lifetime of Warm Core Ring 82B: April, June and August. In April, 82B had a strong anticyclonic circulation with maximum currents of 1 m/sec. By August, the currents had decreased to approximately 0.5 m/sec. Vertical profiles of horizontal velocity revealed a weak subsurface velocity maximum, consistent with the hydrographic sections of density which showed isopycnals sloping upward near the surface while those below 100 dbars were depressed relative to the surrounding Slope Water. The angular rotation rate of the ring core increased from 1.6×10^{-5} sec^{-1} in April to 2.5×10^{-5} sec^{-1} in August.

Ring Currents were decomposed into radial and azimuthal components relative to a moving ring center. In June, the maximum azimuthal current occurred at 40 km from ring center. There was not a significant radial component to the velocity. Vorticity calculations were done for a radial section of 82B revealing a core of uniform relative vorticity. A polynomial fit to the azimuthal velocity field was subtracted from the June data. The presence of the shelf-slope front and a cyclonic ringlet northeast of ring center were noted in the residuals. The remaining residual structure is attributed to ring translation.

NSF'S REVIEW

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The National Science Foundation's interest in acoustic profiling stems from the Division of Ocean Sciences, one of 18 research support divisions within NSF which with the addition of the Ocean Drilling Program, has become the largest research support division within NSF, with a total budget of approximately $112 million - that is the good news. The bad news is that while our budget went up about 10 percent during the last year, our proposal pressure went up about 20 percent - we are still looking at only about a 25 - 30 percent success ratio of all proposals that we receive. The Ocean Sciences Research Section is comprised of four parts - physical oceanography is the one that really has the interest in acoustic profiling. We cover as many of the same areas as Tom Spence discussed with ONR, we coordinate very heavily between us. We had a large physical oceanography component of the warm core ring experiment. We are also studying the physical processes of the benthic boundary layer work, fronts, jets, eddies, mesoscale, and the microscale. So again I want to emphasize the science point of view of what Tom said "that we are interested in learning how we can apply the technology that has been discussed here to the ocean science research objectives that we have."

The other area of interest, other than pure science, is development. The Oceanographic Facilities Support Section has a 30 some odd million dollar budget, about 80 percent of that - $27 million goes merely to get the oceanographic research vessels away from the dock. It buys fuel, crew and it doesn't really address doing science at sea. The Technology Section addresses such things as winches and wires. We've started a program in the last two years that says we can drive these ships around the ocean forever and unless we get good instrumentation, up to state-of-the-art instrumentation on these ships, we might as well be offering a very expensive taxi fleet. So we were able to wrestle some money - about 1/2 million in 1982 and 1/2 million in 1983 and I think three days after the announcement for instrumentation development proposal program went on the street, Roger L'Hermitte was in the office with a proposal. We are not able to do development to the state that NASA did without some more work at NSF, which we are continuing to do. This is the third year for this instrumentation development.

Right now I have $2.5 million worth of proposals on my desk and about half a million dollars worth of potential funding. These are all really good ideas - all top notch people proposing to do this work - this is the type of pressure it takes to present our case if we are to increase our funding. We would like to be able to use acoustic profiling techniques in the work that we sponsor. We would like to have your people come to us to show us how acoustic doppler profiles can be used in the context of the work that we support. There is one additional possibility within NSF and that concerns small business innovations research programs. This is something that is supported in most of the major agencies now. We have a program, like the Navy does, where we will receive proposals from small business, defined as those companies having less than 500 employees. We receive these proposals in a central office and they are distributed around the Foundation to the different research sections. We are undergoing the final phases of the review process for FY 84 of small business proposals where we received 40 proposals from small business for ocean sciences related activities. Of those 40, I think 6 had to do with acoustics, signal processing or Doppler. That is another potential for very specific funding.

PULSE COHERENT DOPPLER SONAR FOR MEASUREMENT OF WATER CURRENT AND TURBULENCE

R. LHERMITTE, University of Miami

The purpose of the instrument presented here is to acquire observations of vertical profiles of water mean velocity and turbulence without interfering with the flow. Progress in the understanding of water turbulence relies heavily on new experimental data. If the measurements reach scales extending down to the turbulence dissipation range, a host of problems can be effectively investigated (turbulence intermittency, mechanisms and conditions for turbulent energy generation, dissipation, and transport to or from larger scales).

A pulse Doppler sonar methodology, which relies on the tracing of small scale water velocity by low-inertia targets, has been selected. If the concentration of the targets is sufficient, the variance of the velocity distribution (Doppler spectrum) can be interpreted as the integral of the turbulence spectrum from a low wave number associated with the scattering volume size to a high wave number derived from the average spacing between targets. Other sources of spectral variance foreign to water turbulence (target transit time in the scattering volume and the effect of mean velocity shear) can be identified and corrected for.

In order to observe the Doppler spectrum effectively, we must rely on a frequency resolution much better than the width of that spectrum. This requirement is incompatible with conventional Doppler sonars in which the Doppler information is extracted from the short dwell time associated with the transmitted pulse duration. The method we have implemented still relies on a pulse waveform, but with phase coherence maintained over a long time, thereby allowing evaluation of the Doppler frequency shift from the pulse to pulse signal phase change associated with targets' movements.

The backscattering signal is continuously sampled at the sonar pulse repetition rate (simultaneously at a multitude of range gates). The maximum coherent signal dwell time and associated Doppler frequency resolution is thus only limited by the transit time of the targets passing through the scattering volume. The sampling is done independently at range intervals equal to the sonar pulse width and the maximum range resolution relates only to the shortest pulse allowed by the sonar wavelength.

The spectrum of target velocity in the scattering volumes is evaluated performing a Fourier transform of the received signal sampled at each of the range gates. The mean and variance of that velocity distribution are derived either from spectral moments or directly from the received signal autocovariance function. The first moment or mean is associated with the mean flow. The variance is related to the intensity of water turbulence.

The sampling of the signal at the sonar repetition rate produces folding ambiguities in the evaluation of both Doppler frequency and target range, which can be dealt with by use of multiple pulse repetition rate techniques. For a given sonar frequency, λ, we have: $R_o V_o = c\lambda/8$, where $\pm V_o$ is the maximum unambiguous velocity, R_o the maximum unamgiguous range, and c is the sound wave velocity in water. A lower sonar frequency is more advantageous, a condition opposite to that applicable to the single pulse Doppler sonar operation.

However, the limitation in coherent signal dwell time which is imposed by the short residence time of the targets in the scattering volume constitutes a limit to the use of low freqnency. This effect is associated with a Doppler frequency smearing, ΔV, proportional to the velocity, V, of the target when passing through the scattering volume. The ratio ΔV/V is inversely proportional to the scattering volume dimension which must therefore increase with the sonar signal wavelength to maintain the same relative accuracy in velocity. This indicates that observations of the velocity distribution inside small scattering volumes (linear dimension of a few centimeters or less) is only practical for short sonar wavelengths.

Several radial velocity components with the sonar beam oriented in different directions are needed to describe the three dimensional velocity process for mean and turbulence. Such measurements have been conducted using a five-beam transducer platform installed on the bottom in a tidal channel, which offers the convenience of well defined and repeatable flow characteristics.

The tilted beams oriented in the N-S-E-W directions are successively switched following a sequence automatically repeated through the experiments. The sequence includes a fifth beam directed vertically which provides accurate vertical velocity data. Recently, the elevation angle of the tilted beams was increased from 45^o to 75^o to provide greater unambiguous horizontal velocity (±40 cm/s with a maximum range of 15 meters) and better immunity from the deleterious effect of vertically directed sidelobes on the data. The beam angles relative to one another are calibrated within better than 0.2^o and to prevent leakage of the much larger mean longitudinal flow into the vertical beam data, the transducer platform must be levelled underwater so that the verticality of the center beam is within less than 0.02^o.

Most of this research has been done so far with fixed beams. However, beam scanning techniques can extend the capabilities of the method. If the transducers are installed at different locations, motion fields can be mapped in two or three dimensional space, using a beam scanning methodology similar to that developed for Doppler weather radars.

Acknowlegments

This research is supported by NSF Grant OCE-82-14018.

Caption for the figure.

Vertical profiles of horizontal velocity, u, and the vertical velocity variance , σ_w^2 and the spectral variance observed with the tilted beams, σ_u^2 and σ_v^2. The observations were made in a tidal channel during a flood regime. Note that below the nose of the u profile the variances of the vertical velocity and the radial velocities observed by the tilted beams are the same which depicts isotropic turbulence. Abose the velocity profile nose, σ_w^2 becomes smaller than σ_u^2 and σ_v^2 which indicates horizontally elongated eddies there.

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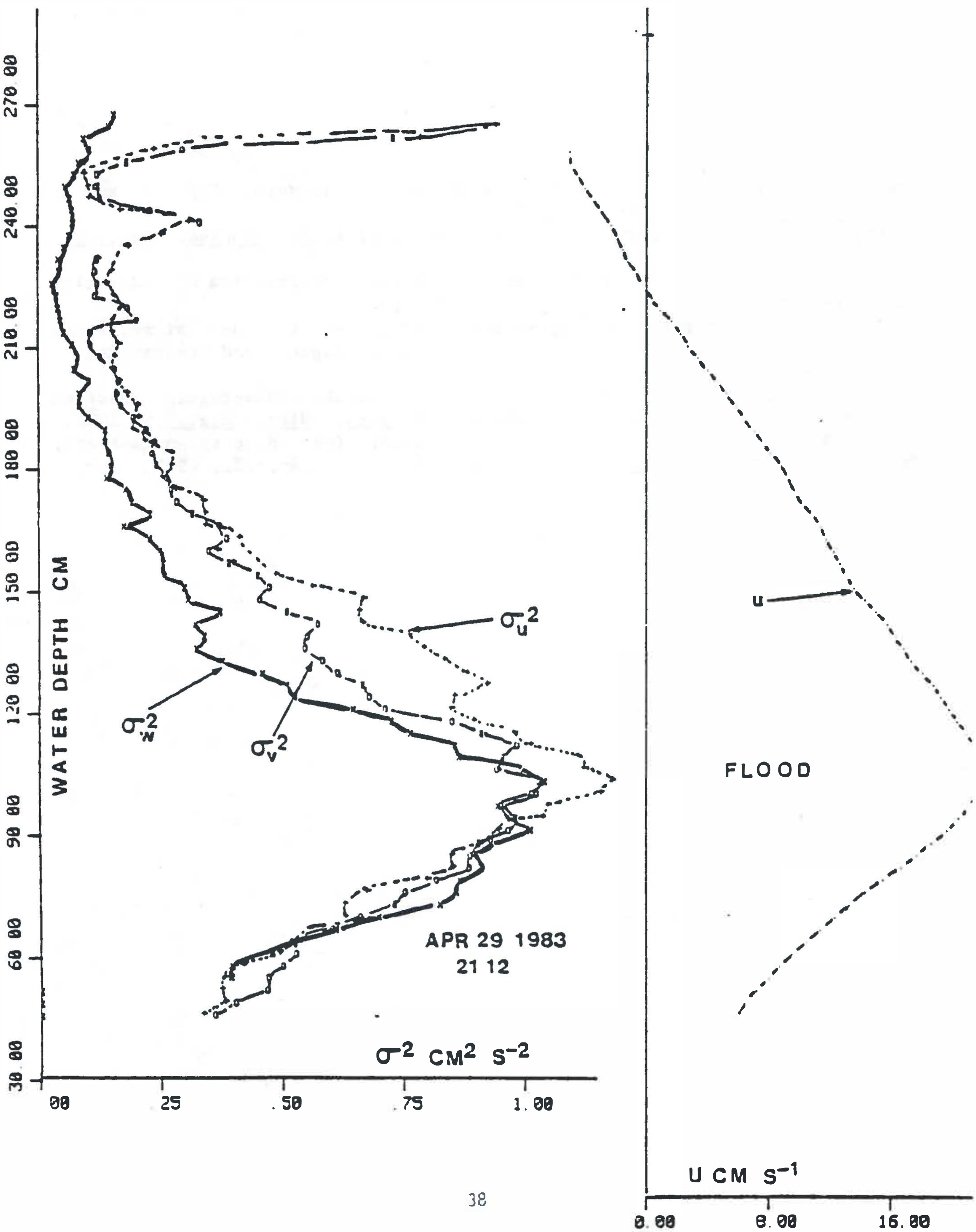

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NRL'S EXPERIENCE WITH ACOUSTIC PROFILERS

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November 2, 1983

NRL has been evaluating acoustic profiling techniques for several years. In 1979, an Ametek/Straza Interim Doppler Shear Profiler (DSP) was obtained and operated during several seagoing experiments. This system is a modified ship's speed log and transmits 300 KHz signals down four beams in a Janus array and then samples the reverberation return in 32 range bins. The evaluation consisted of checking the systems reliability, i.e., its ability to record data, within the precision limits of the system, that accurately portray the currents beneath a ship and to determine what the precision limitations are. NRL produced a report* in September 1982 that concluded that the system was extremely reliable, but that its precision was poor particularly with regard to vertical resolution.

As part of the evaluation, NRL developed software to convert the Doppler shifts into velocity profiles that utilized roll, pitch and heading data and a reference layer concept to obtain geophysical velocity estimates, relative to a given depth range, on each ping--before averaging. This software is continually being improved.

In the Spring of 1982, the new Ametek/Straza Doppler Current Profiler 4400 (DCP) was delivered to NRL. This system comes in two versions; one using 115 KHz signals transmitted down three beams and sampled at 64 range bins and another using 300 KHz signals transmitted down four beams and also sampled at 64 range bins. The difference between the two is that the 115 KHz version will record data to deeper depths (200-300 m), but the 300 KHz version will be more accurate and have greater depth resolution. After two seagoing tests, NRL feels that the new processor on the DCP is definitely superior to the interim processor, particularly with regard to vertical resolution which is about three times better. It is felt that this processor is about as good as can be obtained with this basic type of system and that any significant improvements would need to involve different types of signal generation such as pulse compression or multiple frequencies. The reliability of the new system

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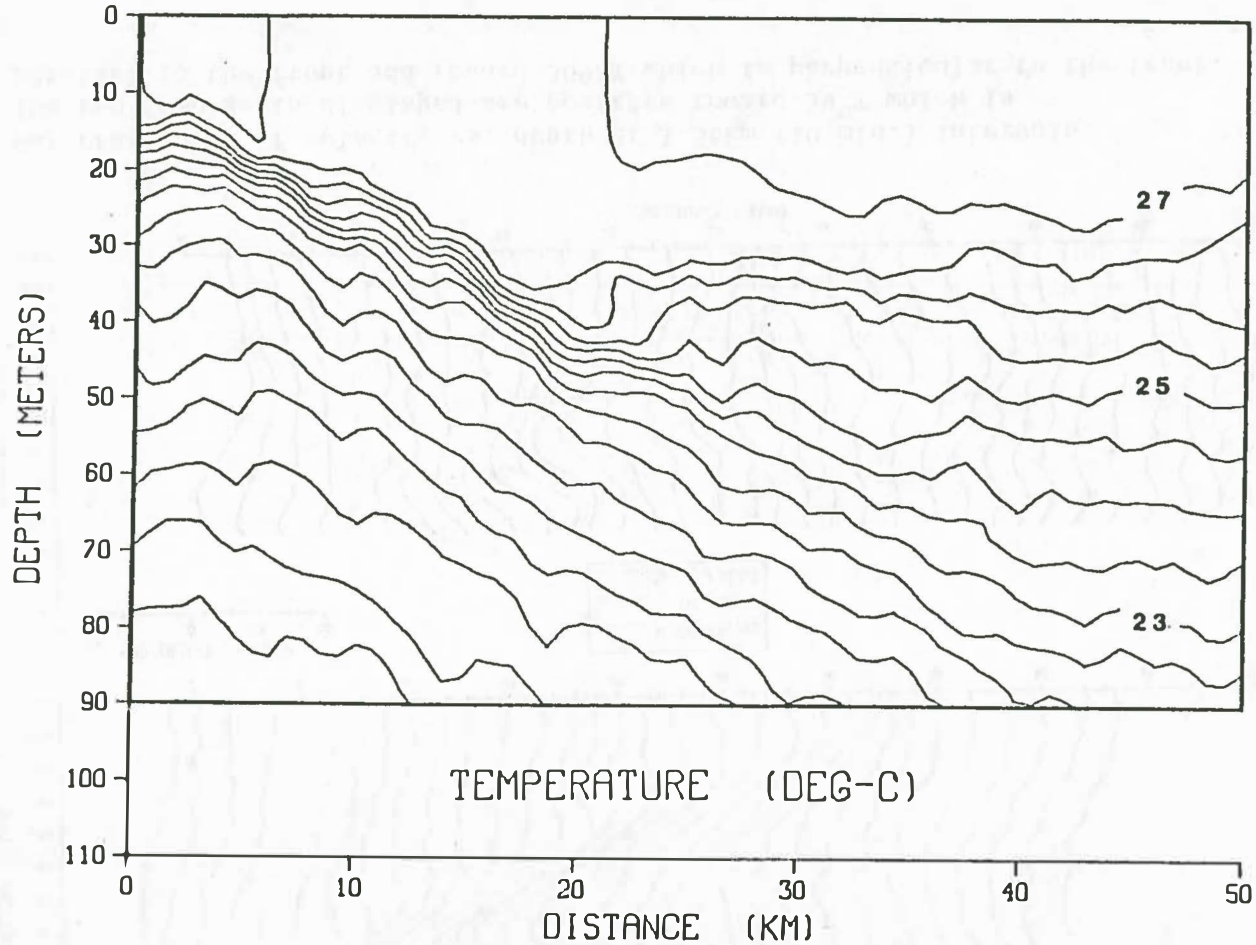
*Hill, R.H. and C.L. Trump, 1982: An Interim Doppler Shear Profiler: Experimental Results, NRL Memorandum Report 4920, Naval Research Laboratory, Washington, D.C.

seems good, but because of a lack of extensive reliability checks, some hardware problems, and an incomplete understanding of the real effect of some of the many control parameters available, this confidence is not as high as desired.

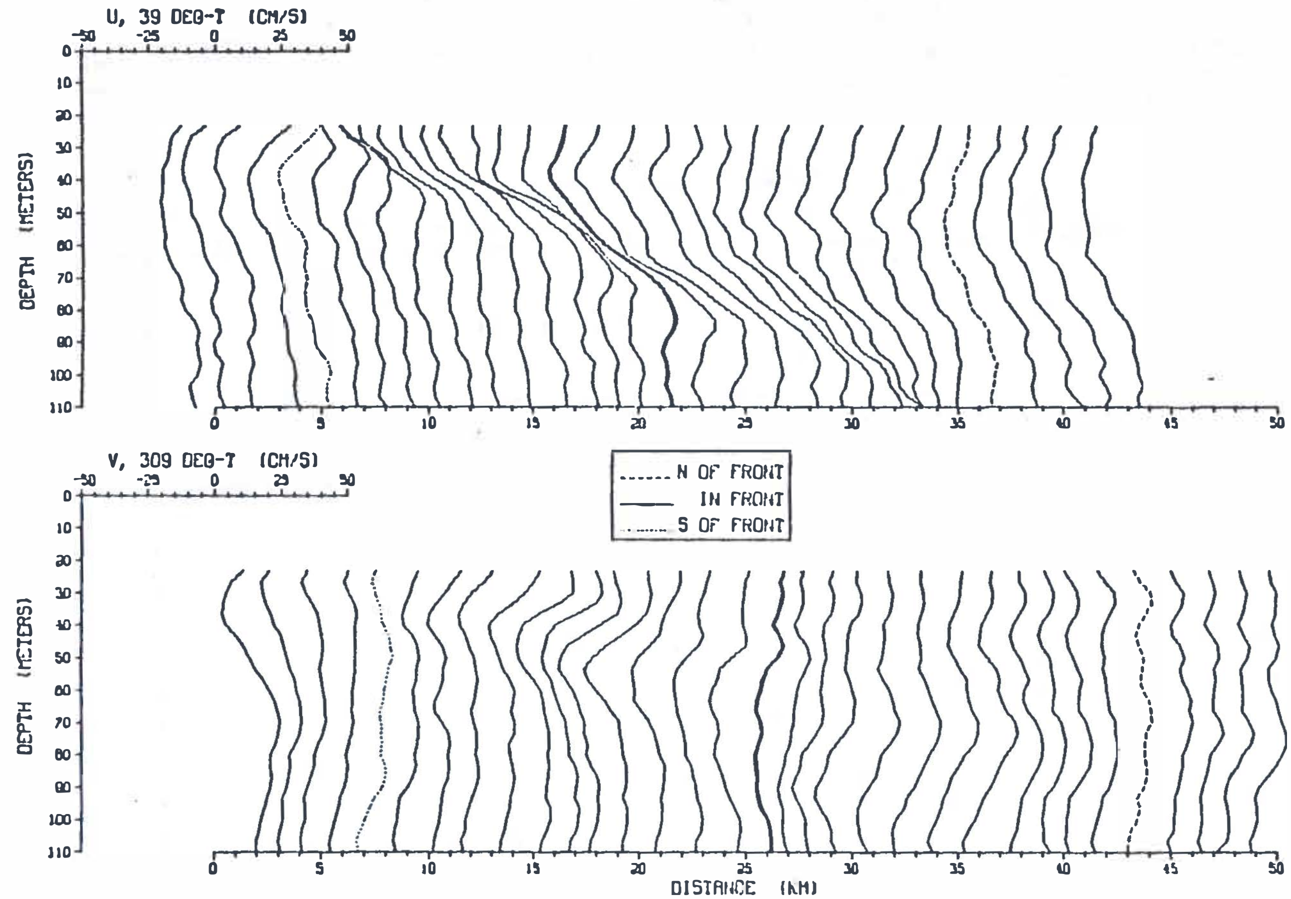
NRL has also had contracts with General Electric for some preliminary development and tests of a correlation sonar profiling system. This type of system offers some definite advantages: one beam instead of three or four, greater depth, and possibly greater resolution and precision. This summer this program resulted in a field test of an experimental correlation sonar that was designed to answer three basic questions: can a reliable profile be produced; what is the precision of the system, and how does it compare to theoretical system models; and can any estimate of the decorrelation time of a given volume of insonified water be made?

The bulk of this presentation will be an example of data taken by the interim DSP system in the Sargasso Sea. The feature described is a near-surface oceanic front that was encountered when NRL was testing its main instrument, a high density thermistor chain. A series of slides will be presented, two of which are reproduced here, that show the remarkable agreement between the structure of the front as recorded by the temperature and Doppler data and the wealth of detail that the Doppler system provides.

In conclusion, NRL feels that the Ametek/Straza DCP as it now stands is a remarkable instrument that can provide oceanographers with a wealth of data only dreamed of in the recent past. It must be noted that this system represents a first generation of Doppler Profilers and that future generations employing new signal techniques will improve the data sets immensely. Also, correlation type systems have the potential of being better than even advanced Doppler systems. The future of acoustic profiling techniques is very promising and the data being collected by existing systems are excellent.



Contour plot of temperature, in ^{o}C, along a ship's track in the Sargasso Sea. Data is taken by a towed thermistor chain. The front is indicated by sloping isotherms. Note that the temperature signature of the front does not reach the surface as there exists an isothermal mixed layer in the upper 20m.



Waterfall plot of velocity vs. depth at 1.56km (10 min.) intervals. The two components displayed are positive toward 39^{o}T which is parallel to the front and toward 309^{o}T which is perpendicular to the front.

ACOUSTIC ISSUES RELATIVE TO DOPPLER ACOUSTIC CURRENT PROFILING

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INTRODUCTION

The Doppler Acoustic Current Profiler (DACP) is fundamentally a sonar system which uses the Doppler frequency shift of acoustic energy backscattered from inhomogeneitys in the medium to infer the motion of the medium. It is the purpose of this paper to illumine some of the sonar issues that effect the performance of the DACP. Sonar engineers generally think about this problem in terms of a sonar equation:

$$\text{RECEIVED LEVEL} = \text{SOURCE LEVEL} - \text{GEOMETRIC SPREADING} - \text{ATTENUATION} + \text{TRANSDUCER DIRECTIVITY}$$

$$+ \text{TARGET STRENGTH OF REVERBERATIONS} + \text{AMBIENT NOISE}$$

ATTENUATION

The term attenuation is generally used to describe the range dependent losses of signal strength that cannot be accounted for by geometric spreading considerations. Attenuation in the frequency range 50kHz to 500 kHz is dominated by the absorption doing mechanical work on sea water and a chemical resonance reaction with magnesium sulfate disolved in sea water. An empirical expression relating acoustic frequency to absorption derived from one given by Francois and Garrison (1982) is:

$$a = \frac{A_2 P_2 f_2 f^2}{f_2^2 + f^2} + A_3 P_3 f^2, \text{ dB km}^{-1}$$

where A is absorption coefficient
f is frequency of interest in range 50-500kHz
$A_{2,3}$ are functions of temperature, salinity, and Sound Speed
$P_{2,3}$ are functions of depth
f_2 is the resonance frequency for the magnesium sulfate reaction

Absorption is plotted as a function of frequency in figure 1. The important thing to note in this figure is the strong temperature dependence of the absorption.

Ambient Noise

Because of attenuation effects at high acoustic frequencies, the noise background in which the DACP will have to operate will be dominated by local sources. Local wind effects will be most important at frequencies near 75kHz and, n fact, measurement of noise level could give a measure of local wind speed. Rain also produces high frequency noise but this drops off markedly at frequencies above 50 kHz. At the highest frequencies (>300 kHz) the noise background begins to be dominated by thermal noise (Clay and Medwin, 1977).

Scattering from Biological Targets

There are two mechanisms active in scattering. Geometric scattering is the mechanism active when the wavelength of the incident acoustic energy is small compared to the size of the scatterer. Penrose and Kay (1979) give an equation for target strength of marine organisms:

$$TS = 20 \log L - 24.5 \quad , \text{dB}$$

where L is size of scatterer in meters.

Rayleigh scattering refers to the situation where the wavelength of acoustic energy is large compared to the size of the scatterer. In this situation the scattered energy is proportional to the fourth power of the radius so scattering of this type is dominated by the largest scatterers.

In the ocean, the scatterers are generally of biological origin and consequently will vary in abundance according to area season, depth, etc. It is possible that there will not always be an adequate number of scatterers in the water column to give the required amount of backscattered energy.

Also, biological origins argue for scattering from sources that are not strictly passive relative to the water column. Sinking of dead bodies and fecal material and the vertical movement of the deep scattering layer could serve to confound measurements of this type.

Transducers

Conventional piston type transducers suffer a serious limitation in this work. While the central beam can be made quite narrow through the use of a piston many wavelengths across, they have troublesom sidelobes. These sidelobes are down by perhaps 18 dB from the main beam, but where the main axis of the transducer is pointed at an angle to the vertical, the sidelobe can be pointed at the surface. Because of the high target strength of the surface, sufficient energy may be available from the sidelobe to swamp the returns from scatterers in the main beam.

There are several possibilities for ways to deal with this problem. An acoustic lens in conjunction with baffles could be used or line arrays or other configurations of multiple hydrophones could be used to suppress the sidelobes. Parametric sonars could also be used to reduce the sidelobes.

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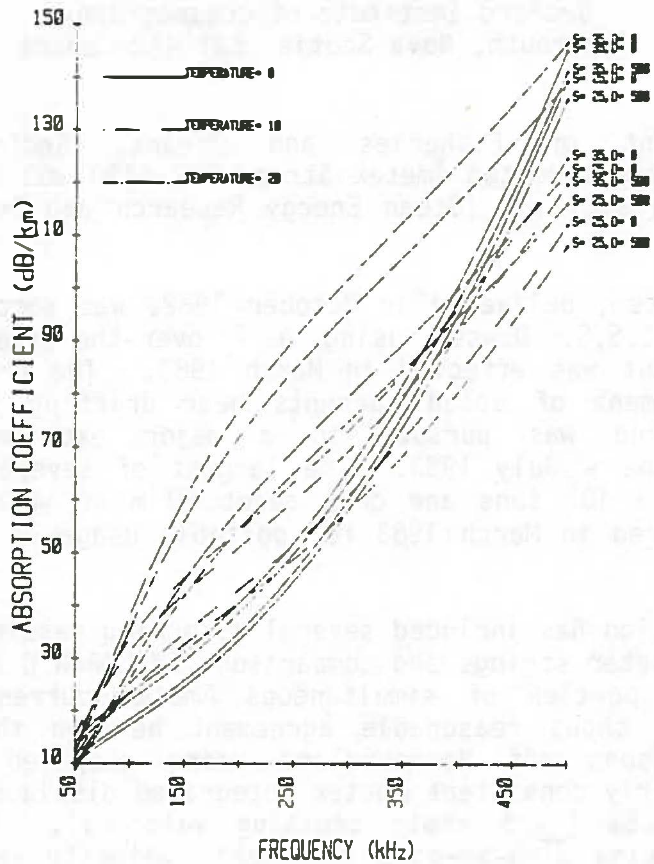

Figure 1. Absorption of coefficient as a function of frequency for Temperatures of 0, 10, and 20 deg, Salinitys of 25 and 35 parts per thousand, and depths of 0 and 500 meters.

ACOUSTIC CURRENT PROFILING AT THE BEDFORD INSTITUTE OF OCEANOGRAPHY

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The Department of Fisheries and Oceans, Bedford Institute of Oceanography, has acquired two Ametek Straza DCP-4400 300 kHz Doppler Current Profilers under an O.E.R.D. (Ocean Energy Research and Development) funding arrangement.

The first system, delivered in October 1982, was successfully tested on Institute vessel C.S.S. Dawson using a 7′ over-the-side transducer boom. Permanent hull mount was effected in March 1983. The primary objective of multidepth measurement of ocean currents near drifting icebergs for drift trajectory modelling was pursued in a major experiment off northern Newfoundland in June - July 1983. The largest of several icebergs tracked displaced about 2×10^6 tons and drew about 90 m of water. A second DCP-4400/300 was acquired in March 1983 for portable usage on offshore industry-related ventures.

System evaluation has included several recording sessions in the vicinity of moored current meter strings and comparisons of LORAN C and Doppler navigation. The small portion of simultaneous Ametek current meter recording currently analyzed shows reasonable agreement between the two techniques. Navigation comparisons off Newfoundland using supplied HP-85 processing algorithms show fairly consistent Ametek integrated displacement overestimates between 2.9 and 3.5% ($\underset{\sim}{\sim}$ 5 knots cruising velocity). More sophisticated offline analysis using ping-by-ping geographic velocity vector decomposition and averaging reduces the error to about 2.4%. Similar tests on the Scotian Shelf indicate an HP-85 derived overestimate of only 0.8%, close to the limits of measurement. These measurements were conducted with transducer thermistor velocity corrections as supplied by Ametek.

Individual ping velocity standard deviations indicate potential performance close to the theoretical limits stated by the manufacturer. Under most operational conditions, ship motion is the major source of measurement scatter, with vertical and horizontal component S.D.'s ranging up to 30 cm/s in moderately heavy seas. The most serious shortcoming to date has been an effective profiling range of only 90-100 m at a 4 db SNR acceptance criteria. The 4 db criteria also appears insufficient to prevent velocity bias in the lowermost valid profile bins. Consistent bottom track was usually obtained to 270-280 m. In general, the system has proven to be reliable, easy to operate, and adequate for the limited objectives above.

During 1984, the shipboard HP-85 real-time processor will be replaced by an IBM XT with integral INTEL 8087 floating point processor and supporting software from MICROWARE. Ping-by-ping geogrpahic vector decomposition will be implemented allowing the vessel freedom of maneuvering during averaging cycles. The ship's instantaneous short period motions will be largely cancelled using inputs from a pendulum stabilized three-axis accelerometer package. Desirable future system developments include: 1) a velocity capability to at least 15 knots allowing operation at normal oceanographic vessel cruising speeds; 2) a more powerful processor/logger capable of utilizing the full data rate of the profiler and providing a more diverse selection of processing algorithms; and 3) about 10 db higher power output to the doppler transducer allowing reliable profiling in excess of 150 m water depths.

Acoustic measurements of sill flows

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and
Len J. Zedel[2]

We describe recent measurements of tidally forced flow over a sill in Observatory Inlet, B.C., made with a single beam Doppler probe, a towed CTD and 3-axis ultrasonic current meter (CTDV) and an echo-sounder. Vessel drift was monitored by microwave positioning equipment. Flows through such constrictions have a significant influence on the surrounding oceanography, but their spatial and temporal variability makes interpretation of conventional measurements difficult. Our goal is to resolve the flow field well enough to permit comparison with various theoretical and laboratory models of stratified flow over obstacles.

The range gated Doppler antenna has a beam angle of 1^{o} and is mounted on a mast and points downwards and forwards at 62^{o} to the horizontal. The system separates at 215 KHz typically with a 10 ms pulse and 2 Hz repetition rate. Both phase and amplitude are filtered and digitized at 2.5 KHz. For the traverses considered here, a 3-axis ultrasonic current meter was towed at fixed depth; trisponder and related navigation data are recorded simultaneously. A 100 KHz echo sounder triggered with the Doppler provided graphic images to assist in subsequent analysis. Use of the Doppler system in dynamic coastal waters introduces several special problems. In shallow water even quite weak side-lobe returns from the sea-floor severely contaminate volume scatter in the main lobe, thus limiting the useful range. On the other hand returns from the sea-floor provide direct measurement of ship motion for flow speed corrections. Strong and highly variable vertical currents can invalidate simplified assumptions used to estimate horizontal speeds from the axial components. In areas of high spatial variability, such as flows over sills, different flow speeds will be encountered between beams pointing in different directions. Care must be taken to account for the horizontal displacement of the sampling volume as a function of depth. In the present study, comparisons made between the towed CTDV and Doppler, while generally similar, showed discrepancies attributable to the spatial separation and also to the different dimensions of sampled volumes of the two instruments.

Two examples of flow profiles resolved along our single beam Doppler system are presented. Figure 1 shows the radial velocity component in an early phase of the ebb tide. The flow accelerates along the upstream portion of the obstacle, subsequently evolving into a jet that hugs the lee face of the sill. The transition from distributed flow upstream of the crest, to formation of the jet is delayed beyond the crest of the sill and is just a few meters thick; it appears that the flow is a hydraulic response to a virtual control condition of the 2nd internal mode, upstream of the crest. In effect the flow is supercritical for some distance upstream of the crest and returns to subcritical via a hydraulic drop, downstream of the crest. Flow sensed along the beam actually changes sign within the downstream rotor. Two hours later the flow speed has increased (Figure 2); the virtual control can no longer be sustained and a transition to

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mode 1 response begins. During this phase a mid-depth jet evolves which diffuses vertically downstream of the crest.

A feature of the backscattered intensity is the presence of sharp changes associated with scattering layers. This is particularly noticeable at the pycnocline, which is drawn downwards over the sill. The coherent structure of the scattering layer can also contribute to significant departures in the shape of the Doppler spectrum from theoretical predictions for a random scatterers distribution. Specifically the spectrum is broadened in a way that cannot be attributed solely to turbulence in the sample volume. The combination of a broad-band echo-sounder with the Doppler profiler has proved a useful combination for analyzing several features of these dynamic flows, including the presence of shear flow instabilities, hydraulic jumps, lee waves and related phenomena.

Figure 1: Profiles of flow speed sensed with a single axis range-gated Doppler sonar during a traverse across the sill in Observatory Inlet. The beam is pointing at 62^{o} to the horizontal and flow speeds are resolved along this axis. Upstream of the crest the flow accelerates slowly; calculations suggest that the flow becomes supercritical with respect to the second internal mode about 200-300m upstream of the crest. Return to subcritical flow via a hydraulic drop is marked by the strong jet on the lee face of the sill.

Figure 2: Profiles made during a traverse 2 hours after Figure 1. The flow speed has increased and a second mode response can no longer be sustained. The transition is marked by a strong jet at sill depth which diffuses vertically as it moves downstream.

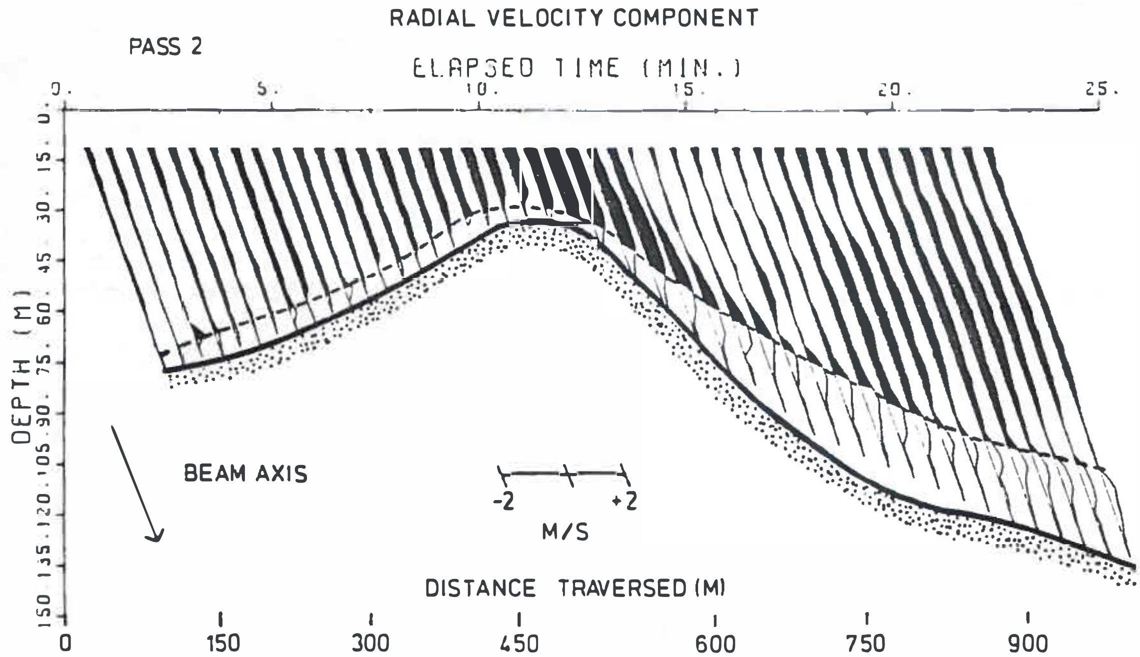

Figure 1

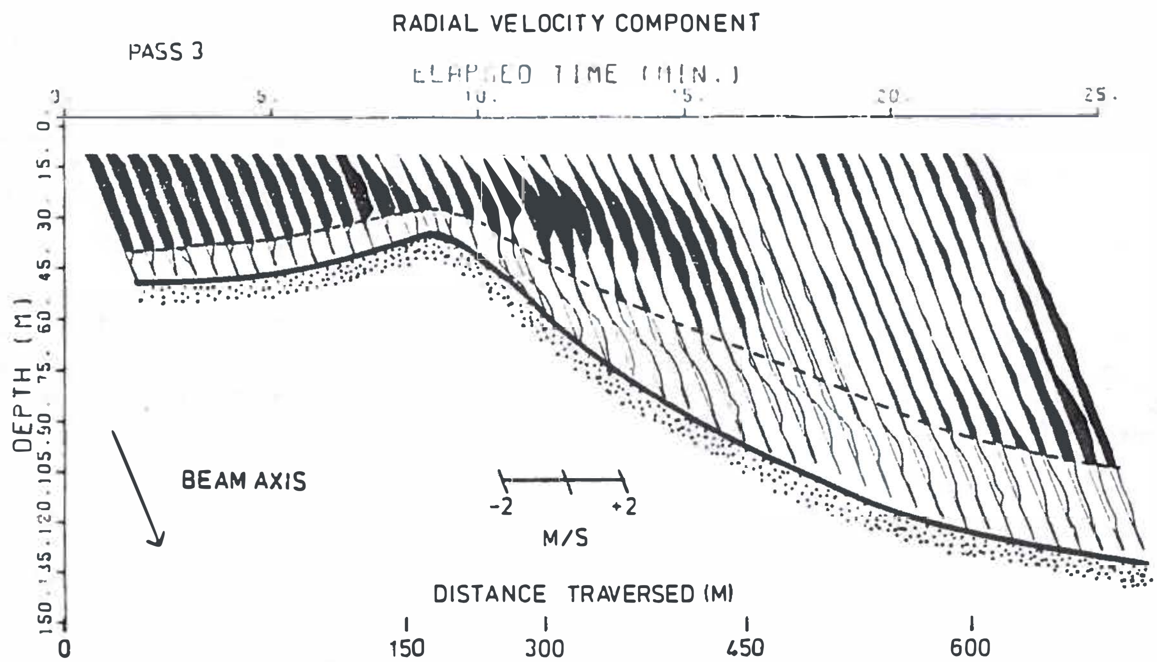

Figure 2

Broadband Determination of Acoustic Attenuation and Scattering Coefficients of Suspended Particles in Water

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Acoustic determination of current velocity profiles in a shallow water environment, e.g., Dutch coastal waters, forms a delicate task. Measurement accuracy may be interferred with by turbulent flow, sub-bottom and surface reflections and variations in particle target strength.

Target strength variations may, e.g., be caused by:

- o Biological activities as a function of time of year
- o Weather conditions
- o Measurement location
- o Tide effects

Most commercial systems therefore show a limited application under these circumstances.

Recently the Netherlands Rijkswaterstaat(RWS) initiated a research program, which aims at the development of both accurate and flexible measurement facilities for acoustic current profiling in shallow waters.

Three distinct research objectives may be distinguished:

1. To obtain fundamental knowledge on the acoustic scattering process, e.g., type and size of scatterers, their concentration and motion pattern.
2. To evaluate both data acquisition and data processing techniques, which supply optimal acoustic information with respect to current velocity.
3. To design and actually construct the eventual measurement system.

With respect to the first research stage, acoustic characterization of the scatterers is obtained by broadband spectral analysis using both transmission and reflection measurements.

In order to avoid unwanted effects, frequently met during in situ measurements, a large series of experiments to define scattering characteristics of suspended particles in water were first conducted in the laboratory.

These in vitro measurements covered a frequency range of 0.2 - 15.0 MHz, using a number of different transducers. In this paper some results of these measurements will be presented.

The design of "so-called" scattering phantoms will be discussed. Main emphasis will be given to the broadband determination of both attentuation and scattering cross-sections. Interesting findings with respect to forward scattering interference and measurements performed in the transducer near field will be discussed from examples.

Finally, the design and construction of a measurement system to characterize acoustic scattering characteristics in situ will be presented as well.

Experiments with an Acoustic Doppler Current Profiler in Dutch Coastal Waters

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A 300 kHz acoustic doppppler current profiler from the Ametek Straza Division was tested in Dutch coastal waters by the Hydro instrumentation department of Rijkswaterstaat. Rijkswaterstaat needs an acoustic current profiler suitable for shallow waters (10-40 meters), because of a storm surge barrier which is being built in the Eastern Scheldt estuary. Since this barrier may cause the waterspeed to be locally as high as 5.0 m/s, an extensive test procedure has been thought necessary before making the system operational. The procedure consisted of both laboratory tests and field tests.

The main goal of the laboratory tests has been to evaluate the mean frequency estimator. The most important characteristics of a doppler signal are varying amplitude and phase and therefore special attention has been payed to frequency disturbance caused by phase jumps. The test signals have been created by adding the amplitude modulated sine and cosine signals of a fixed frequency.

The second test phase has been performed on the vessel "Molenvliet" during the first part of this year. Monitoring the strength of the back-scattered signal it appears that both in a tidal area like the Eastern Scheldt estuary as in stagnant waters, the signal strength is strong enough to be handled by the doppler current profiler.

The doppler current profiler has been compared with a propellor type instrument during an eight hour test. The acquired velocity profiles by both instruments match quite well, although there is a tendency that the doppler current profiler measures approximately 0.04 m/s higher.

Although the profiler performed rather good during the test program there are some remarks to be made:

- The profiler is very complex in operation because of 25 selectable parameters. Introducing the profiler to the shipboard operators we found it necessary to set the parameters on fixed values.

- Due to the complexity of the profiler system it is difficult to detect or to locate errors in performance. A built-in test procedure or at least a test box which will check the main functions of the system is thought to be essential.

- A 300 kHz system is not optimum for shallow waters. A higher transmit frequency and a better space resolution are preferable.

The Rijkswaterstaat is conducting this research program because the acoustical current profiling technique is not fully comprehended. The main goals of our research are:

- To get an understanding of the scattering phenomena with respect to frequency.

- To study the scattering phenomena under laboratory conditions and in open waters.

- And with the knowledge of the scattering mechanism, to extract from the received signals the information we need, e.g., current profiles (via doppler or correlation techniques) and characteristics of the scattering particles.

PERFORMANCE OF A CLASS OF DOPPLER CURRENT PROFILERS AS A FUNCTION OF IMPLEMENTATION

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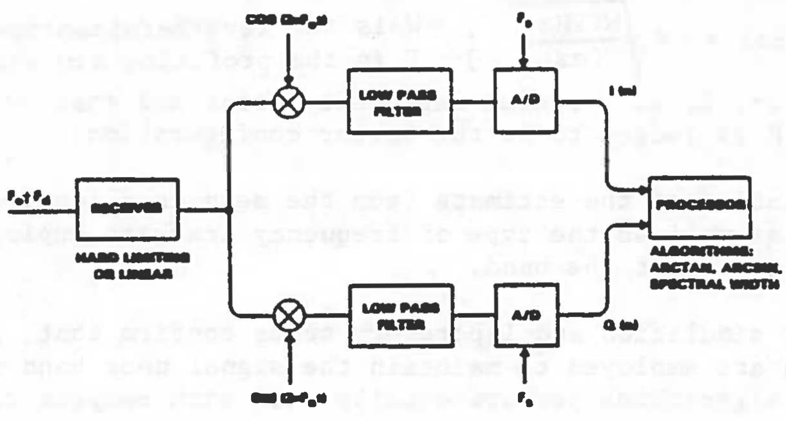
INTRODUCTION: The DCP4400 Doppler Current Profiler manufactured by AMETEK/Straza Division estimates the mean Doppler shift in a multitude of adjustable width depth bins in several narrow acoustic beams. The technique employed to perform this function is a form of non-coherent signal processing. In general, the performance of this type of processor varies as the square root of the observation interval. This paper presents some of the results of theoretical analysis, laboratory tests, computer simulations and sea trials of the AMETEK processor. Results are presented in terms of the attainable precision resulting from various system configurations and processing algorithms.

BASIC IMPLEMENTATION. Figure 1 illustrates the basic implementation of the DCP4400. The reverberation signal received on each beam is amplified and down converted to in-phase and quadrature channels, sampled by analog to digital converters and passed into a microprocessor. The receiver type may be linear or hard-limiting and the processing algorithim may be a so-called ARCTAN or ARCSIN type.

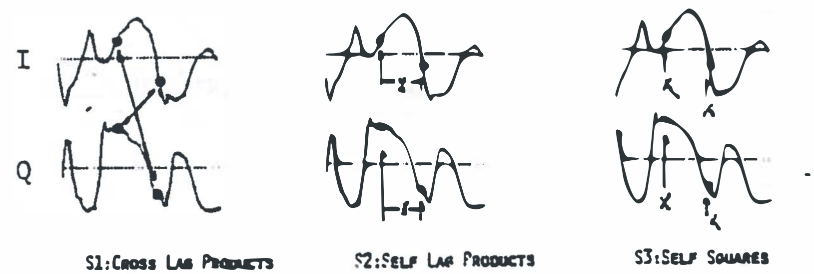
The centroid of the reverberation spectrum in each of the 63 profile bins on each beam is computed from the lag products of the in-phase and quadrature channels as shown in Figure 2. Three distinct summations of these lag products are required to form the ARCSIN and the ARCTAN estimators.



EACH CURRENT PROFILER BEAM REQUIRES A HIGH GAIN RECEIVER FOLLOWED BY DOWN CONVERSION TO IN-PHASE AND QUADRATURE BASEBAND CHANNELS

Figure 1

The products of the various samples of the in-phase and quadrature channels are illustrated in Figure 2. Shown in this figure is a representation of the noise-like character of the reverberation signal in the two channels. The operation of the system depends on the fact that, whereas each transmission will result in similar noise-like reverberation signals, these signals are statistically independent and the mean is preserved from one transmission to the next.



THREE SUMMATIONS ARE FORMED

$$S1 = \sum \left[I(n)Q(n+1) - Q(n)I(n+1) \right]$$

$$S2 = \sum \left[I(n)I(n+1) + Q(n)Q(n+1) \right]$$

$$S3 = \sum \left[[I(n)]^2 + [Q(n)]^2 \right]$$

Figure 2

The process of accumulating and averaging a multitude of spectral estimates will therefore ultimately extract the mean doppler shift in the various bins.

The mean frequency derived from an ARCTAN estimator is shown in equation 1, while the mean frequency derived from an ARCSIN estimator is shown in equation 2.

(1) $$F_0 = \frac{1}{2\pi\tau} \tan^{-1}\left[\frac{S1}{S2}\right]$$

WHERE: τ IS THE SAMPLE INTERVAL

(2) $$F_0 = \frac{1}{2\pi\tau} \sin^{-1}\left[\frac{S1}{S3}\right]$$

The performance of the system is judged on the basis of the standard deviation of the estimate as well as the truness of the resulting mean. The general form for the standard deviation for a system transmitting a rectangular pulse is:

(3) $$\sigma(Hz) = K\sqrt{\frac{W(kHz)}{T(ms)}}$$

; W is the reverberation spectral width
T is the profiling bin width

The factor, K, is a system dependent factor and that system with the smallest value of K is judged to be the better configuration.

The deviation of the estimate from the mean is a function of the estimating algorithim as well as the type of frequency trackers employed to maintain the signal in the center of the band.

Computer simulation and laboratory tests confirm that, providing linear frequency trackers are employed to maintain the signal near band center, the ARCSIN and ARCTAN algorithims perform equally well with respect to the accuracy of the mean.

The value of K has been determined by least mean square data fitting techniques to a variety of system configurations operating in a variety of environments with results shown in the following table.

VALUE OF K AS A FUNCTION OF SYSTEM IMPLEMENTATION

RECEIVER TYPE	ALGORITHM	SOURCE	VALUE OF K
LINEAR	ARCTAN	THEORETICAL	234
HARD LIMITED	ARCSIN	LAB MEASUREMENT	266
HARD LIMITED	ARCTAN	LAB MEASUREMENT	308
LINEAR	ARCTAN	COMPUTER SIMULATION	290
LINEAR	ARCSIN	COMPUTER SIMULATION	249
HARD LIMITED	ARCTAN	COMPUTER SIMULATION	341
HARD LIMITED	ARCSIN	COMPUTER SIMULATION	289
HARD LIMITED	ARCSIN	SEA TRIALS	300

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ACOUSTIC CURRENT PROFILING SYMPOSIUM

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Over the past 2 1/2 years, RD Instruments has been engaged in joint programs with university oceanographers developing and manufacturing products employing the acoustic Doppler technique to remote measurement of vertical profiles of water currents. A battery power compatible, microprocessor based Acoustic Doppler Current Profiler (ADCP) SONAR has been developed and successfully tested in a bottom mounted configuration by the University of New Hampshire and WHOI in comparison to a moored string of VMCM's. This basic Doppler SONAR has been expanded into a product line of ADCP instruments which are now commerically available.

RD Instruments ADCP's remotely measure 3 axes current components to accuracies of $\pm$0.2% $\pm$0.5% cm/sec in up to 128 depth cells (1 to 32 meter depth cell size) over a depth range of up to 1000 meters. They are available in three basic configurations:

- RD-DR Direct Reading,
- RD-SC Self Contained,
- RD-VM Vessel Mounted,

providing for fixed platform mounted, unattended mooring, and moving vessel current profiling applications. In addition, five optional plug-in transducers operating at 75, 150, 300, 600, and 1200 kHz; two optional acoustic power levels; and other operator programmable features allow tailoring ADCP current measurement performance to each application.

The RD-DR and RD-SC units are packaged in a 6 inch ID, 42 inch long pressure vessel with the acoustic transducer located on one end and an I/O connector on the other end. The RD-SC units contain internal batteries and magnetic tape recorders. Lithium batteries and Sea Data cassette tape recorders (10^7 bit capacity) are standard. Deployment life of the RD-SC ADCP's is typically 2-6 months, being limited primarily by the tape record capacity.

RD Instruments RD-VM series ADCP's are physically configured for vessel installation in two assemblies - a vessel hull mount compatible transducer assembly, and a 19 inch rack mount electronics assembly. Vessel pitch, roll, and heading data are also digitized in the electronics for transmission to the data acquisition system.

An optional HP9816 computer based data acquisition system will soon be available to process the profiler data in the real time together with vessel attitude, heading and position data to produce vector averaged current profiles in earth referenced coordinates. Processed data may be logged on the 9816 dual floppy discs and graphically displayed in real time on the CRT or hard copy plotter. The data acquisition system software includes a menu driven user interface to allow operators without computer experience to interact with the current measurement system via the keyboard/CRT.

Other ADCP products currently under development at RD Instruments include a surface moored ADCP, a pulse-to-pulse coherent ADCP, and a high capacity low power data acquisition system. The development of an ADCP suitable for use from surface moored or drifting buoys involves development of a highly directive (low sidelobe) transducer to avoid acoustic interference from mooring cables and other strong acoustic reflectors in the general region of measurement. The high resolution, high accuracy pulse-to-pulse coherent ADCP under development will profile 3 axes currents in 20 cm range resolution cells over a 10 meter range. Short-term current measurement accuracy is expected to be less than 0.3 cm/sec within 0.2 second measurement intervals. Since a large volume of data can be collected with this instrument, RD Instruments is also developing a high capacity, low power data acquisition system to support unattended deployments. A HCD-75 DC 600 1/4 inch cartridge tape syustem is being adapted to battery power useage. This unit will provide a record capacity expandable for 67 to 804 megabytes. It is configured in 1 to 5 eight inch ID pressure vessels.

OCEAN CURRENT PROFILES USING CORRELATION SONAR*

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The correlation sonar technique for measuring velocity offers some significant advantages over the more familiar doppler sonar technique. This paper outlines the similarities/differences between the two systems, describes the operational principles of correlation sonar and presents the initial results of remotely measured current profiles from a ship.

It can be shown that the direction/frequency power density spectrum of an acoustic field and the space/time correlation function are related through the Fourier Transform. This leads to the interpretation that in a correlation velocity measuring system the velocity information is encoded in the space and time domain while in a doppler system the velocity information is encoded in the direction and frequency domain. This relationship between the two systems is illustrated in Table 1.

TABLE 1 - CORRELATION/DOPPLER DUALISMS

SYSTEM PARAMETER	CORRELATION SYSTEM	DOPPLER SYSTEM
SOURCE OF VELOCITY INFORMATION	SPACE/TIME DOMAIN	DIRECTION/FREQUENCY DOMAIN
VELOCITY COMPONENT PARALLEL TO ACOUSTIC PROPAGATION	TEMPORAL CORRELATION	FREQUENCY SPECTRUM
VELOCITY COMPONENT NORMAL TO ACOUSTIC PROPAGATION	SPATIAL CORRELATION	NOT AVAILABLE
PREFERRED SIGNAL BANDWIDTH	WIDEBAND	NARROWBAND
PREFERRED TRANSMIT/RECEIVE BEAM PATTERNS	WIDE BEAMS	NARROW BEAMS
TRANSMIT APERTURE (in wavelengths)	SMALL	LARGE
RECEIVING ARRAY DIMENSION	ACCURACY IMPROVES WITH SIZE	LARGE
PREFERRED DIRECTION OF ACOUSTIC PROPAGATION	NONE	PARALLEL TO VELOCITY VECTOR
PREFERRED ORIENTATION OF SCATTERING SURFACE	NONE	NORMAL TO VELOCITY VECTOR

Specific advantages of the correlation sonar techniques include:

- Ability to measure three velocity components from the same water volume.
- Ability to utilize large BT product signal waveforms to improve estimation accuracy without degrading the range resolution.
- Ability to operate at low frequencies with a modest sized aperture for long range measurements. (Beamwidths are limited by resolution rather than accuracy requirements.)

The fundamental premise underlying correlation sonar is the waveform invariance principle which states that the waveform received from an ensemble of scatterers is a unique function of the transmitted waveform, the positions of the source and

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receiver and the scatterer geometry. For specific combination of source, receiving and scatterer displacement the received signals for two identical transmissions remain correlated. The application of this principle to the measurement of velocity is illustrated in Figure 1. Here we consider a single fixed source, T; two receivers, R1 and R2; and a scattering volume which moves from S1 to S2 in the time interval between transmissions, T_r. In the far-field the reverberation at some instant in time will be from spherical surfaces with centers at O1 and O2. Translations of these centers by an amount equal to the translation of the scatterers in the time between pulses will result in the reception of identical waveforms at the receivers R1 and R2. The separation vector between R1 and R2 is thus directly related to the velocities of the scatterers within the insonified volume.

$$\overline{V} = \frac{\overline{\sigma}_{R1-R2}}{2T_r}$$

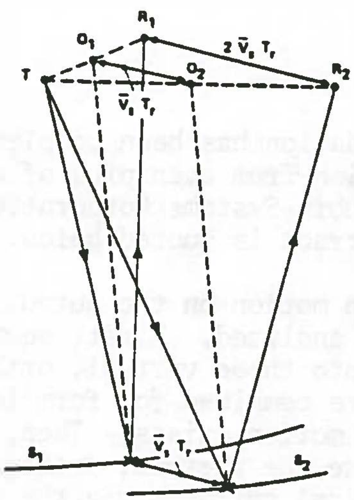

FIGURE 1 - WAVEFORM INVARIANCE GEOMETRY

In practice the correlation function is sampled in space and time using an array of receiving hydrophones. The three-dimensional separation vector corresponding to the maximum correlation is then found by interpolation.

A field test was carried out to demonstrate the application of this technique. Analog recordings of the received waveforms from an array of six hydrophones were made under various operating conditions. These data were then digitized and cross-correlated at various ranges. The hydrophone separation vector corresponding to the best correlation was found for each range cell using a curve fitting procedure.

Thus far results have been generated for runs with pulse lengths of one and ten msec which correspond to range resolution of about 1.3 and 9 m, respectively. The results represent the coherent average from 64 pulse-pair transmissions (25.6 seconds). Current profiles to 162 and 253 m have been obtained for these two conditions.

Effects of Ship Motion on the Output of a Tribeam Acoustic Doppler Current Profiling System

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The analytical foundation has been completed for estimating and removing the effects of ship motion from each ping of a tribeam ADCP. The results of this work are contained in Daubin Systems Corporation Technical Report DSC TR 02-83 of 31 Jan 1983, whose abstract is quoted below:

"The effects of ship motion on the output of a tribeam Acoustic Doppler Current Profiler (ADCP) are analyzed. First, equations are derived which combine the actual ADCP beams into three virtual, orthogonal beams; currents projected along actual ADCP beams are combined for form longitudinal, transverse and vertical currents where no ship motion exists. Then, for non-zero roll and pitch, transformation equations relate the virtual, orthogonal beam currents to actual longitudinal, transverse and vertical currents via the values of the roll and pitch angles and other ship motion variables. In the event ship motions are not accounted for, three types of error, based on cause, are defined: attitude, bin depth and transducer velocity errors. The sensitivities of each type of error to various sea conditions are calculated. Transducer motions generate the largest errors, followed by attitude (grazing angle) errors and bin depth errors in that order. An experimental procedure is outlined to demonstrate the reduction of current profile variance which would follow from taking ship motions into account. A procedure for waterborne transducer alignment calibration is described. This procedure will derive values for three misalignment angles, one about the pitch axis and one about the roll axis. Results of an alignment calibration procedure are presented, which was conducted for an ADCP installation aboard USNOSS RESEARCHER (OSS3) in September 1982. Values found for the misalignment angles in degrees are: yaw, -2.67 ±0.79; pitch 1.93 ±3.42; roll -3.24 ±6.53."

A significant reduction of variance was not observed during the September 1983 RESEARCHER tests. This is thought to be a result of the calm conditions under which the tests were conducted. Data from subsequent rough water measurements on RESEARCHER are currently being analyzed.

Bounds on Pulse-Doppler Current Profiler Performance

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Pulsed-Doppler current profile measurement systems are a useful tool for the determination of upper-ocean current and shear structures. These systems measure velocity by tracking the Doppler shift of the ocean's reverberation (scattering) response to a tone burst, simultaneously in each of four beams offset from vertical. The resulting time sequences of estimated frequencies are combined to obtain estimates of horizontal velocity and shear as a function of depth. The objective of this investigation is to characterize the accuracy (statistical standard deviation) with which such velocity and shear profiles can be measured, both for this general type of instrument, and for a particular instrument in use by NRL.

Our technical approach involved, first, the definition of a simple, and somewhat optimistic, model for the medium's reverberation response, and second, computation of a lower bound on attainable measurement accuracy (variance) using the Cramer-Rao bound, a standard statistical method. The result is an optimistic lower bound on measurement accuracy, one that is unlikely to be achieved by any actual (not idealized) instrument. That is, any practical instrument will provide measurement accuracy worse than the bound values presented below.

Our model assumes that the Doppler shift (velocity) to be measured is constant over a single observation volume (over one coherent integration time period), that the scattering process is of uniform strength and independent from range increment to range increment, and that the measurement system geometry is fixed and perfectly aligned (no ship motion, beam directions exactly known). We further assume that coherent integration (averaging) time equals pulse duration, and that a central-difference (non-overlapping pulse) formula is used to estimate shear; these are typical operating conditions and data processing procedures for the NRL system.

Application of the Cramer-Rao lower bound technique to this model leads to the general lower bounds:

$$\sigma_v^2 > \frac{c^2}{8T^2\omega^2\sin^2\phi}$$

$$\sigma_s^2 > \frac{c^2}{4T^2\Delta z^2\omega^2\sin^2\phi}$$

where

σ_v^2 = horizontal velocity component estimate variance, $(\mathrm{m/sec})^2$

c = sound propagation velocity, m/sec

T = pulse duration, coherent averaging time, sec

ω = operating frequency, rad/sec

σ_s^2 = component shear estimate variance, sec^{-2}

Δz = depth interval used in shear estimation, m

ϕ = beam angle off vertical

These bound expressions are asymptotically approached (from above) for very large signal-to-noise ratios (typical for the NRL instruments, based on an idealized sonar equation analysis). Note that these expressions are not a function of SNR, so that performance cannot be improved to an arbitrary level by simply increasing SNR: the system is reverberation-limited. Also, we see that a performance improvement achieved by increasing T (or Δz) yields a decrease in spatial resolution.

For the specific case of the NRL system operating frequency (300 kHz), assuming as small a Δz as possible (velocity estimates from adjacent but non-overlapping pulses), and allowing for incoherent averaging of N estimates, we find

$$\sigma_v > \frac{5.6\times10^{-4}}{T\sqrt{N}} \text{ m/sec}$$

$$\sigma_s > \frac{6.1\times10^{-7}}{T^2\sqrt{N}} \text{ sec}^{-1}$$

For example, if T=10 msec, we require N > 125 to achieve σ_v = .5 cm/sec and N > 38 to achieve $\sigma_s = 10^{-3} sec^{-1}$.

In summary, we have shown that pulsed-Doppler current profiling systems are reverberation-limited, so that performance cannot be improved past a certain point by increasing transmitted power. We presented quantitative lower bounds on the accuracy with which velocity and shear can be estimated; these indicate that improved performance can be obtained by increasing pulse length/averaging time, by averaging over a larger number of independent pulses, or by increasing operating frequency. The first two decrease spatial resolution; the last may decrease system maximum range if maximum transmitted power is limited. Finally, we again emphasize that the numerical bounds on performance which we have computed are extremely optimistic, as they ignore various error sources, and, thus, are unlikely ever to be achieved in practice.

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