Current Velocity Measurements Using Acoustic Doppler Backscatter: A Review

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Abstract—**Acoustic Doppler backscattering techniques have been exploited for measuring water velocity for nearly 40 years. Although most early applications centered on measuring ship speed, much work has been done during the last 20 years to adapt the techniques to measure oceanic velocity fields. The purpose of this paper is to summarize the work that has been done and to discuss the state of acoustic Doppler technology.**

I. Introduction

DOPPLER sensors infer relative water motion by transmitting high-frequency sound in a narrow beam and measuring the frequency shift (Doppler) of the returned sound as it is scattered from irregularities in the water. The major attraction of this technique is its remote measuring capability. That is, it can in principle measure flow velocity at selectable distances away, profiling the water column, in contrast to conventional *in situ* current meters that measure at the instrument and hence inherently disturb the signal of interest. However, the accuracy and precision of the Doppler flow measurement is a complex function of the interaction between a number of controllable variables (system operating parameters: signal power, frequency, pulse length, transducer characteristics, spectral estimating techniques) and uncontrollable variables (backscatter strength, type and distribution of scatterers, platform motion). To fully characterize the performance of this technique the complex interaction must be determined and described. This is a difficult task at best and numerous investigators have worked on the problem for many years with mixed results. This paper briefly reviews previous and ongoing efforts aimed at oceanographic applications of the Doppler technique.

II. Review

In the early 1960's the first concerted efforts began toward developing an *in situ* Doppler current measuring device. This work was done in Miami, Florida, and reported on throughout the decade variously by Koczy *et al.* [1] and Kronengold and Vlasak [2]. They spent a number of years working on a bistatic (separate transmitter and receiver), 10-MHz, short-range (10 in) instrument that by design observed signals scattered from a relatively small volume defined by the intersection of the transmitting and receiving beam patterns, and was manufactured by Airpax Electronic Inc., of Fort Lauderdale, Florida. Squier [3] reported on his results of a research application of a modified Airpax Doppler meter aboard the Scripps R/V FLIP. In 1968, Vlasak, then at George Washington University, reported that the Doppler instrument was still a complicated and unproven device requiring further refinements.

In 1969–1970, the Naval Ordance Laboratory at White Oak, Maryland, also carried out some experiments on equipment patterned after Kronengold.

Although *in situ* current measurement by this time had become relatively routine, it was the more rugged and presumably easier to understand Savonius rotor devices that enjoyed widespread use rather than the "advanced" techniques such as Doppler. However, the real incentive to look for alternative fast response noninertial current sensors for general oceanographic applications came during the Mid-Ocean Dynamics Experiment (MODE) in the early 1970's. It was then confirmed that Savonius rotor current meter data could be badly contaminated due to the rotor's inability to accurately respond to the upper ocean dynamics (imparted directly or through the motion of surface following moorings). The Doppler technique appeared to be a promising candidate and the large quantities of buoy sensors projected for the emerging National Data Buoy Project (NDBP) provided sufficient incentive for EDO Western Corporation to adapt their speed log to a current meter configuration suitable for a buoy sensor application and sell the idea to the NDBP. Technical difficulties with building and understanding the sensor and a reduction in NDBP scope combined to effectively put an end to that work.

Wiseman *et al.* [4] reported on their development of an upward-looking, three-axis, 10-MHz Doppler current meter at the Chesapeake Bay Institute. The device was developed as part of a program to study turbulence in estuaries and never progressed beyond the research tool stage.

In 1972, The Engineering Development Lab (EDL) of the National Oceanic and Atmospheric Administration's (NOAA) National Ocean Service (NOS) Office of Marine Technology began a program aimed at determining the feasibility of using acoustic Doppler techniques to measure water currents at ranges up to 100 m. The envisioned application was for a bottom-mounted upward-looking system. With support from EDL, Emmanuel and Mandics [5] concluded that, on the basis of available information on the concentration and size distribution of scatterers in estuarine, coastal, and open ocean areas,

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estimates of scattering cross sections showed that a pulsed Doppler current measuring system was feasible. This result led the way toward seven years of analysis and experimentation with both bottom-mounted and ship-mounted applications. Much practical experience was gained during this time although minimal and sporadic funding limited the amount of work that could be done. Extensive analytical modeling efforts at Catholic University were undertaken and reported by Clark and Scherer [6], while Scherer *et al.* [7] reported one of the first "sea truth" experiments in an estuarine environment and Peynaud and Pijanowski [8] described the Thomas CSF French shipboard system.

In 1976, Sperry Marine Systems, Inc., and AMETEK-Straza Division, feeling that they had the technology in hand and perceiving a potential market for a shipboard Doppler current measuring system, each prepared proposals for development of Doppler systems both patterned after their speed logs. Neither was able to generate sufficient fiscal interest from the Government so Straza decided to go it alone with corporate funds. They were successful in merging their early development efforts with two investigators at Scripps Institution of Oceanography (SIO), L. Reiger and R. Pinkel. Regier and Pinkel were research oceanographers who viewed the Doppler system, in this case the Straza device, as a viable research tool which could be developed into a useful well-understood operational device through an effective user/manufacturer relationship. This work was quite extensive and helped pave the way for Straza to market their DCP-4400 line of current profilers [9]–[13].

Responding to an operational need expressed by the U.S. Naval Oceanographic Office in the late 1970's, the Naval Ocean Research and Development Activity (NORDA) tasked the Naval Research Lab (NRL) to evaluate acoustic methods for measuring current velocity from underway ships. Results of this program are reported by Hill and Trump [14]. In the summer of 1981, D. Farmer, at the Institute of Ocean Sciences (IOS), Sidney, British Columbia, Canada, performed a controlled sea truth experiment in a northern British Columbia fjord using a single-beam Doppler system fabricated at IOS and attached to a ship. Independent current measurements were provided by Aanderaa current meters on four moorings in an area whose flow characteristics are well understood.

The early 1980's saw expanded shipboard applications of both the original 300-kHz Straza systems as well as the next-generation lower-frequency 115-kHz systems by investigators including Joyce at the Woods Hole Oceanographic Institution [15], [16], Schott at the University of Miami, Bitterman *et al.* at the NOAA Atlantic Oceanographic and Meteorological Lab [17], Cochrane at the Bedford Institute of Oceanography, and Milburn and Pullen at the NOAA Pacific Marine Environmental Lab.

Also in 1981, ROWE-DIENES Instruments (RDI), Inc., was formed and began working jointly with oceanographers to develop and manufacture products employing the acoustic Doppler technique for remotely measuring vertical profiles of water currents. Both bottom-mounted [18], [19] and shipboard [20] configurations have resulted. In NOAA a renewed effort in the early 1980's began to focus its activities on commercially available acoustic Doppler profilers. NOS formed a Remote Acoustic Doppler Sensing (RADS) project within the Ocean Systems Division in 1982 to investigate the developing RADS technology and explore its application to NOS measurement programs. A series of "sea truth" experiments was conducted with the first in the Chesapeake Bay using a bottom-mounted AMETEK Straza DCP-4400 300-kHz system operating in real time [21]. The results were so encouraging that the system was later deployed in an experimental configuration at Ambrose Light Tower, New York [22], and most recently in the Port of Miami. Both of these were in the bottom-mounted, upward-looking, real-time configurations. An RD Instruments RD-SC1200 also was deployed in Delaware Bay in August 1984 and a similar unit was deployed in Miami in December 1984 for intercomparison with the Straza system. These experiments and sea truth data sets are among the most definitive and extensive work done to date on determining the performance characteristics and operational uses of the Doppler system.

In the summer of 1983, NOAA began a joint program with the Scripps Institution of Oceanography, AMETEK-Straza Division, and EXXON to determine the feasibility of deploying a commercially available Doppler acoustic current profiler aboard a commercial "ship of opportunity." The approach was to attempt 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. The system was successfully installed and operated aboard the 42 000-ton oil tanker EXXON Jamestown. The results are reported in [23]. Following the NOAA lead, the U.S. Naval Air Development Center (NADC) purchased two of the "piggyback" systems for the installation aboard two U.S. Naval Oceanographic Office survey ships [24]. Shakedown cruises are completed and a report is in preparation.

In addition to these applications of commercial devices, small groups of researchers are engaged in exploratory efforts to develop alternative acoustic current profiling methods including different system geometries and signal processing techniques. These include the transverse Doppler system [25], the pulse coherent Doppler sonar [26], and the correlation sonar [27].

Because of this expanded interest and application of these new devices, a broad and varied perception of their utility and capability has developed within the community. In November 1983, the Acoustic Current Profiling Symposium was convened in Washington, DC, to focus specific attention on this area of ocean technology and to collectively provide a review of the status of the technique [28].

III. Available Technology Overview

Acoustic Doppler current profilers are presently marketed by two California based manufacturers: AMETEK-Straza Division in El Cajon and ROWE-DIENES Instruments, Inc., in San Diego. A brief overview of these systems is provided below.

Hardware configurations for both shipboard and bottom/platform deployments are presently available. The maximum profiling depth of each is generally dependent on operating frequency—at a given acoustic power level, higher frequencies yield shorter depth ranges. The systems are available at several different operating frequencies ranging from 75 to 1200 kHz with a variety of options for acoustic pulse length, depth cell length, and pulse rate. Each of these operating parameters as well as the number of pulses selected for averaging has an impact on the statistical accuracy of the current velocity estimate. For example, AMETEK-Straza specifies a measurement precision of 3.7 cm/s for a depth resolution of 2 m, a 115-kHz operating frequency, and a 400 ping (pulse) average.

Because competition between the two manufacturers of these systems precludes further generalization about the system capabilities, the reader is encouraged to consult the manufacturers' brochures and the open literature for more specific details and evaluation results.

IV. Discussion

The evolution of Doppler current measurement technology is characterized by a history of sporadic and sometimes unrelated research and/or commercially oriented project efforts. From the commercial standpoint, it is clear that this technology suffers from the same problem as most other new ocean instrumentation. The market volume is simply too small for a manufacturer to justify adequate amounts of up-front dollars to do a full and complete product development. Typically, an early prototype, the characteristics of which are partially understood, is volunteered for use in (sometimes sold to) a measurement program. The program becomes a convenient "demonstration" vehicle for the measurement system and if the data "look good" by some subjective yardstick, the system may catch hold in the community and may even gradually evolve to become a useful tool whose performance is well understood and documented. This is a "bootstrap" approach but it must be accepted as a reality in the ocean community in which we work. Some investigators, on the other hand, have avoided buying hardware and have fabricated their own Doppler system in an effort to understand the technique better while they use it as a tool for oceanographic research.

The complicating factor, which acts to polarize organizations and individuals working on Doppler techniques and makes it difficult to assess system performance, is that the technique does not lend itself easily to performance characterization. It is a remote-sensing device that makes a measurement in a manner which no other device can or does make. Some who are presently using the systems typically accept the Doppler data based on its reasonableness and its consistency. Others suggest, however, that the measurement is so complex that interpretation of measured data without a thorough understanding of the variables contributing to the measurement uncertainty is folly. The authors suggest that a balance between these divergent viewpoints should be the underlying philosophy of the acoustic Doppler efforts in the community.

How far has the technology progressed? In the past several years it has been demonstrated through controlled intercomparison experiments that the acoustic Doppler technique can make a measurement which, under certain environmental conditions, compares well with independent measurements from other "conventional" systems. The increased availability of commercial systems has enabled more investigators to apply them under a broader range of operating conditions. The result has been steady and significant progress in empirical approaches to performance assessment, although suitable parallel analytical efforts have been lacking. Expanded use of the system has demonstrated that our understanding of how the system operates under and interacts with certain and many times unknown environmental conditions and flow characteristics is still limited. Although it is essential to determine whether problems are method inherent or specific instrument or installation related, at this stage of system development it is still very difficult. This has made the accurate diagnosis and treatment of unforeseen sources of error very difficult. For example, some shipboard applications have experienced unexpected velocity differences on opposing beams in the near-surface portion of the water columns [29]. Analysis performed to date has attributed this to effects of ship-induced flow. Although attempts are being made to solve the problem by adjusting selected system operating parameters, the process is complex because the exact ship flow characteristics are unknown and nearly impossible to duplicate.

The issue of performance of these systems has been and continues to be complicated by the lack of any type of device that could be considered a "standard." Although field intercomparison measurements continue to be the most accepted method of performance verification, a well-designed, easily applied, broad-band signal calibration device would be a valuable addition to the system hardware.

V. Summary

The technology is continuing to evolve at a rapid pace with continued improvements a certainty in the next generation products. The present user should be cautious with the interpretation of his data products and maintain careful quality control of his measurements. Prospective purchasers should be aware of the developmental nature of the technology and be ready to take the risks and apply the caution necessary to assure measurement quality. The evolution will be slow, as with most innovative new ocean technologies, but the rewards are promising and, in the authors' opinion, well worth the investment.

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