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## Developments in Acoustic Doppler Current Profiling and its Technical Application in Deepwater Drilling

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### Abstract

The continued expansion of E & P activities in deepwater has resulted in a growing demand for reliable ocean current measurements and criteria throughout the entire water column. To satisfy this demand there has been an increasing requirement for refinement of instrumentation, deployment systems and real time display and forecast software.

This paper describes the approach of oil companies, a service company and an instrument manufacturer to these requirements and shows how the close collaboration of these organizations has resulted in optimizing the data available to the operational decision makers and engineers. The paper discusses the developments in instrument technology, both hardware and firmware, optimization of data through system deployment approaches and the development of software appropriate for the offshore oil and gas industry.

Examples of floating structure, drilling rig and riser (BOP stack) deployed systems are presented, together with recorded data sets. Considerations in deployment configuration and real time software and their impact on overall data quality are reviewed.

Future requirements of the oil and gas industry in deep water are considered. In particular achieving full water column profiling capability in depths beyond 1,000m and enhancement of real time current prediction.

### Introduction

For the last ten years the exploration and production of oil and gas reserves have increased in the deep waters at the edge of the continental shelf. Deep water exploration is subject to the

same environmental demands as shallow water exploration coupled with the complex problems associated with moorings and station keeping rigs in deep water and the increased significance of hydrodynamic forces on subsea components of the drilling operation. Currents at the shelf edge are often strong and variable and can potentially cause many operational challenges in the exploration and production of oil and gas reserves.

Requirements for current information include: vessel/rig selection (station holding), riser design, deployment and performance, and ROV operations. These requirements have led the industry to demand real time current measurements throughout the water column. The measurement of real-time currents requires instrumentation with commercial availability, economy, ease of installation, performance and reliability. RD Instruments has been manufacturing 75 kHz ADCP with ranges up to 600m for more than 10 years and has recently developed a long profiling range 38 kHz Phased Array (PA) ADCP in response to the deep water exploration requirement. This instrument uses a patented ( Patent # 5,808,967) 2-D phased array transducer with selectable processing modes.

### ADCP Installation And Operating Environment Considerations

Deep water exploration and production of oil and gas reserves have presented many operational challenges to offshore operators and drilling companies. With over 60 new deep water rigs being built, at an investment of more than \$12 billion, oil companies are committed to solving the problems before them.

The ability to acquire, display, interpret and disseminate current information in real-time can assist greatly in operational planning, resulting in a safer working environment and providing potentially large cost savings. Shell E & P Company, the leading deep water operator in the Gulf of Mexico has worked with Fugro GEOS to better understand this unique environment for successfully operating ADCPs.

Each rig offers its share of technical challenges when deploying conventional 75 kHz or PA-38 ADCPs. The experience and documented processes that Fugro GEOS has developed in 75 kHz ADCP rig deployments has been essential in the successful deployment of PA 38 ADCP off

similar structures (**Fig. 1**).

The key factor in determining measurement range is the transmission frequency of the instrument. A 75 kHz BroadBand ADCP can achieve a range of approximately 500 - 600 meters in optimal conditions. Until recently, this performance has been adequate for most drilling rig applications. Today's extension to deeper water drilling, however, has created a need for significantly longer current measurement ranges.

Two alternatives to achieve this increased range requirement have been developed. The first is the use of multiple ADCPs located at different depths such that each profiles a different portion of the water column. The second is the development of a longer range ADCP.

**Multiple ADCP arrays.** Typically in cases where one ADCP is used, the instrument is suspended at approximately 40m below sea level on a twinned guide wire system, or the unit is rigidly fixed to the hull of the vessel. In the latter case heading information, used to resolve current vectors into earth coordinates is derived from a Gyro compass. For the guide wire system the ADCP heading is derived from an internal compass. The guide wire based system although requiring more maintenance has two main advantages over systems where the unit is fixed to the rig. It requires no subsea engineering during installation, and allows the ADCP performance to be optimized by positioning it in a lower noise environment.

The use of multiple ADCPs is conceptually simple but is highly complex in practice. Among the difficulties involved are (1) the need to communicate and control data acquisition over great depths via electromagnetic or acoustic means, (2) the remoteness of the system and problems recovering it for servicing and maintenance, (3) the potential for acoustic interference between ADCPs, and (4) the need for synchronization of the ping cycles.

By careful planning these difficulties can be largely overcome, however deploying an ADCP on a guide wire system at depths greater than 500m can introduce many problems; the ADCP orientation cannot be controlled and riser reflections may corrupt data, the deployment system may interfere with other rig operations and become entangled with the riser, ROV etc. To avoid these complications, yet to allow data to be collected over full water depth the first BOP mounted upward looking 75 kHz was installed by Fugro GEOS in 1998 for Mobil, west of Shetland (**Fig. 2**).

The key difficulties with this installation were (1) water depth, (2) proximity of the ADCP to the riser, and (3) communication with the ADCP

All elements of the system including the ADCP, underwater junction boxes and housing for the modems had to be depth rated to 3,000m. To overcome the problem of the close proximity of the ADCP to the marine riser the ADCP was modified by RD Instruments disabling both the transmit and receive element for one beam. During installation this beam was pointed directly at the riser. Communication between the ADCP and rig was facilitated by means of two RF

modems, connected using a spare co-axial cable available on the riser. Reliable communications was the most difficult problem with the installation to overcome, and due to insurmountable problems with them the system was finally deployed with simplex data transmission, the ADCP being preconfigured prior to deployment. Using this technique data were successfully transmitted from the ADCP and examples, showing data from the BOP mounted system and that from a downward looking ADCP, are presented later in this paper

**Development of Long Range ADCPs.** To increase the range of an ADCP, by operating at a lower frequency, (38 kHz), using conventional four-beam technology was impractical because of the extremely large physical size and weight of such an instrument. By using the principle of forming the four required beams from a single, multi-element planar array transducer, the 38 kHz Phased Array ADCP, which can profile to around 1000 meters, is essentially the same size as the conventional four-beam 75 kHz systems.

One issue which affects both conventional and phased array ADCPs when used in drilling rig applications is acoustic reflection from objects in the water column. These objects include the riser, tensioning cables, subsea rig hull, and ROVs. If any of the transmitted beams intersects such an object, the reflection from it can easily overwhelm the scattering from the small particles in the water which the ADCP uses to measure currents. The result can be a degradation of the current data in the depth range of the interfering object.

Different methods can be used to alleviate this problem with a conventional versus a phased array ADCP. With conventional systems, the ADCP must be carefully orientated so that the beams do not strike any submerged objects, or one beam must be disabled. At least three beams must always be operational in order to get a complete solution for the currents. The difficulty with the orientation approach is that it can be undone by any changes in the positions of suspended objects. Electronically disabling a beam is not a designed-in feature of existing ADCPs.

The phased array ADCP has several potential advantages in solving this problem. First, by very careful manufacture of the array and beamformer, acoustic sidelobes can be minimized. In addition, different acoustic frequencies and/or different signal codes can be used on each transmitted beam to reduce cross coupling. Finally, enhancements to the beamformer are currently in the design phase which will permit the operator to easily suppress one transmit beam and to vary the orientation of the beams electronically. These capabilities will give greatly enhanced capabilities to avoid unwanted acoustic reflections without the need for reorienting the transducer. Dynamically Positioned (DP) rigs present major noise problem for the PA-38 ADCP. With large positioning thrusters running on a continuous basis the operating range of the system will be greatly reduced if certain installation techniques are not followed. What has been found to be successful has been a combination of lowering the PA-38 ADCP into deeper water (200m), away from the thrusters (15m) and outfitting the transducer with an acoustic baffle

"jacket" to suppress the surface noise from the back and sides of the transducer. The other major technique under development will be to operate the system in the NarrowBand mode (NB).

To better understand the acoustic noise environment on these types of rigs a field study has been undertaken. A 38 kHz phased array ADCP installed on a drilling rig exhibited a profiling range that was less than expected. Measurements of the acoustic noise environment were made in the water where the ADCP was located by lowering a calibrated hydrophone. The noise signature of the drilling rig was measured with the hydrophone located between 20m and 100m depth at 20m intervals. At each level, 10 data files were collected at a 250 kHz sampling rate, and 10 data files at a 100 kHz sampling rate. 2 sets of data with 20 files for each set were collected.

The noise spectrum data were analyzed by performing an FFT on data collected after compensating for the known frequency response of the hydrophone. **Figs. 3, 4 and 5** show the typical noise spectra collected at 20m, 40m, and 100m, for 250 kHz, 100 kHz and 45 to 25 kHz, respectively.

The noise spectrum is generally flat for frequencies above 20 kHz. The noise level is strongest at 20m and 40m, near the thrusters located at 30m depth. It is reduced with increasing depths. At 100m, the noise level is about 15 dB below the levels at 20 & 40m.

The primary noise source is probably the thrusters, because the noise level decreases with increasing depth 15 dB per 60m. The relatively flat noise spectrum suggests that 38 kHz is a desirable frequency for an ADCP on an drilling rig. It had previously been suggested that the noise spectrum might drop by from 6 to 12 dB per octave in this spectral region. If so, this would tend to favor the 75 kHz systems. However, based on these measurements, this is not the case and that superior current profiling ranges can be achieved by a 38 kHz ADCP.

## System Description

The PA-38 ADCP used on drilling and production rigs is similar to the PA-38 ADCP developed for moving vessel applications, which has been described in separate publications, as has the 75 kHz BroadBand units. The features emphasized in this paper are those most applicable to floating issues.

The basic ADCP unit consists of a transducer assembly coupled to a topside electronics unit and a data processing unit. The transducer assembly is a novel 2-D planar phased array assembly which simultaneously emits and receives up to four beams, oriented in the conventional ADCP Janus configuration.

The electronics unit connects to the transducer assembly, supplies power to all modules, receives, processes, and controls all functions, and interfaces to a data processing, display and archiving system.

**2-D Phased Array Transducer Description.** The 2-D phased

array transducer is the enabling technology that makes it possible to increase ADCP profiling range by operating at lower acoustic frequencies than practical with larger conventional "piston" transducers. The planar phased array transducer has a flat face as it is constructed out of hundreds of ceramic elements and other special materials aligned geometrically in one plane. (**Fig. 6**) Housed inside the top-hat of the transducer housing are an optional fluxgate compass and an attitude sensor for applications where the transducer alignment cannot be controlled.

For a given range and frequency, a 2-D planar 38 kHz phased array transducer has an order of magnitude smaller volume as compared to a Janus configured transducer of similar performance. This transducer has a housing diameter of 915mm and is 121mm high. The housing is made of naval bronze with a weight in air of 248 kg. The array is rated for 300 psi at this time.

The array beam pattern, like any other ADCP transducer, is a critical factor for an ADCP's performance, particularly in applications where highly reflective underwater objects are common. Therefore, narrow beams and high off-axis rejection of interference targets is essential for accurate current measurement. The 38 kHz PA unit has a 2-way beamwidth of approximately 4 degrees and cross beam rejection of typically better than 35 dB. In addition, improved beam suppression techniques are currently under development.

The electronics unit is contained in the same 19" rack mountable chassis used in RD Instruments vessel mounted ADCPs.

The unit uses a 32-bit floating point digital signal processor (DSP) and a Field Programmable Gate Array (FPGA) to control and execute all transmitting, receiving and data processing functions. Four serial communication ports are available for the rig sensor and data processor interface. Currently, the PA-38 ADCP operates in a pulse coherent "Broadband (BB)" mode, operating at approximately 5% fractional bandwidth.

In the future it will also operate in a conventional but improved pulse incoherent "NarrowBand" (NB) mode when longer range is preferred over the higher resolution (BroadBand) of the operation. The NB-mode employs iterative narrow band processing to avoid velocity measurement errors present in previous RD Instruments narrowband ADCPs. A signal bandwidth on the order of 0.5% is used, providing approximately a factor of 100 (20dB) improvement in the signal-to-noise (S/N) ratio. Hence, the NB-mode of operation will increase profiling range in addition to the range increase due to the lower system frequency. The user has the choice to select either mode or to alternate between operating modes depending on the application requirements.

## Software

To allow data produced by the ADCP system to be effectively used by rig personnel it is essential that derived current profiles are presented in a clear and easily understandable

display. Fugro GEOS' RIGADCP software package provides the user with a series of readily interpreted graphical views of the measured data. The instantaneous profile plot, shown in **Fig. 7**, illustrates measured current speed and direction in each depth cell. It also provides a clear, numerical display of the maximum current speed through the water column. This screen is of particular interest to ROV operators. Other screen options include short-term and long-term time series displays at selected depths.

**Current Forecasting.** The foregoing text describes systems for the provision of measured current data. During years of measurement and operation, in deep-water west of Shetland, for a number of major oil companies the complexities and extreme variability of current conditions have become apparent. What is often required offshore, to assist in operational planning, is not knowledge of what the current velocity is now, but how it is likely to develop over the next few hours. Currents in the region regularly exceed 1 meter per second (2 knots) and many operations can only be performed successfully below a particular current speed threshold (such as ROV deployment, riser deployment and recovery, 'spudding in', ship loading etc.). The costs of suspended operation during unfavorable current conditions can be extremely high; equally, major damage may occur if current-sensitive operations are commenced without due regard to the forthcoming flow development.

To develop a prediction module extensive numerical analysis has been undertaken on previously measured deep-water current profile data. Harmonic analysis was used to determine the predictable tidal component of flow, and then empirical pattern-recognition techniques were developed to estimate the highly variable non-tidal component of flow. The non-tidal flow comprises a persistent north-easterly ocean current component, intermittent passage of eddies and various high-frequency effects. The approach taken with the prediction software was to provide a robust empirical prediction procedure rather than to attempt a full hydrodynamic interpretation of the available data. During the development phase, various prediction algorithms were tested on past data to assess how well they would have performed in real-time. The preferred scheme was then encoded into a real-time software application.

RIGADCP provides the user with an easily interpreted graphical display (**Fig. 8**) showing time series at two selected depths through the water column. To the left of the centerline, current speeds measured over the last 24 hours are shown, together with past predictions that were made N-hours before each measured data point. The N-value is selected by the user. Comparison between measurements and past predictions provides an indication of how well the prediction scheme is working at the present moment in time. To the right of the centerline, predicted current for the next 24-hour period is displayed. This is shown for the predictable tidal component (faint line) and also for the total current (heavy line) which

also includes all the variable non-tidal effects.

The current prediction software has now been operational offshore for more than 2 years. Since its initial installation, various refinements have been made to improve the quality of the forecast and to optimize the form in which the information is displayed to the decision-maker.

The prediction module now provides an effective tool to support operational planning in selected offshore regions and will continue to be developed and refined.

## Data Analysis and Presentation

Unlike conventional current meters which provide speed and direction time series for a discrete height above the bed ADCPs provide a significantly more comprehensive data set, including time series of current profiles and additional parameters, such as vertical velocity. To allow effective use of these data it has been necessary to develop a number of custom presentations and analysis techniques for the data.

Data from the ADCPs is written in a rigorously applied database format; this is essential for quality control of the data. The ADCP provides a great deal of data on instrument performance including echo amplitude and percentage good pings for Narrowband ADCPs and correlation coefficient for BroadBand units. To allow determination of the quality of the data, it is essential that these data are reviewed. To allow this, color contour plots of these parameters are printed and assessed.

On completion of the QC of the data set, a number of data analyses and presentations are produced in addition to standard presentation produced for current meters. The following are undertaken (1) color contour plots of orthogonal velocity and vertical velocity, (2) analysis of the data to derive extreme profiles and percentiles, which are subsequently presented in profile form, (3) operational window analysis, this involves the persistence analysis of profile data, this can be used, for example, to assess the likelihood of period of vortex induced vibration (VIV) on the riser string to be determined, and (4) Rotary Spectral analysis, allowing summary of flow properties through depth.

Preparing such types of presentation greatly increases the value of the ADCP data, and allows the reader to understand quickly and accurately the water column characteristics.

## Data Collection/ADCP Performance

Data presented in the first example was collected from a platform in the Gulf of Mexico operated by Shell Deepwater Production Inc.

The 38 kHz phased array transducer was deployed from the platform at an angle of about 15 degrees from the vertical (**Fig. 9**), this offset ensured 3 beams were unobstructed and that beam 4 was orientated towards the hull column. The beam 4 data, therefore, have been disregarded in the data processing.

**Fig. 10** shows range and echo intensity data. The average echo intensity of beams 1 through 3 is plotted in **Fig. 10** along

the x-axis. The y-axis is the range in meters. The system was set up to collect 32 bins where every bin is 32 meters in size. Hence the plotted range reflects the total range that was selected and was not limited by system performance.

At approximately a range of 350 meters, the average scattering strength increases again by about 18 counts near a range of 500 meters. This increase is equivalent to about 8 dB. The cause of this change in volume scattering strength has not been investigated in this paper. A possible reason is a concentration of zooplankton at this depth.

Beyond a range of 500 meters the echo intensity decreases as expected. Near a range of 950 meters the bottom echo is beginning to influence the signal. That is, the bottom is fully illuminated within the next few bins.

The echo intensity is a measure of signal to noise ratio (S/N). In the BB-mode of operation the S/N ratio that corresponds to a signal correlation threshold up to which the signal is considered acceptable is 0 dB; this relationship is shown in Eq. 1. This level is reached approximately at an echo intensity between 20 and 30 counts (This range of counts is according to RD Instruments' experience. A more accurate measure can be obtained if the system is calibrated). Thus, the maximum range in this application was strictly limited by the system setup as it seems that there is at least a S/N ratio margin of 15 dB available.

$$\mathfrak{R} = \frac{b}{1+1/SNR} \dots\dots(1)$$

**Fig. 11** shows the range vs. normalized signal correlation magnitude. It supports the claim that the maximum range was not reached. The correlation magnitude threshold is, by default, set to 50%. At a correlation of 50% the S/N ratio is about 0 dB. **Fig. 11** shows that at a range of 1000 meters the correlation has just dropped to 96 – 97 %; which is still an exceptionally high correlation value at 1000 meters. Presentations of corresponding easterly, northerly and vertical current vectors are presented in **Figs. 12, 13 and 14**.

Therefore, the conclusion is that the range obtained for this installation is more than that given in the Ocean Surveyor's specification. However, it should be mentioned that this range is not achieved in all cases. One of the single most important environmental parameters in obtaining this range is volume scattering strength. Provided that the scattering level does not fall below about -95 to -98 dB and the sea state is near zero, the specified range should be obtainable in most cases. Other equally important factors are ambient noise caused by sources such as thruster-generated noise (propeller noise) and other mechanical noise.

**Fig. 15** shows a comparison of data collected west of Shetland, using a multiple ADCP array. The data was obtained from the overlapping bins of a downward looking 75 kHz ADCP and upward looking BOP mounted ADCP described earlier in the paper, with one beam, which was orientated directly at the riser disabled. It can be seen from the presented datasets that very close correlation exists and

confirms that this deployment technique is viable when installation of a single long range unit is not feasible.

**Future System Enhancements**

There are several system enhancements scheduled for the PA-38 ADCP to provide improved operation on rigs.

Image beam and adjacent beam suppression algorithms are being developed for both BB and NB-modes of operation. These algorithms are designed to suppress the image and adjacent beams by at least an additional 20 dB beyond the level of conventional piston transducers. The effect is a reduced cross talk that will reduce the velocity bias effect due to non-uniform scattering between beams. This is commonly encountered in rig applications with submerged objects such as ROVs ,drilling risers, & mooring cables.

The implementation of a hard transducer face will reduce the damage from long term bio-fouling and decrease the chances of handling damage to the transducer face in rig applications.

To better deal with rig and surface noise and to improve its versatility, the PA-38 ADCP transducer and electronics will be designed to operate at depths of over 1500 meters. This will allow the user the option to deploy the instrument either downward facing from the rig or pointing upward with near-bottom deployment. This upward application typically will provide longer profiling ranges than downward deployments because of typically higher near surface biological backscatter concentration at the end of the profiling range and due to the reduced rig noise.

The ability to shut down transmit on any one beam electronically will also be provided. This will improve ADCP operation on certain types of structures e.g. TLPs and on BOP installations where it is impractical to orient the four beams to avoid acoustic interference from structural columns, cables or risers.

Many enhancements to RIGADCP are currently under development. As computer systems are more likely to be connected via local, wide area or internet networks automated archiving of data in near real time to databases on servers and the distribution of data on intranets and the internet have become viable propositions. Future implementations of RIGADCP will incorporate network communication capabilities, for both instrument control and databasing, and presentation of data using web pages. Further developments of ADCPPRED will include enhancement of empirical algorithms and also the incorporation of more sophisticated hydrodynamic models. These developments are designed to extend the geographical applicability of the software.

**Conclusion**

The development of deep water current measurements for drilling rig environments have been made possible by the close collaboration between an expert user; Shell E & P Company, an experienced system integrator; Fugro GEOS and

an instrument manufacturer; RD Instruments.

The PA-38 ADCP with the ability to profile currents over 1000m has shown how it could be successfully deployed and integrated into the complex operations of different types of mobile rig environments. The benefits of real time current data has been found to be essential in the support of many drilling rig operations.

### **Acknowledgements**

The authors wish to thank Ram/Powell asset of Shell Deepwater Production Inc. and many of the operators west of Shetland, in particular BP and Mobil North Sea Limited, for their support in the preparation of this paper.

### **Nomenclature**

$\hat{A}$  = Correlation magnitude

$b$  = Decorrelation factor, for this purpose assumed to be 1

SNR = Signal to noise ratio (linear form)



Fig. 1.--PA-38 ADCP deployment frame for suspension off a Drilling rig.



Fig. 2.--BOP mounted 75 kHz ADCP, transducers are just visible below protective steel cover, which is removed prior to deployment.

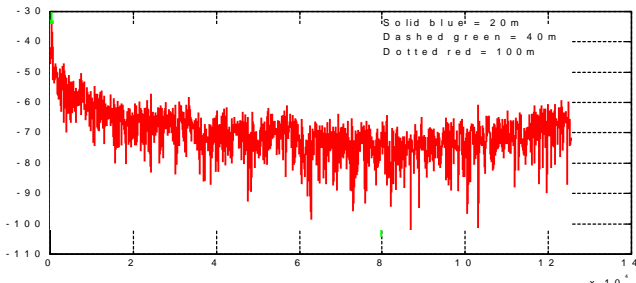


Fig. 3.--Noise spectrum at 250 kHz

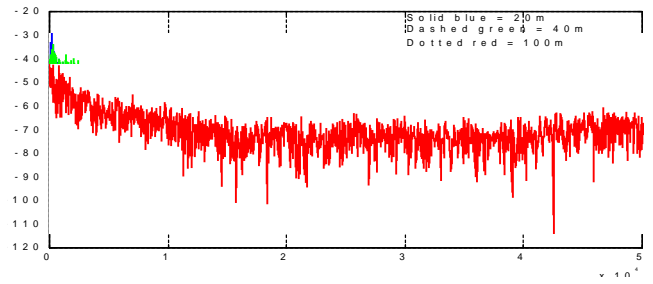


Fig. 4.--Noise spectrum at 100 kHz.

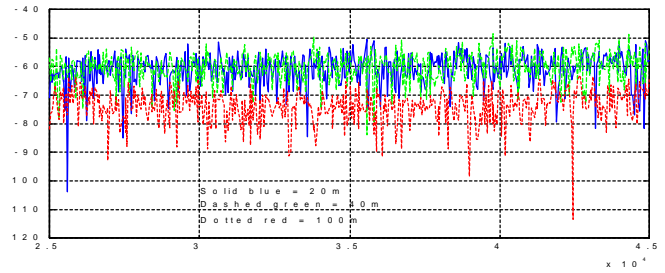


Fig. 5.--Noise spectrum at 25 - 45 kHz.

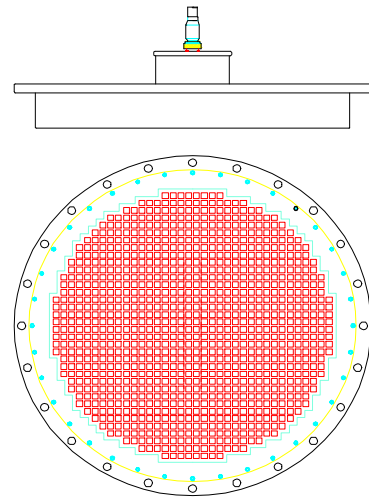


Fig. 6.--38 kHz PA Transducer Design.

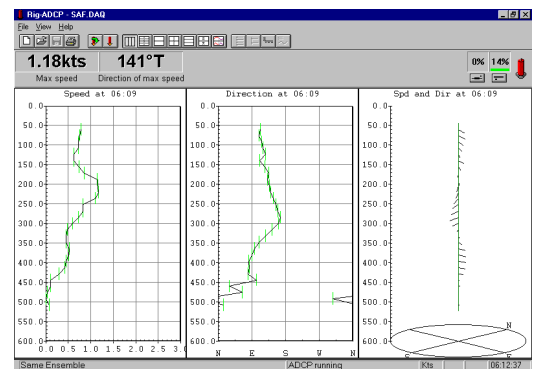


Fig. 7.--Default real-time display of RIGADCP.

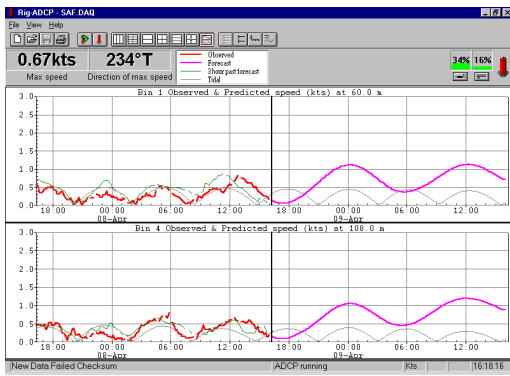


Fig. 8.—RIGADCP real-time display showing observed and predicted currents.



Fig. 9.—Deployment frame of the PA-38 ADCP that was used to collect some of the data presented in this paper.

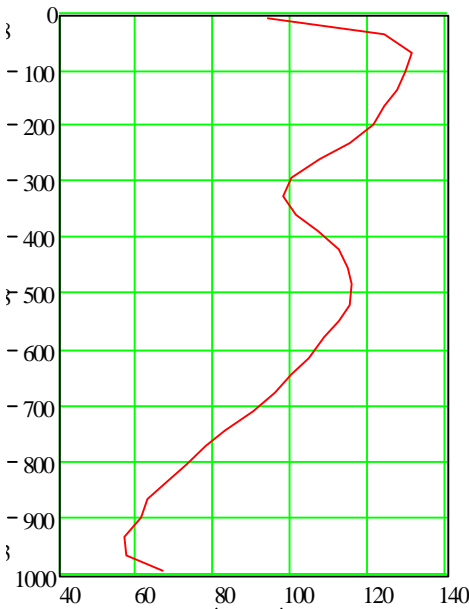


Fig. 10.—(Vertical axis-meters) Range in meters vs. average echo intensity in counts of Beam 1 through 3. A count equals about 0.42 dB in change of intensity. A significant change in scattering strength can be observed between a range of 200 to 500 m. Near a range of 950 m, the bottom reflection becomes apparent.

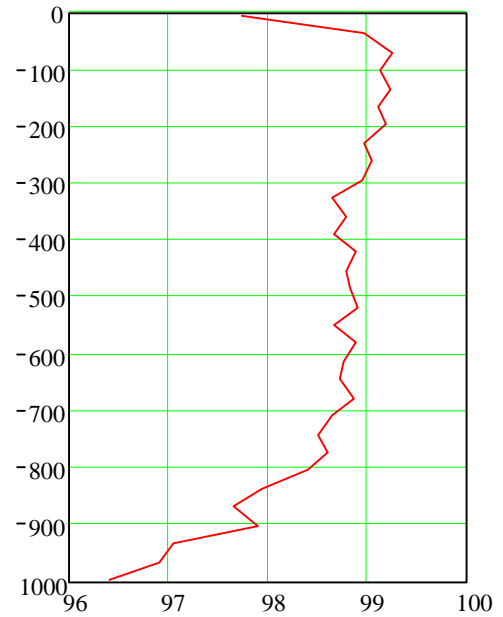


Fig. 11.—(Vertical axis-meters) Range in meters vs. normalized correlation magnitude in percent. The graph shows that the typical correlation threshold of 50% as required for the velocity measurement to be considered valid has not been reached yet.

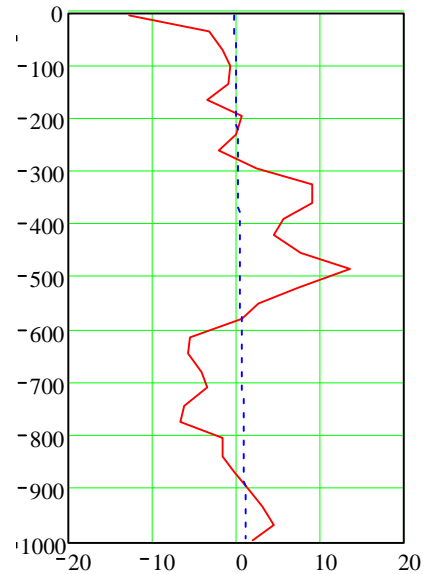


Fig. 12.—(Vertical axis-meters) The solid line is the range in meters vs. easterly average velocity profile in cm/s. The dashed line is linear best fit to the profile.

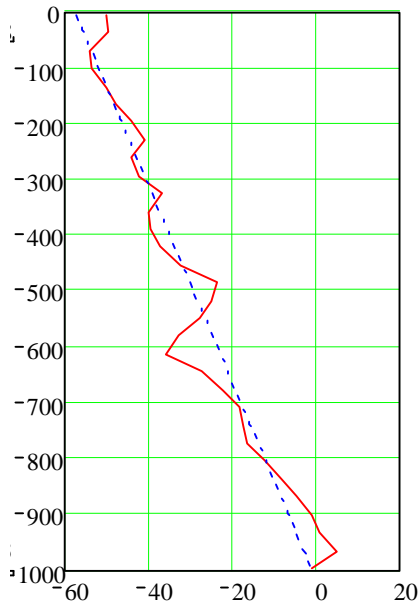


Fig. 13.--(Vertical axis-meters) The solid line is the range in meters vs. northerly average velocity profile in cm/s. The dashed line is the linear best fit to the profile.

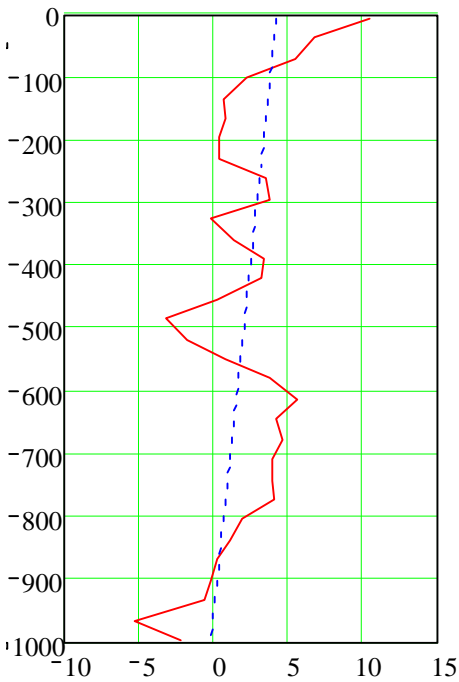


Fig. 14.--(Vertical axis-meters) The solid line is the range in meters vs. vertical average velocity profile in cm/s. The dashed line is the linear best fit to the profile.

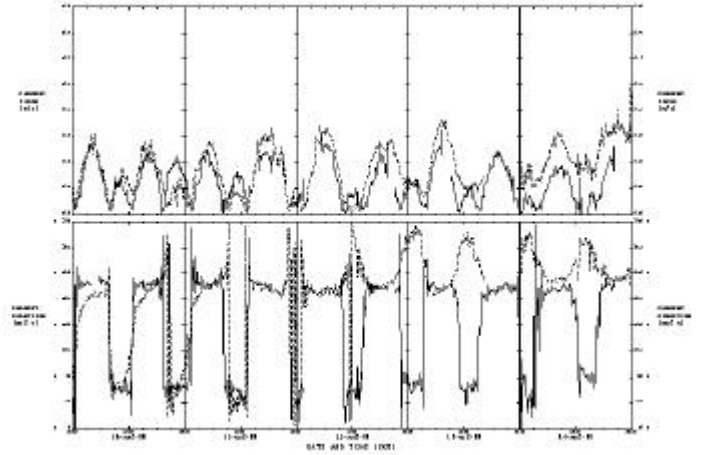


Fig. 15.—Inter-comparison of upward looking BOP mounted 75 kHz ADCP (solid line) with downward looking 75 kHz ADCP (dashed line).