Long-Range Current Profiling from Moving Vessels

Max Edelhauser*, Fran Rowe*, Frank Kelly**,
*RD Instruments, **Texas A&M University

ABSTRACT - Experiences over the last decade measuring upper-ocean current profiles from underway ships with Acoustic Doppler Current Profilers (ADCPs) have demonstrated significant capabilities, but also identified serious limitations of existing ADCP systems. This paper describes recent advancements in shipboard ADCP technology that attempt to address these limitations such as range, accuracy, data robustness, reliability, and ease of use. New two dimensional phased array transducer technology, developed under our sponsorship is combined with adaptable pulse-coherent "broadband" and pulse-incoherent "narrowband" digital signal processing within one unit. We will describe these implementations and other improvements that deal with the limitations of current ADCPs, and predicted performance characteristics of 38, 75 and 150 kHz ADCP systems. Finally we will present and discuss 38 and 150 kHz ADCP data collected in recent shipboard applications.

I. INTRODUCTION

Historically, users of ADCPs had to trade off range against measurement precision. One or two orders of magnitude of higher velocity measurement precision is the key feature of pulse-to-pulse coherent "broadband" (BB) ADCPs [1], while "narrowband" (NB) ADCPs achieve a vertical range that is at least 20 % larger than that of a BB system of comparable acoustic source level and receiver sensitivity. For the majority of users of vessel borne ADCPs this tradeoff is not desirable. Typically, these users average over sufficient large spatial scales, and hence relative large temporal scales that allows them to average the data for the purpose of increasing the measurement precision to the desired value.

Practical restrictions on the physical size of a conventional transducer assembly in Janus configuration limits the lowest usable system frequency, and thus the maximum profiling range that can be obtained with any real ADCP. For this reason it seems that the profiling range of current ADCP technology can not be increase beyond to what is achievable with a 75 kHz NB system. Made out of Naval-Bronze, a RDI 75 kHz transducer's weight is about 211 kg, and the diameter of a vessel's well has to be almost 1 m in diameter. A conventional 38 kHz transducer in Janus configuration made out of the same material presumably would weigh in excess of 800 kg and require a well of about 2 m in diameter. The installation difficulty and impact upon issues of a vessel's hull design and integrity would be potentially severe. The situation would be not significant different for any non-Janus configuration transducer that resolves current in three spatial dimensions too.

A new line of vessel-borne Phased Array (PHA) based ADCPs by RD Instruments (RDI), named the Ocean Surveyor (OS), attempts to resolve many of the described issues, and to improve upon others. Specifically, we attempt to solve or improve upon the following:

- Increasing profiling range due to two dimensional (2-D) PHA, reduced BB-mode bandwidth, due to NB-mode of operation and reduced flow noise from flat face transducer;
- Simplifying transducer installation due to reduced physical size and weight;
- Improving accuracy due to improved NB-mode processing, image and cross beam rejection processing, effective integration with modern vessel motion sensing systems (e.g. 3-D GPS), and echo intensity calibration feature;
- Improving operational, data, and bio-fouling reliability, due lower component count, robust NB processing and data screening, and hardened transducer face;
- Improving operating system (Software) by e new developed Windows®[1] based operating system that is flexible and easy to use.

II. SYSTEM OVERVIEW

A) System Description

The Ocean Surveyor consists, like other RDI ADCPs, of a transducer assembly, an electronics unit, and a data acquisition system (DAS).

The transducer assembly, unlike other ADCPs, consists of a novel 2-D planar phased array assembly. The transducer simultaneously emits four beams, oriented the same way a conventional Janus configured transducer would do. A beamformer is mounted inside the transducer assembly, and forms the four receive beams by applying appropriate phase shifts to the various staves of the array. The PHA transducer

[1] Windows is a registered trademark of Microsoft Co.

connects to the OS electronics unit via a transducer cable. This cable supplies power to the beamformer and an optional attitude sensor package, transmitter power to the 2-D array, and connects the beamformer output signals to the receiver inputs. Also a temperature sensor signal connection is supplied.

The electronics unit, besides connecting to the PHA transducer assembly, supplies power to all modules, receives, processes, and controls all functions and interfaces from and to the unit. Interfaces, such as serial communication and Syncro-to-Digital Converter (SDC) are also provided. The electronics unit is contained in a 19” rack-mountable chassis that is supplied by mains voltage of 85-250 V~, 45-500 Hz.

B) 2-D Phased Array Transducer Description

The 2-D phased array transducer is the enabling technology that makes it possible to reduce an ADCPs practical system frequency by one octave, decreasing weight, and volume relative to conventional piston transducers operating at an octave higher frequency. Such a planar phased array transducer has a flat face as it is constructed out of many individual elements aligned geometrically in one plane. The 2-D phased array has several key advantages:

- For a given range and frequency a 2-D planar phased array transducer has an order of magnitude smaller volume as compared to a Janus configured transducer of similar performance.
- Relative higher reliability due to less exposed surface area and ease of incorporating a hardened face exposed to the water. This 2-D array has nominally less than 1/4 to 1/8 of the non-metal area exposed to seawater as compared to a Janus configured transducer of the same frequency and beam-pattern. The reduced and hardened surface area provides less chance for leaks and marine growth.
- Easier installation due to its comparative small size, weight, and volume. Also acoustic window design and installations is easier as well.
- Lower flow noise due to its simple aperture and flat face. The apertures that are currently in use are either circular or elliptical shapes.

The array samples the propagating pressure wave. The general mathematical construct is like that of a Finite Impulse Response (FIR) filter (this is not of a surprise as often the process of beam forming is called spatial filtering also). The output at time *k*, *y(k)* is the sum of the *n* transducer elements’ responses $x_m(k)$ at time *k* and weighted by factors a_m:

$$y(k) = \sum_{m=0}^{n-1} a_m{}^* x_m(k) \qquad (1)$$

where * is the complex conjugate. However, for simplicity the weightings used for this array are simple phase shifts that are produced by all-pass filters of the well-known form:

$$T(s) = \frac{s - a_0}{s + a_0} \qquad (2)$$

The magnitude of such filters is always 1. Compare Fig. 1 for a schematic representation of the beam forming process.

The array pattern, like any other conventional transducer, is a critical factor for an ADCP’s performance. Beam-width usually defined as a one way drop in amplitude of 3 dB, and image-beam suppression are two such characteristics. Image and cross beam rejection of typically better than 35 dB without the use of other image beam suppression methods have been verified; the one-way beam width for a circular 36x36 element transducer is about 3.6° [3]. Various configurations have been build and being used, such as 24x24 circular, 32x32 circular, 36x36 circular and 36x24 elliptical arrays. The 36x24 element elliptical array is the recommended choice for vessel applications, and is shown in Fig. 2 below. Currently, higher ADCP system frequencies us circular shaped arrays only.

C) Electronics Unit Description

The electronics unit is contained in a 19” rack mountable chassis of similar size than current RDI vessel mount ADCPs. The electronics unit consists of only four major assemblies,

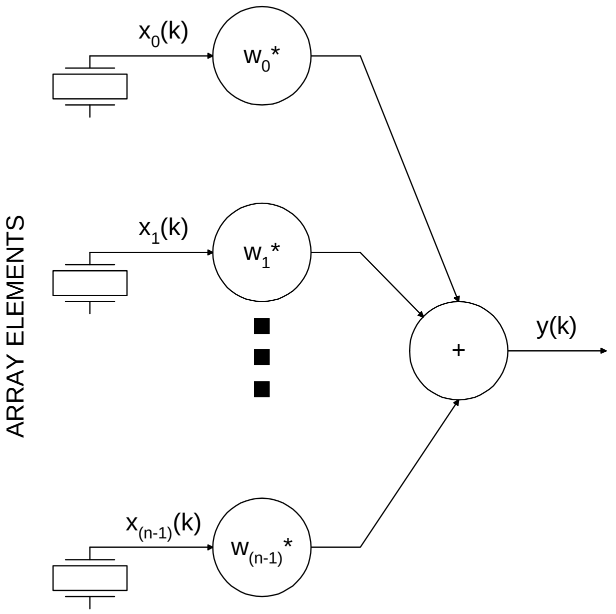

Fig. 1: Schematic of basic beamformer. A beamformer forms a linear combination of the sensors outputs. The sensor’s outputs are each multiplied by a complex weight and then summed.

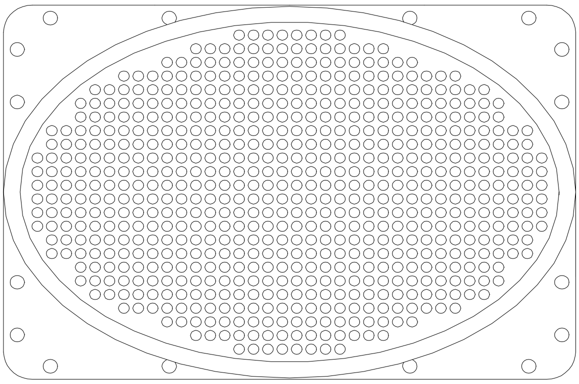

Fig. 2: Front view of 38 kHz elliptical array for vessel applications. The array consists of 656 elements, where the major axis has 36 elements and the minor axis has 24 elements across. The major axis of the array is oriented in the fore-aft direction of the vessel and has a beam width of 3.6 °. The dimensions are 794 x 550 mm (L x W). The weight is approximately 150 kg in air. Its volume is about 46 liters.

that is the processor assembly, a power assembly that also carries the 2 or eventually 4-channel transmitter, and a SDC assembly. The fourth assembly is an off-the-shelf switching power supply with international mains input voltage range.

The core of the processor assembly is a state of the art and powerful 32-bit floating point digital signal processor (DSP) that executes all instructions within 50 ns. A Field Programmable Gate Array (FPGA) provides all glue logic and timing generating functions for the transmitter and demodulator drive. A quad Universal Asynchronous Receiver Transmitter (QUART) provides all internal and external asynchronous serial communication ports. A parallel port for downloading firmware upgrades is available as well, although normal download of firmware upgrades would be accomplished via the main serial communications port. The FPGA configuration is embedded in the system's firmware code, and hence truly field programmable also. This feature makes these systems very user friendly as firmware upgrades can now be accomplished "on the fly" and with ease.

The receivers filter, amplify, and demodulate the beamformer signals into quadrature base-band signals. These complex base-band signals are then passed trough low-pass filters, and are sampled. The digitized signals are stored in real time and concurrently processed.

D) Signal Processing Description

Currently, the OS is processing the signals in 1) a BB-mode of operation. A 2) NB processing mode is under development and will be available in the near future.

1) BB-mode of operation uses a pulse-to-pulse coherent signal-processing scheme similar to the RDI BB-ADCP signal processing [1]. The difference to the BB-ADCP is that the system bandwidth is reduced to about 1/3 of the BB-ADCP bandwidth. This is required, as the phased array transducer's beam angle is sensitive to frequency. However, the reduced bandwidth improves the signal-to-noise (S/N) ratio by nearly 5 dB as well. A BB-mode Bottom Track algorithm has been implemented and tested also.

2) A NB-mode of processing is under development. Earlier RDI NB-ADCPs used real-time tracking filters that are used for positioning of the Doppler shifted signals within the processing filter. This is needed to avoid bias errors caused by filter skew. In the presents of shear velocities these tracking filters caused errors due to the dynamic behavior of the environment and the filter's loop response [2]. In the OS NB-mode of operation these bias errors are avoided. All sampled raw data are stored in memory and data can be re-processed in an iterative loop. The filtering is adaptive as filter bandwidth and position can be changed from one iteration loop to the next until the result does not improve any longer. A signal bandwidth in the tenth of one percent improved the S/N ratio significantly. Hence, the NB-mode of operation will increase profiling range in addition to the range increase due to the lower system frequency. However, this will be at the expense of about a factor of 2 lower velocity measurement precision as compared to the BB-mode of operation.

The user has the choice to select either one or alternating between operating modes depending on the application requirements.

E) Software Description

RDI's new Windows software for Vessel Mounted ADCPs has several design goals that cover a wide range of requirements. These range from (a) taking advantage of the power of today's PC-type computers for improved acquisition and display of both ADCP and ship-based data to (b) allowing expert users flexibility for re-processing and post processing data. This flexibility includes users plugging in their own modules to RDI's processing package and exporting data in non-RDI formats to 3rd party products.

A theme for improving RDI's software is to optimize data quality for both external ship-related input to the processing (e.g. heading) as well as ADCP specific data (e.g. velocity). We place greater emphasis on detecting and eliminating poor quality data as well calculating outlier-resistant averages for data ensembles.

A major goal of the software is to have revealing displays of data that help the user focus on informational content rather than data reduction. Users are able to see simultaneously the data set as a whole as well as choose/zoom a selected section. Our primary goal is to aid interpretation of the data by producing informative data summaries that show structure within data sets. To achieve this we have significant flexibility in data presentation, both in the data types chosen and the type of variation to be emphasized (depth, time), as well as some new more-informative displays.

F) Possible Enhancements

Several system enhancements are possible. Currently it is planned to (a) incorporate image and adjacent beam suppression algorithm for both, the 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 any beamformer and array can realistically provide, and even beyond of what conventional transducers are able to. The effect is a reduced cross talk that will reduce velocity bias effect due to non-uniform scattering. Further, an (b) in-situ echo intensity calibration feature will allow the calibration of that part of the system that is mostly responsible for the lot and temperature dependent offset, linearity, and scaling errors of the echo intensity measurement of current BB-ADCPs. The goal is to calibrate the intensity measurement to a relative accuracy of $|0.5|$ dB, although an additional single point calibration of the transducer assembly would still be required for absolute backscatter level measurement.

III. PERFORMANCE PREDICTIONS

RDI has developed a theoretical performance model. It predicts range and horizontal velocity measurement precision that is based on well-published Doppler Sonar principles and Doppler signal processing schemes that are implemented in RDI’s ADCPs. This model has been verified through testing and field experience, and through many contributions of the current users of ADCPs.

Fig. 3 and Fig 4 show the computed range and horizontal velocity measurement precision for a 38 kHz system. Predicted performance can differ from actual results as the model makes assumptions about the environment. This includes the backscatter strength at ranges of >1000 meters. It should be noted that the range past much of 1000 meters has not been verified yet, but seems reasonable when the volume backscatter strength at these ranges does not fall below –90 dB. Nevertheless, to demonstrate the potential performance in the NB-mode of operation the NB-mode range is plotted in Fig. 3 as well.

The current specifications for range and precision of the various PHA OS, listed in TABLE I, are to the best of our knowledge. The values are listed for default bin sizes of 32 m, 16 m, and 8 m for 38, 75, and 150 kHz systems respective. Per Fig. 3 and Fig. 4, smaller or larger Bin sizes give a lower or respective higher velocity measurement precision, and somewhat shorter or longer ranges. The authors recommend using the default Bin size whenever it is practical.

The velocity measurement precision in Fig.4 and TABLE I is the initial horizontal velocity precision, that is where the

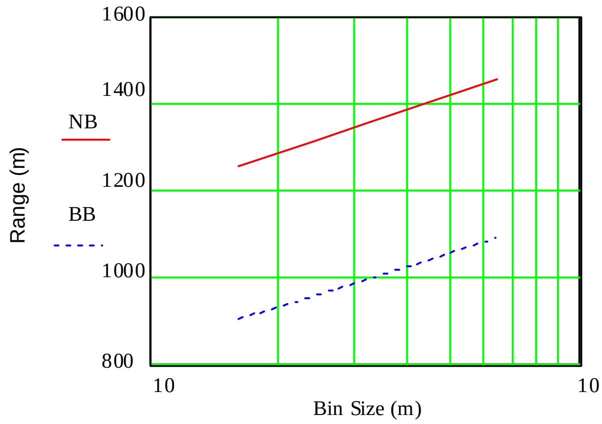

Fig.3: Computed range in meters as a function of Bin size inmeters for a 38 kHz system. The BB and NB-mode are shown as the dashed and solid line respective. The range of in NB-mode is not verified.

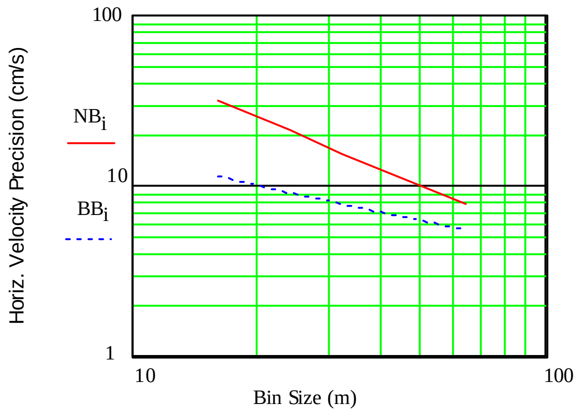

Fig. 4: Computed horizontal velocity measurement precision (standard deviation) in cm/s as a function of Bin size in meters for a 38 kHz system. The BB and NB-mode are shown as the dashed and solid line respective.

TABLE I
Performance Specifications for PHA OS for the default Bin size.

	Range (m)		Precision (cm/s)	
	NB	BB	NB	BB
38 kHz	1000	800	16	8
75 kHz	630	450	16	8
150 kHz	350	250	16	8

@ For default Bin sizes of 32, 16, and 8 meters for 38, 75, and 150 kHz respective.

correlation magnitude has not degraded from its best value. Typically this range is approximately 10 default range bins. However, per (3), as the S/N ratio degrades over range the correlation magnitude decreases as a result [1]:

$$\Re = \Re_0 \cdot b / (1 + 1/SNR) \tag{3}$$

where $\Re$ is the correlation magnitude, $\Re_0$ the ideal correlation magnitude, b is the decorrelation factor, and SNR the Signal-to-Noise Ratio. Decorrelation is caused by factors such as thermal noise, non-uniform scattering strength, beam divergence, finite residence time of scatters in the sample volume, vessel motion, and others.

The velocity measurement precision however is a function of the correlation magnitude, and is determined by (4) [1]. The computed single ping horizontal velocity measurement precision over range for the default Bin size in NB and BB-mode for a 38 kHz system is plotted in Fig. 5.

$$s \propto \sqrt{\Re^{-2} - 1} \tag{4}$$

IV. FIELD EXPERIENCE

The presented data below are in support of the claims made in regards to range, accuracy, and performance of the 38 and 150 kHz PHA OS operating in BB-mode. The data that are available currently are not very numerous; nevertheless, we believe sufficient to collaborate the capabilities of these new systems. Data for 75 kHz OS are not available as the only such systems deployed are on non-moving platforms.

A) Range

During June 11-12 of 1998, the vessel Shoyo-Maru, operated by the Fishery Agency of Japan, performed tests

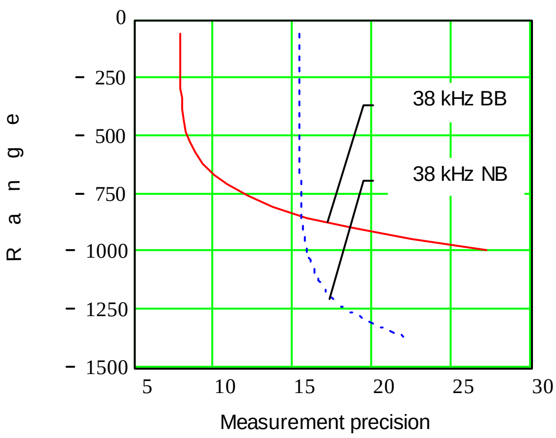

Fig. 5: Computed single ping horizontal velocity measurement precision as a function of range for a 38 kHz system.

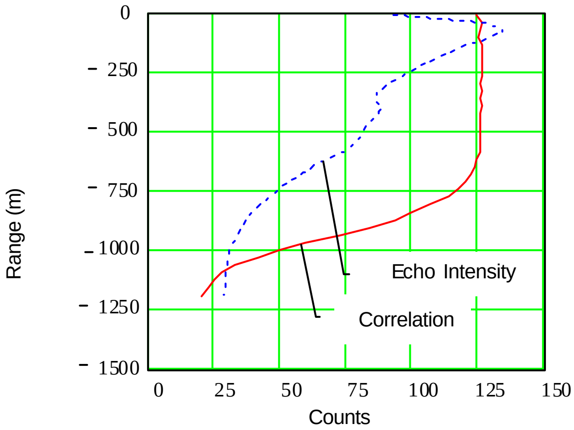

Fig. 6: Averaged correlation and echo intensity counts. The usable profiling range extents up to a correlation magnitude of ≥ 50% of the initial value. In this case the range extents to 30x32+8=968 meters off of the transducer's face.

using a 24x24-element phased array transducer and a BB-ADCP electronics unit adapted for the phased array transducer. The data file used for Figures 6-8 was labeled ENUJ005R.000. This file was selected because it used the default Bin size of 32 meters. The sea floor was out of range. The data was taken with the vessel adrift, and the sea-state was calm. It is the author's opinion that the R/V Shoyo-Maru took exemplary care in installation of the transducer. It used an acoustic window in front of the transducer, which reduces the effects of flow noise and aerated water in front of the transducer. RDI can only recommend the use of such windows for most, if not all installations.

A good range indicator is the correlation magnitude. Per default, the data are usually screened based on a correlation magnitude of 50% of the initial value. The plotted data in Fig. 6 are an average over 11 minute and 44 seconds. The obtained range based on the above default criteria are 30 Bins of 32 meter size; the blanking distance was 8 meters. Thus the range extents to 30x32+8=968 meters past the transducer's face.

Fig 8 and Fig. 9 show the averaged velocity components. Again, the average is taken over a time of 11 minutes and 44 seconds. A range of 30 Bins is shown. The ensembles were screened for removing outliers that were larger than $|200|$ cm/s. Because of the reduced correlation toward the end of the profile only 45 % of the ensembles had 100 % good data. From the discarded data about 90% were contained in the last two Bins. The plotted range is that range, that extents beyond the transducer's face and not the actual depth. The measurement precision of the averaged ensemble is about 1 cm/s at the first 300 meters of the range and about 2 cm/s toward the end of the range.

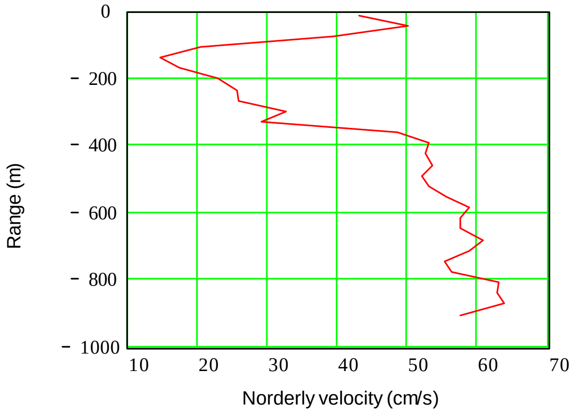

Fig. 7: Norderly velocity profile. Data averaged over 11 minutes and 44 seconds. Vessel's velocity not subtracted from measured data.

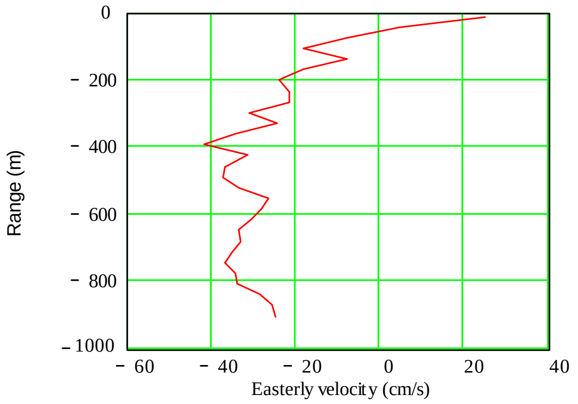

Fig. 8: Easterly velocity profile. Data averaged over 11 minutes and 44 seconds. Vessel's velocity not subtracted from measured data.

The data from the R/V Shoyo-Maru demonstrate that the specified range for 38 kHz systems is obtainable; but conditions are often not as favorable. Acoustic windows are a good installation practice for reducing flow noise and aerated water. Experiences with other installations show that it can not be stressed enough that for low-frequency Sonars it is imperative to minimize flow noise and aerated water. Propeller and truster noises are also factors that can reduce the profiling range significantly.

Decorrelation of signal can also be caused by excessive vessel pitch and roll rates. The maximum allowable roll-rate ψ is a function of allowable angular displacement and range, as shown in (5):

$$\frac{\partial y}{\partial t} = \Delta \frac{c}{r} \qquad (5)$$

where D is the maximum angular displacement, c the sound speed in m/s, and r the vertical range in meters. By some account the angular displacement must be less than ½ of a one way beam width. The reasoning is that if an angular displacement of about one half of a beam has taken place then only half of the energy returns to the receiver, and only one half or less of the scatters will correlate. Lets assume a one-way beam width of 4°, and a speed of sound of nominally 1500 m/sec. With these parameters the maximum roll-rate at a range of 800 meters is < 3.75 °/s. Pitch rates would compound this problem. If the same pitch rate is assumed than the combined maximum pitch and roll rate is perhaps a factor $1/\sqrt{2}$ smaller than a single pitch or roll rate, that is $3.75/\sqrt{2} < 2.65$ °/s. Vessel speed adds additional beam displacement. An exact analysis of permissible vessel motion rates is beyond this paper, and the above example serves for illustrating the problem of ship motion. It seems however clear that vessel dynamics impose additional restrictions on the obtainable range beyond ship and flow noise.

B) Accuracy

The specified accuracy of the phased array OS is 1 % ± 0.5 cm/s. There are no extensive field data yet that can collaborate this specification. However, RDI had conducted accuracy test runs with a 150 kHz PHA OS system on Lake Hodges near San Diego, California. The lake was chosen because it provides repeatable conditions. The purpose of those tests were to compare a PHA OS with a 600 kHz Workhorse (WH) ADCP that has a verified accuracy of 0.25% ± 0.25 cm/s. A PC and specialized software controlled the alternating ping cycle of both systems. Also, for those comparative tests, both systems were set up in the same way. In particular the Bin sizes were set to 4 meters, and the bandwidth of the WH was set to be equivalent to the OS in BB-mode of operation.

Fig. 9 plots a scattergram of the velocity magnitude of the 150 kHz OS against the 600 kHz WH reference system. As expected, the 150 kHz PHA OS generates a circular shaped cluster about the reference velocity. The distribution of the individual measurements appears to be normal. The test results are listed in TABLE II. The listed results show that the accuracy of this particular system is as good as the reference system's accuracy, and is well within the system specification. However, the authors do not claim that this test result constitutes the proof of the accuracy of a 38, or 75 kHz OS system, but rather is an indication of the potential accuracy of these phased array based OS systems. By deduction one can argue that these other systems are in compliance to their specified accuracy, especially if one considers that the basic technology for all three systems is identical.

In addition, a Bottom Track (BT) algorithm has been implemented. It allows to track a vessel's position and

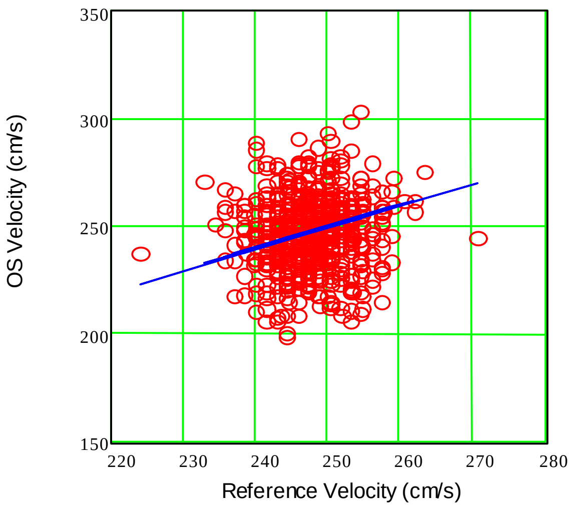

Fig. 9: Scattergram of velocity magnitude of 150 kHz phased array OS vs. 600 kHz WH reference system. The solid line are velocities measured by the reference system. The circular measurement points are the velocities as measured by the OS.

velocity, and thus to obtain a earth reference velocity that can

TABLE II
Comparative test results between a 150 kHz OS and a 600 kHz Workhorse, using 4 meters bin size.

Parameters:	600 kHz WH	150 kHz OS
Mean velocity	247.403 cm/s	247.389 cm/s
Single ping precision	3.791 cm/s	15.128 cm/s
Ensemble precision	0.151 cm/s	0.600 cm/s
Rel. mean of differences	0.027 %	
Rel. Joint precision	0.251 %	

be used to subtract the vessel’s velocity from the measured velocity. At this time, preliminary lake tests resulted in an accuracy of about 0.45%. Thus we have reason to assume that the obtainable BT accuracy will be well within the currently specified accuracy of 1% ± 0.5 cm/s. Details of the BT testing are not discussed here, as more testing has to be conducted.

C) Precision

The specified measurement precision is defined as a system’s non-deterministic uncertainty that is added to the actual measurement by the system; thus, it can be considered as a system specific lower bound thereof.

Determining the precision of any measuring device is best accomplished under controlled and repeatable conditions. Invariably, a user would be most interested to know what precision can be expected in the environment the instrument is going to be used in. However, to determine actual system specific uncertainties under usual deployment conditions accurately is difficult at least, and impossible if vessel dynamic motion data are not available. Hence, measurement precision is often influenced by the environment, which always decreases the precision.

The comparison in TABLE III used data from the lake test at Lake Hodges and two trial runs onboard of larger research vessels. RDI had chosen the lake test for its repeatable conditions. The trial run near the coast of Newfoundland experienced problems mostly due to firmware errors; the remainder of the usable data however had the closest match in measurement precision to the predicted value. The lake test showed a surprising 34 % larger standard deviation, while the Shoyo-Maru had the largest deviation of nearly 60%. It is noteworthy to point out that all systems used non-standard setups either by the selected Bin size or the size of the transducer.

The measured precision is the standard deviation σ of the horizontal error velocity. RDI computes the horizontal error velocity *e* using (6):

$$e = \frac{v1 + v2 - v3 - v4}{2\sqrt{2}\cdot\sin(q)} \qquad (6)$$

where *v*1-*v*4 are the radial velocities of beam 1 through 4, and *q* is the slant angle, which is 30 degrees for all current phased array transducers. Although the authors believe that the results of the measured precision are within the roam of reasonableness and may be an acceptable trade-off against the

TABLE III
Comparison of predicted velocity measurement precision and measured horizontal velocity precision.

Parameters:	Predicted precision	Measured precision
Lake Test @ 150 kHz @ 4 m Bin @ 32x32 el. array	11.3 cm/s	15.1 cm/s
Trials Off the coast of Newfoundland @ 38 kHz @ 24 m Bin @ 24x24 el. array	9.1 cm/s	10.1 cm/s
Trials by R/V Shoyo-Maru @ 38 kHz @ 32 m Bin @ 24x24 el. array	7.8 cm/s	12.4 cm/s

increase in range, the reduction in weight and volume, and the ease of installation. Notwithstanding, more analysis and testing has to be conducted for determining the cause for the discrepancy.

CONCLUSION

New phased array based systems have been presented that extend the usable profiling range well beyond the current limits, or extend the profiling range significantly for installations where size is the limiting factor. This improvement is primarily accomplished by utilizing 2D-phased array technology which reduces the transducer volume by an order of magnitude for a given system frequency. Flexible signal processing allows one to trade-off additional range for measurement precision within a single system. Improvements will make these systems more accurate and more versatile for all users. Last but not least, more analysis and tests are necessary for proofing accuracy, range, and precision, and the conditions under which these specifications are met.

ACKNOLEDGMENT

We would like to thank Dr. Watanabe and Mr. Sawada of the Fishery Agency of Japan for supplying the data collected by the R/V Shoyo-Maru, Mr. Chikara Shimoda of Sea Corp. for obtaining the permission to use these data, and Dr. Peter Spain of RDI for his contribution about software.

REFERENCE

[1]. Brumley, B. H., Cabrera R. G., Deines K. L., and Terray E. A., “Performance of a Broadband Acoustic Doppler Current Profiler,” IEEE Journal of Oceanic Engineering, vol.16, #4, pp402-407, October 1991.

[2]. Chereskin T. K., Firing E., and Gast J. A., “Identifying and Screening Filter Skew and Noise Bias in Acoustic Doppler Current Profiler Measurements,” Journal of Atmospheric and Ocean Technology, vol. 6, pp1040–1054, 1989.

[3]. Yu X., Gordon L., “38 kHz Broadband Phased Array Acoustic Doppler Current Profiler,” Proceedings of the IEEE Fifth Working Conference on Current Measurement, Feb 7-9, 1995, St. Petersburg, FL, pp53-57.