NOVEL TWO DIMENSIONAL HIGH FREQUENCY PHASED ARRAY BASED DOPPLER VELOCITY LOG FOR UUV APPLICATIONS

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Abstract – A novel Two-Dimensional High Frequency Phased Array is nearing the final stages of its development at RD Instruments. This paper discusses the technology that brings small, low power, high precision Doppler Velocity Logs to the next generation of Unmanned Underwater Vehicles.

Funding by the Office of Naval Research has enabled RD Instruments to apply its patented 2-D Phased Array technology to provide a Hull Form, High Frequency (600 KHz) Phased Array Doppler Velocity Log and Acoustic Doppler Current Profiler for the next generation REMUS vehicle.

Here, we discuss the fundamentals of the Phased Array, general characteristics of the transducer and developments in RD Instruments' Next Generation Sonar Platform. Furthermore, the possibilities for system improvements enabled by these technologies to provide higher accuracy and resolution in navigation are explored.

I. INTRODUCTION

The advancement of Unmanned Underwater Vehicle (UUV) technology has enabled a variety of new applications to be explored. A number of these applications require smaller vehicles with less power consumption and higher navigational accuracy.

This requirement within the industry prompted RD Instruments (RDI) to develop smaller Doppler Velocity Log (DVL) technologies to meet the need. Utilizing RDI's patented 2-D Phased Array Technology [1] to provide higher frequency systems in combination with up to date electronics was not only logical but also feasible.

The 2-D Phased Array is an acoustic array capable of simultaneously forming multiple transmit and receive beams inclined within two planar orientations normal to the array face. For DVL applications, two sets of narrow dispersion, broadband or narrowband acoustic beams are formed with minimal transducer aperture size.

The Next Generation Sonar Platform (NGSP) is an electronics package that uses today's technologies and takes advantage of faster, smarter, smaller and lower power consuming components.

RDI is currently working on the refinement of the transducer manufacturing procedures and the implementation of Phased Array functionalities into its new electronics package in order to provide the next generation of small UUV's with DVL capability.

II. BACKGROUND

RDI has pioneered the development of the 2-D Phased Array. Since 1996, RDI has built and shipped upwards of 125 systems. The production of such systems with frequencies ranging from 38 KHz to 150 KHz is now commonplace at RDI; with the first reports on the success of the technology dating back to 1995 [2] and 1999 [3].

The first High Frequency Phased Array prototype was built for the REMUS AUV. It was delivered to Woods Hole Oceanographic Institute under a development contract in May of 2000. This hull form DVL, seen in Figure 1, provided significant improvement in size and weight. Furthermore, it enabled other technologies such as an Inertial Navigation System to claim the freed up real estate.

Figure 1: 600 KHz Phased Array Development Unit for REMUS.

The system shown in Figure 1 was a true stepping stone to where we are today. It houses the predecessor of today's NGSP set of electronics and a High Frequency Phased Array transducer built by RDI engineers. The delivery of this system allowed WHOI to obtain further funding from the Office of Naval Research (ONR), which in turn enabled RDI to develop the necessary manufacturing techniques to transfer the product into its production facility for larger quantities.

This paper is intended to introduce this new technology and provide for a starting point of discussions regarding it, and it's applications in the next generation of UUVs.

III. THE PHASED ARRAY

The 2-D Phased Array transducer is the enabling technology that makes it possible to reduce the size, and thus the weight of a transducer when compared to a conventional piston transducer. For instance, such a 2-D planar Phased Array transducer may occupy an order of magnitude less in volume as compared to a Janus configured transducer of similar performance. For a size comparison refer to Figure 2.

Figure 2: Size comparison of RDI' 600 KHz 4-beam piston and model 2-D Phased Array transducer technology.

To resolve instrument speed over ground and/or water currents in three vectors, a minimum of three acoustic beams are needed. RDI standard Doppler Velocity Logs and Acoustic Doppler Current Profilers (ADCP) provide four acoustic beams. The advantages to this are two-fold at a minimum. First, the base assumption of flow homogeneity, which pertains to all Doppler measurements, can be verified by resolving the Error-Velocity.

This quality indicator can be used in real time decision-making processes to use or reject a particular measurement. Calculating the Horizontal Error Velocity is simple:

$$e = \frac{v1 + v2 - v3 - v4}{2\sqrt{2} * \sin(\theta)} \qquad (1)$$

Where:

- *v1* through *v4* are the radial velocity components of beams 1 through 4
- θ is the beam slant angle, which is 30 degrees for all current Phased Array transducers produced by RDI.

For the stated 30 degree beam slant angle (1) reduces to:

$$e = \frac{v1 + v2 - v3 - v4}{\sqrt{2}} \tag{2}$$

As this is a fourth, independent, piece of information, it is obvious that it cannot be obtained using only three beams.

Secondly, the fourth beam provides redundancy in the system. As only three beams are required to resolve the velocity vectors in three spatial components, the loss of one beam does not result in total loss of data. This built in redundancy can be highly desirable for unmanned vehicles, especially for those that operate autonomously.

The 2-D Phased Array that is presented here provides four beams simultaneously, utilizing the advantages of a Janus beam configuration while occupying the volume of a single piston transducer.

The 2-D Phased Array also offers an additional benefit, in that the horizontal x-y velocity components are independent of the speed of sound. This can be shown as follows:

Let:
c = speed of sound
d = distance between adjacent array elements
f_0 = transmit frequency
f_D = Doppler frequency
v_h = horizontal velocity components
v = radial velocity (along beam axis)
θ = beam slant angle
λ = wavelength

From array theory, the beam slant angle in terms of wavelength and array element separation is:

$$\sin(\theta) = \frac{\lambda}{4d}\,. \tag{2}$$

Which, in terms of speed of sound, is then:

$$\sin(\theta) = \frac{c}{4df_0}\,. \tag{3}$$

Further, the Doppler shift is:

$$f_D = \frac{2f_0 v}{c}\,. \tag{4}$$

The Doppler shift in the horizontal plane (parallel to the array face) follows:

$$f_D = \frac{2f_0 v_h \sin(\theta)}{c} \tag{5}$$

Substituting (3) in (5) and simplifying leads finally to:

$$f_D = \frac{v_h}{2d} \tag{6}$$

Hence, the Doppler shift in the horizontal x-y plane, the plane that is parallel with the face of the transducer, is independent of the speed of sound.

A. Basic Array Principle

Refer to Figure 3 for reference. Consider a line-array of equally spaced and equally phased elements, where the spacing is d = λ/2. Furthermore, let a sinusoidal plane wave be incident at the beam slant angle θ. The phase delay of this plane wave of wavelength λ to travel from element m to element m+1 is [4]:

$$u = \frac{2\pi d}{\lambda}\sin(\theta) \tag{7}$$

Therefore, a beam slant angle θ of 30 degrees results in a phase delay between adjacent elements of u = π/2 radian, or 90 degrees. This relationship is fundamental for this type of Phased Array and to the design of the Beamformer.

Lets arbitrarily assign a relative phase delay of 0 to element 0. Then every element in sequence will have a 90-degree phase shift. At element 4, the phase delay is 360 degrees, or 0 again. Thus, the phase delays repeat every 5th element. If the line array contains more than 4 elements, then every element that has the same phase delay is connected in parallel, which is every 5^{th} element in sequence.

Thus, 4 groups can be formed that have 4 signals with relative phase delays of 0, 90, 180, and 270 degrees. For convenience lets call these groups R0, R90, R180, and R270, where the prefix R stands for row.

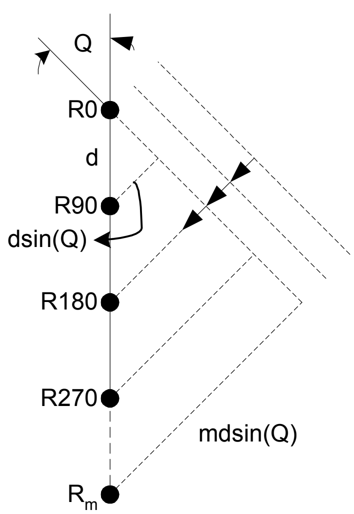

Figure 3: Line array of equally spaced elements.

A maximum response in the direction of beam slant angle θ is generated by applying the proper phase shifts to the 4 groups of R0 through R270 and summing these signals. That is, in principle, a phase shift of 270, 180, 90, and 0 degrees is applied to R0 through R270 respective. A second beam in the direction of -θ can be formed if phase shifts of 0, 90, 180, and 270 degrees to R0 through R270 respective are applied. Thus, two beams in one dimension are now formed with beam slant angles θ = ±30°. Lets name this dimension X.

B. 2-D Array Description

A 2-D Phased Array simultaneously produces 4 beams as shown in Figure 4, where pairs of beams are orthogonal in two dimensions on a plane surface. That is, a pair of beams is now generated that are orthogonal to dimension X. Lets name the second dimension Y.

To form this second pair in the Y dimension, the array has not only rows but also columns of elements with adjacent element spacing of d = λ/2 as well. That is, one face of the transducer is connected in rows while the other face is connected in columns orthogonal to the rows. This is where the difference lies between a one-dimensional and the patented 2-D array. As a result, the 2-D array produces signals R0 through R270 and C0 through C270, where C is the prefix for column.

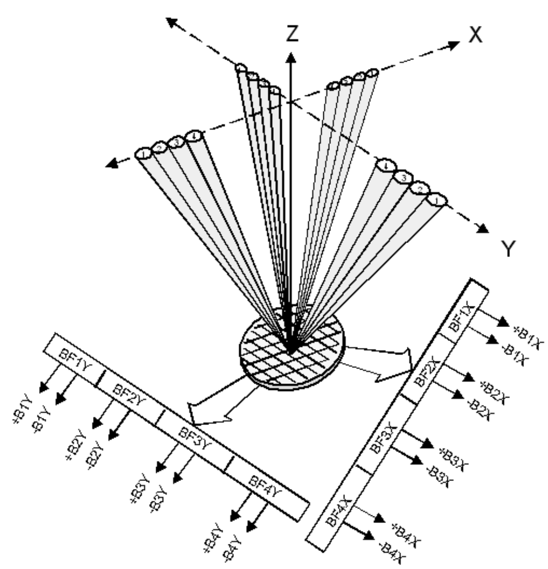

Figure 4: Four Janus beams simultaneously being formed form single 2-D Phased Array Transducer.

C. The Transducer

A circular array of 58 x 58 elements at the centerline was chosen for final production. The fact that each piezo electric ceramic element is less than $1mm^2$ in size with a height of less than 2.5mm and spaced at less than 0.3mm apart has brought about quite a manufacturing challenge.

RDI is currently refining the manufacturing techniques deployed to build this transducer array in a repeatable, reliable fashion within its production group. The extreme accuracy required in the positioning of the elements is achieved with the introduction of a CNC Dicing Machine into the RDI production arsenal. A solid piezo electric ceramic is prepped to become a transducer and with this machine, diced to the desired form with full automation.

The transducer is built up with flex print circuitry on either side of the ceramics in order to run them in the required fashion with further material on one side to act as the backing for the transducer. The entire array is then encapsulated in a housing to provide the final product with an overall diameter of 8.382 cm and an overall height of 1.905 cm. See Figure 5 for reference.

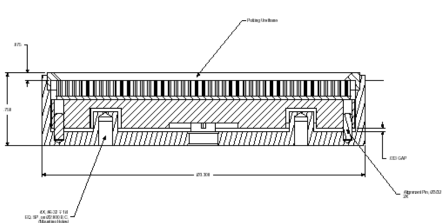

Figure 5: The current design in pre production stage. 3.3 " Diameter with a height of 0.75"

D. Beam-Former Description

The Beamformers' purpose is to generate both beam pairs, using 4 signals R0 through R270, and C0 through C270 respective. Let's discuss here the forming of a single beam first. For this purpose we will use signals R0 through R270. Lets also define the beam pattern of groups of staves with n elements:

$$H(\theta) = \frac{\sin(n\frac{u'(\theta)}{2})}{\sin(\frac{u'(\theta)}{2})} \quad (8)$$

Where u' is defined as being the phase delay between one such group of staves, that is:

$$u'(\theta) = 4\pi \sin(\theta) \quad (9)$$

Note that the distance between these groups in terms of wavelength is 2λ. A group of staves constitutes a quartet of adjacent R0 through R270 individual staves.

The four signals that are received are:

$$R0(\theta) = H(\theta) \quad (10)$$
$$R90(\theta) = H(\theta)e^{-j\cdot u(\theta)} \quad (11)$$
$$R180(\theta) = H(\theta)e^{-j\cdot 2u(\theta)} \quad (12)$$
$$R270(\theta) = H(\theta)e^{-j\cdot 3u(\theta)} \quad (13)$$

When applying the proper phase shifts to these array signals (10-13) and adding the shifted signals, a single beam in the direction of the desired beam slant angle θ is formed (14):

$$B_1(\theta) = H(\theta)\sum_{q=0}^{3} e^{-j\cdot q(u(\theta)-\frac{\pi}{2})} \quad (14)$$

Note that the above calculations are for an *n x n* array. To obtain the response of a circular array the individual staves must be weighted.

To form a beam in the same dimension but in direction -*θ*, the signs of the 90 degree phase shifts are changed (15).

$$B_2(\theta) = H(\theta)\sum_{q=0}^{3} e^{-j\cdot q(u(\theta)+\frac{\pi}{2})} \quad (15)$$

A Beam-Former for a 2-D Phased Array would have a second identical set of phase shifters and adders, likewise to equations (14) and (15), but with the four signals produced by columns C0, C90, C180, and C270, as their inputs likewise to equations (10) through (13). Since these columns are orthogonal to the rows, beams B3 and B4 are now formed that are also orthogonal to beams B1 and B2, and hence, the Beam-Former has formed four simultaneous beams in a Janus configuration.

IV. SONAR HARDWARE PLATFORM

A. Overview

Not surprisingly, the hardware architecture is similar to other RDI DVLs and ADCPs, although the NGSP has significant differences that result in greater flexibility, lower power consumption, smaller size, and lower cost as compared to the Workhorse line of products. Typically, an NGSP-based ADCP consists of the Power I/O (PIO), Digital Signal Processor (DSP), Receiver (RCVR), and Sensor Interface boards. Figure 6 shows a typical NGSP board stack without the Sensor board.

Figure 6: Typical NGSP board stack; Power I/O, Digital Signal Processor, and Receiver board. The receiver shield is shown between the receiver and the DSP.

B. Power Input/Output Board Description

The Power Input/Output board (PIO) accepts the input power to the system, generates and regulates all necessary volatile and non-volatile voltage supplies to the electronics, as well as an isolated supply voltage for the isolated user interfaces.

Systems with operating frequencies from 300 kHz and higher operate from a supply voltage of 10 VDC minimum, and up to 18 VDC. The nominal supply voltage is 12 VDC, which is very convenient as such supply voltages are readily obtainable.

The transmitter consists of four independent transmit channels, one for each beam. Thus, redundancy is provided which increases reliability over systems that use only three transducers and three transmitters, or less.

Finally, the PIO provides a multitude of user Input/Output (I/O) options, selectable via a Personality Module. Options include RS-232, RS-422, RS-485, SDI-12, and programmable Trigger Input and Output. To make system integration less problematic all I/Os are isolated from electronics power.

C. DSP Board Description

The core of the computational engine and control of the NGSP line of products are all based on a powerful 32-bit floating point low-power DSP. The DSP is performing all processing functions at or near real-time. Although not implemented currently, the NGSP DSP architecture allows the use of a hardware correlator without change to the basic architecture (although a change of the hardware and firmware would be required). The firmware is in-circuit downloadable; that is, firmware updates can be loaded into the system via the user RS-232 port without opening the system.

Further, the DSP board employs a state-of-the-art Field Programmable Gate Array (FPGA). It contains the timing generator for the transmitters, local oscillator (LO) generation, data path manipulation, sample logic, nearly all ‘glue’ logic, and other essential functions. For some applications it may be desirable to reduce transmit power. Average transmit power can be reduced via command. This is accomplished by transmit waveform duty cycle control, which is also implemented within the FPGA. To make upgrades of the FPGA easier too, its code is also in-circuit programmable, and is loaded together with the system firmware via the user interface.

The DSP board has all logic and circuitry necessary to sample the demodulated receiver signals to enable the processing of signals in broadband as well as in narrowband mode.

D. Receiver Board

The receiver board carries four identical receiver and demodulator channels. Each such channel is comprised of transducer tuning and impedance matching network, transmit and receive switch, pre-amplifier with gain control and bandwidth selection switch, logarithmic amplifier (compressor) with buffered received signal strength indicator (RSSI) output, quadrature mixer, low-pass filters with bandwidth selection switch, hard-limiters for BB processing, and linear buffers for NB processing. Gain control options include the choice of time varying gain (TVG), fixed gain, or a gain step.

E. Sensor Interface

The Sensor Interface board is a standalone module that contains all necessary functions for interfacing to temperature, pressure, and tilt sensors (compass is planned in near future).

It has an onboard very low power micro controller unit (MCU) that controls the analog to digital converter ADC, and other auxiliary functions necessary for sensor operation. This MCU performs all basic conversion from measured counts to physical quantity.

Since the NGSP employs an 18-bit ADC the obtained resolution of the measured quantity is very high and exceeds most requirements for DVL and ADCP applications. This high resolution makes it also possible that scaling amplifiers external to the ADC are avoided, and thus also the errors associated with these scaling amplifiers, resulting in more accurate sensor measurements.

The system interfaces to the sensor interface board using one of the two system internal serial high-speed peripheral interface buses.

F. Power Consumption

Average power consumption, and therefore energy consumption too, is determined by the three basic operating cycles; that is, sleep power, transmit power, and processing power. Table 1 lists the NGSP power consumption for the three basic operating cycles. Note that the processing power includes the power needed for the 4-beam Beamformer. As mentioned earlier, the transmit power can be reduced via software control. This is important for applications that use Bottom Tracking. When Bottom Track is used, system power consumption is very much dominated by the transmit power consumption. Thus, reducing the transmit power via software control allows a trade-off between Bottom Track range and power consumption.

Operating Cycle	Power[1] (W)
Asleep	$0.1*10^{-3}$
Transmit	63
Processing	1

Table 1: NGSP Power Consumption with Beamformer for four beams @ f = 600 kHz, Vsupply = 12 VDC.

NGSP based products have a much reduced sleep and processing power as compared to Work Horse based products.

Processing power reduction has been accomplished by employing state of the art circuit design techniques and components, and despite an increase of the digital processors' clock rate of about a factor of three. A large reduction is due to the fact that the NGSP uses 3.3-volt supplies for all digital and analog circuitry, and 1.8 volts for the DSP and FPGA core supply voltage. Despite the increased clock rate, the low core voltage

[1] Power consumption is an estimate based on currently available hardware.

enables the processing power to be only about 40% of that in Work Horse products.

Sleep power is very important for non-real-time applications, where deployment times of several months are desired. Sleep power reduction has been the result of a very efficient generation of the non-volatile voltage supply (refer to section B for a more complete description). Recent testing completed at RDI has shown that the NGSP platform consumed only 11% of what the Work Horse electronics would have in order to maintain its sleep circuitry over a period of 58.85 days.

For real-time applications, such as for DVLs, sleep power is less important than processing and transmit power. Using the power consumption from Table 1, the average NGSP power for an application that is set up to profile 60 meters using a 2 meter Bin size, and that pings once a second, is an estimated 0.28 watts.

Even in this scenario, 67% of the average power is determined by the average transmit power. Using the programmable power feature of the NGSP and trading off some range against transmit power can further reduce the average power consumption. For instance, programming the transmit power for a reduction by a factor of two approximately balances average processing and transmit power, where the profiling range is reduced only by approximately 10%. For this case, the systems' average power consumption is now only 0.18 watts; a savings of about 35% over using the full transmit power.

V. SYSTEMS DEVELOPMENT

The combination of the new high frequency transducer array and the capabilities of NGSP electronics provides for new avenues to develop enhanced firmware. The following are only a few of the possibilities for next generation systems.

A. Improved Low Altitude Bottom Tracking

The current Workhorse Family of products can offer bottom tracking for altitudes as little as 0.3 meters.[2] This product family is subject to higher levels of bottom tracking noise due to single bit phase sampling. RDI refers to this as "clipping noise". This clipping noise becomes problematic at low altitudes because it cannot be easily averaged out within the relatively short averaging time available from the bottom return.

With the next generation systems, RDI will have the ability to do phase sampling linearly by utilizing a multi-bit ADC. This method of sampling has demonstrated that the noise source can almost entirely be eliminated; resulting in further improvements to the shallow water bottom tracking capabilities currently offered with the Workhorse Family of products.

B. Improved Bottom Location

The NGSP electronics package can sample the Return Signal Strength Intensity (RSSI) of the system 20 times faster than the Workhorse electronics package. In turn, this allows for higher resolution and permits more accurate location of the bottom within the return signal. Therefore, the overall velocity processing is rendered more robust and shows improved accuracy.

C. Higher Order Algorithms

The increased processing speed provided with the Field Programmable Gate Array (FPGA) and Digital Signal Processor (DSP) in the NGSP electronics package can not only reduce ping time, permitting for lower noise measurement per unit of energy, but can also handle the implementation of more advanced and/or robust algorithms to expand the operating regime.

[2] 1200 KHz Workhorse Navigator operating in Bottom Mode 7.

D. Reduced Side-Lobe Contamination

Cross talk between beams can be especially troublesome for moving platforms. The platform motion along one axis can cross-couple to the orthogonal axis and generate a false Doppler.

The independent transmitters incorporated into the NGSP electronics allows for this issue to be minimized by transmitting psuedo-random codes that alternate from ping-to-ping. These alternating transmit codes enable the cross talk errors to cancel each other out when the pings are averaged, hence reducing any side lobe contamination in the measurement.

E. Improved Station-Keeping Performance

The desired echo for proper bottom tracking is one from the main lobe reflecting off a solid bottom. Station keeping errors can start creeping in when scatterers in the water directly above the bottom corrupt the echoes. Furthermore, the bottom as seen through the side lobes could also add to the corruption of the desired, main lobe echo.

The combination of the possible improvements in firmware due to the NGSP electronics package mentioned herein alone provide the capabilities required to minimize the station-keeping errors which result from unwanted echoes in the bottom return.

VI. CONCLUSION

The completion of the design and development efforts for the High Frequency Two Dimensional Phased Array and the accompanying Next Generation Sonar Platform electronics is nearing.

These new technologies drastically reduce the space required to incorporate a Doppler Velocity Log into Unmanned Underwater Vehicles while providing for long-term sustainability and higher precision navigation with lower power consumption.

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