DISTRIBUTED VERTICAL LINE ARRAY (DVLA) ACOUSTIC RECEIVER

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Abstract: *A Distributed Vertical Line Array (DVLA) receiver able to span the full water column in water up to 6000 m deep has been developed to allow both modal and ray-based analyses of acoustic propagation. The DVLA is made up of distributed, self-recording hydrophones with timing and scheduling provided by a small number of central controllers, called D-STARs. The enabling technologies for this approach are (i) the availability of flash memory modules that can store several gigabytes of data and be located in a small pressure case at each hydrophone, making it unnecessary to transfer data from the hydrophones to the central controllers for storage, and (ii) inductive modems that allow low-bandwidth communication for command, control, and time synchronization between the D-STAR controllers and the Hydrophone Modules over standard oceanographic mooring wire. The DVLA is modular, consisting of subarrays with a nominal length of 1000 m, each of which has one D-STAR controller and up to 99 Hydrophone Modules. A D-STAR controller is shackled in-line at the top of each subarray. The Hydrophone Modules are clamped to the mooring wire at the time of deployment, making the DVLA readily configurable for different experiments. The D-STAR clocks are synchronized acoustically, avoiding electrical interconnections. The DVLA is navigated using acoustic transponders positioned on the seafloor around the mooring. The Hydrophone Modules make precision temperature measurements throughout the time that the DVLA is deployed, in order to provide the sound-speed profiles needed for beamforming.*

Keywords: *Array technology, sound propagation in deep water*

1. INTRODUCTION

Uncertainty due to ocean variability limits the ability to make accurate predictions of acoustic propagation. Scattering due to internal waves and other ocean processes limits the temporal and spatial coherence of the received signal. Recent experiments to study the basic physics of low-frequency, long-range acoustic propagation in deep water and the effects of environmental variability on signal stability and coherence have been constrained by the lack of vertical line array (VLA) receivers capable of spanning the full water column in deep water. Such arrays are required to enable the separation of acoustic modes using spatial filtering and to fully characterize the acoustic time fronts formed in deep water propagation.

The earliest low-frequency, long-range acoustic propagation experiments, starting with the discovery of the deep sound channel in 1944, used wideband explosive sources. These experiments formed the basis for understanding propagation through a deterministic ocean and have shed some light on the statistics of its variability. But it is the development over the last two decades of low-frequency, wideband acoustic sources driven by controlled waveforms and large vertical receiving arrays, including ones that can store a year or more of data, that have finally provided the means to measure the spatial and temporal statistics of the acoustic fluctuations [1]. This technology allows individual multipaths and normal modes to be resolved and long time-series to be collected. These statistics are needed to advance the understanding of the effects of ocean variability on acoustic propagation.

Fully autonomous VLA receivers originally developed in the early 1990s for the Acoustic Thermometry of Ocean Climate (ATOC) project have been the workhorses in deep-water, long-range ocean acoustic propagation experiments for over a decade [1]. These arrays, which were developed to test and improve the understanding of acoustic propagation out to ranges of 3–10 megameters, were first used in the ATOC Acoustic Engineering Test in 1994 [2]. The ATOC VLAs consisted of two 20-element, 700-m long subarrays, forming a 40-element, 1400-m long array with hydrophones spaced 35 m apart [3]. It is difficult to deploy substantially longer VLA receivers using this technology, however, because of the weight of the complex electromechanical array cables, even though full-water-column spanning VLA receivers are sorely needed to further the understanding of deep-water propagation.

A modular, distributed VLA receiver that is capable of spanning the full water column in water up to 6000 m deep has therefore been developed to allow both modal and ray-based analyses of acoustic propagation in deep water.

2. DISTRIBUTED VLA (DVLA) ARCHITECTURE

The DVLA is made up of distributed, self-recording Hydrophone Modules with timing and scheduling provided by a small number of central controllers, called D-STARs (DVLA - Simple Tomographic Acoustic Receivers). The enabling technologies for this approach are (i) the availability of flash memory modules that can store several gigabytes of data and be located in a small pressure case at each hydrophone, making it unnecessary to transfer data from the hydrophones to the central controllers for storage, and (ii) inductively coupled modems that allow low-bandwidth communication for command, control, and time synchronization between the central controllers and the Hydrophone Modules over standard oceanographic mooring wire. The DVLA is fully autonomous, recording during time periods specified *a priori*. The maximum duty cycle for a one-year deployment is approximately 8%, depending on the sample rate.

The DVLA consists of subarrays with a nominal length of 1000 m, each of which has one D-STAR controller and up to 99 Hydrophone Modules. The D-STAR is shackled in-line at the top of each subarray. Hydrophone Modules are clamped to the mooring wire at the time of deployment, making the DVLA readily configurable for different experiments. The D-STARs and Hydrophone Modules are rated for operation to a depth of 6000 m. The DVLA uses a long-baseline acoustic navigation system to measure the array position and shape as the mooring moves in response to ocean currents.

2.1. Inductive Modem

The data link connecting the Hydrophone Modules to the D-STAR controller employs commercially available inductive modem technology that uses standard 3x19 jacketed oceanographic wire rope, avoiding the need for a custom electromechanical array cable [4]. Inductively coupled modems use toroidal transformers to couple data to and from instruments clamped on the mooring cable. At each Hydrophone Module, the mooring cable passes through a ferrite toroid, forming a single-turn primary winding for data transferred from the D-STAR controller to the Hydrophone Module. The Hydrophone Module has a 20-turn secondary winding to receive the data. The toroids are split in halves, so that they can be clamped around the cable without the need to thread the mooring cable through the toroid. A seawater return is used to complete the electrical circuit. The swaged fitting on the end of the mooring cable distant from the D-STAR controller provides one seawater ground.

Although the D-STAR could also use a toroidal transformer to couple to the mooring cable, it is more convenient to use a small transformer internal to the pressure case that is connected to the end of the mooring cable through an underwater connector. In this case, the end of the mooring cable is isolated from seawater and a clevis fitting is used to provide both the mechanical termination and the seawater ground.
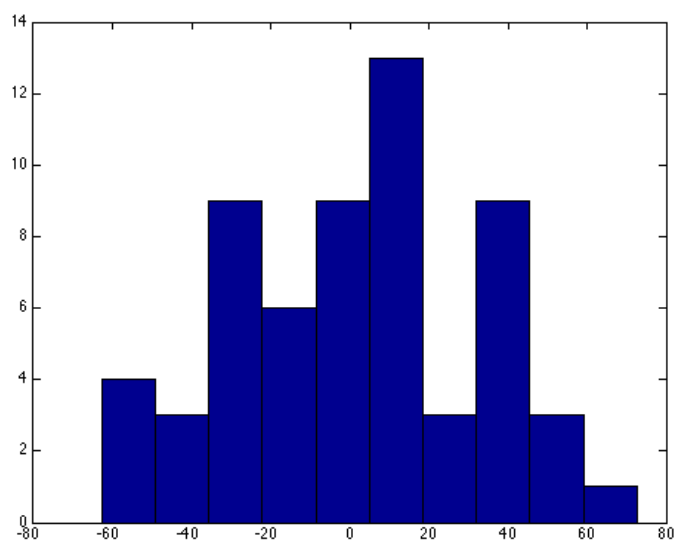

Fig. 1: Histogram of the time differences (μsec) between two Hydrophone Modules with 100-turn windings on the inductive couplers.

The DVLA uses Inductive Modem Modules (IMM) and other components supplied by Sea-Bird Electronics, Inc. [4]. Sea-Bird's inductive modems use Differential Phase Shift Key

(DPSK) modulation on a 4800-Hz carrier, providing 1200-baud, half-duplex communications. The system is not optimized for time transfer, however. Sea-Bird therefore modified the IMM firmware to provide precision time transfer using the IM Flag line. Laboratory tests indicate that the modified firmware provides time transfer with a standard deviation of 31 μsec between Hydrophone Modules (Fig. 1). The absolute time delay from the D-STAR controller to the Hydrophone Modules with a loop resistance of 100 (1000) ohms is 9.34 (9.54) ms.

2.2. D-STAR Controller

The D-STAR controller is based on the Simple Tomographic Acoustic Receiver (STAR) data acquisition system and acoustic source controller previously developed at Scripps Institution of Oceanography for ocean acoustic tomography (Fig. 2). The STAR provides a precision time base capable of keeping time autonomously with an accuracy of about 3 ms per year. A low-power (80 mW) microcomputer compensated crystal oscillator (Q-Tech MCXO QT-2002) serves as the primary system oscillator. A much higher power (10 W @ 25°C operating) rubidium oscillator (Symmetricom X72) is turned on periodically (typically once per day) to serve as a reference to measure the frequency of the QT-2002. The difference frequency is logged and used to correct the STAR clock after recovery.

Fig. 2: D-STAR controller and a Hydrophone Module being deployed during the 2009 North Pacific Acoustic Laboratory (NPAL) Philippine Sea Pilot Study/Engineering Test (PhilSea09). (Photograph by L. Green, Scripps Institution of Oceanography.)

The STAR also includes a long-baseline acoustic navigation system to measure mooring motion with an absolute precision of approximately 1 m rms, using acoustic transponders deployed on the seafloor. The D-STAR uses a single-frequency interrogate (9.0 kHz), multiple-frequency reply (11.0, 11.5, 12.0, and 12.5 kHz) system. The D-STAR controllers typically transmit interrogation signals once per hour continuously throughout the experiment and record the transponder replies using a 15-s recording window.

Finally, the STARs provide a RS-232/RS-422 serial port for an external modem. In the D-STARs, an IMM and transformer are added to the STARs, the underwater modem connector

is used for the connection to the mooring cable, and the D-STAR firmware is modified to provide control and timing signals to the Hydrophone Modules over the inductive modem communication link.

There are no electrical connections between the D-STAR controllers. Their clocks are therefore synchronized acoustically using the long-baseline interrogation signals. Each D-STAR records the interrogation signals of the other D-STARs. This is equivalent to having the D-STARs transpond off one another (although with some delay between the interrogate and reply signals) and allows the D-STAR clocks to be compared.

2.3.   Hydrophone Modules

The Hydrophone Modules are designed (i) to record low-frequency acoustic signals, sampling at 976.5625, 1953.1250, or 3906.2500 Hz, (ii) to record the high-frequency, long-baseline acoustic navigation signals, sampling at 39,062.5 Hz, and (iii) to make precision temperature measurements ($\pm$ 0.005°C). Separate channels of a quad, 24-bit, delta-sigma analog-to-digital converter (Texas Instruments ADS1274) are used for each of the three measurements. The signal conditioning and anti-aliasing filters differ from channel to channel, as appropriate. Each Hydrophone Module writes the data to a 16 GByte Secure Digital (SD) card. The SD cards are removed from the Modules following the experiment in order to download the data.

The same hydrophone (High Tech, Inc. HTI-90-U), which is rated for operation from 2 Hz to 20 kHz, is used for both the low-frequency acoustic and navigation channels. It has an integral preamplifier. Its equivalent self-noise is below Sea State 0 (Table 1). The self-noise levels of the signal conditioning circuitry and ADC in the low-frequency acoustic channel are below the equivalent self-noise of the hydrophone.

Frequency (Hz)	Equivalent Self-Noise (dB re 1 μPa / √Hz)
10	54
100	35
1000	26

Table 1: Equivalent self-noise vs. frequency for the HTI-90-U hydrophone.

High-pass filters are included in both the hydrophone preamplifier ($f_{High\text{-}pass}$ = 10 Hz) and Hydrophone Module signal conditioning circuitry ($f_{High\text{-}pass}$ = 7.7 Hz) to mitigate the effects of low-frequency mooring strum due to vortex induced vibrations (VIV).

The Hydrophone Modules make precision temperature measurements throughout the time that the DVLA is deployed, in order to provide the sound-speed profiles needed for beamforming.

The Hydrophone Modules are normally completely powered off, except for the Inductive Modem Modules, which are in a micropower state waiting for a wake-up signal from the D-STAR controller. After broadcasting a wake-up signal, the D-STAR waits for the oscillators (20-MHz Maxim DS4026 TCXO) in the Hydrophone Modules to warm up prior to setting the clocks in the Modules and sending them instructions.

Each Hydrophone Module includes a USB port for programming and testing. Each Module operates from a single 40-Amp-hour lithium battery (Electrochem, Inc. 3B6100, Size TSD).
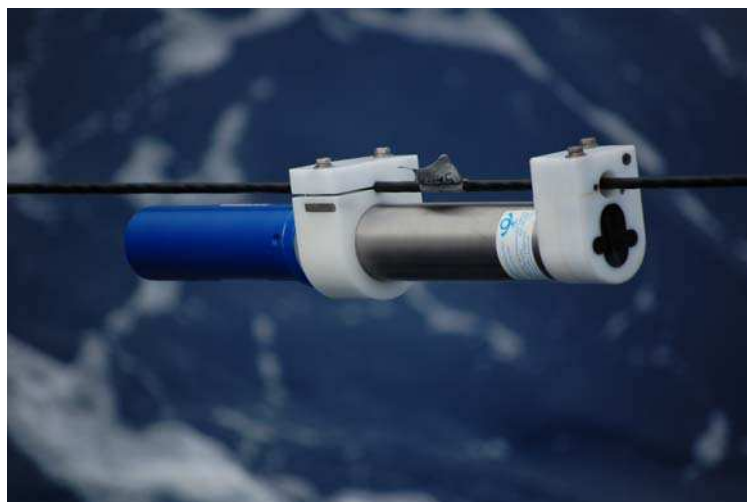
Fig. 3: Hydrophone Module being deployed during PhilSea09. (Photograph by L. Green, Scripps Institution of Oceanography.)

3. ACKNOWLEDGMENTS

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