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UNIVERSITY OF CALIFORNIA, SAN DIEGO

Depth Profiling Ambient Noise in the Deep Ocean

A dissertation submitted in partial satisfaction of the
requirements for the degree Doctor of Philosophy

in

Oceanography

by

David Readshaw Barclay

Committee in charge:

Professor Michael Buckingham, Chair
Professor Wolfgang Berger
Professor William Coles
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2011

The Dissertation of David Readshaw Barclay is approved, and it is acceptable in quality and form for publication on microfilm and electronically:

Chair

University of California, San Diego

2011

DEDICATION

Dedicated to Larry Barclay

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Chapter II, in full, is a reprint of the material as it appears in Marine Technology Society Journal, 2009. Barclay D. R., Simonet, F., and Buckingham, M. J., Marine Technology Society, 2009. I was the primary researcher and author of this manuscript, and Dr. Michael Buckingham directed and supervised the research along with Fernando Simonet.

Chapter III, in full, is a reprint of a manuscript submitted for publication in the Journal of the Acoustical Society of America. Barclay, D.R., Buckingham, M.J., Journal of the Acoustical Society of America, 2011. I was the primary researcher and author of this manuscript, and Dr. Michael Buckingham directed and supervised the research.

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PUBLICATIONS

Barclay, D.R., Buckingham, M.J., **(2011)**, “The depth-dependence of the power spectral density and the vertical directionality of rain noise in the Philippine Sea,” J. Acoust. Soc. Am., Submitted

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Barclay, D.R., Buckingham, M.J., **(2009)**, “On the shapes of natural sand grains,” J. Geophys. Res., **114**, B02209

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ABSTRACT OF THE DISSERTATION

Depth Profiling Ambient Noise in the Deep Ocean

by

David Readshaw Barclay

Doctor of Philosophy in Oceanography

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Professor Michael Buckingham, Chair

Deep Sound is an un-tethered, free-falling acoustic platform designed to profile the ambient noise field in the ocean from the surface to a pre-programmed depth, at which point a ballast weight is dropped and the instrument returns to the surface under its own buoyancy. Three iterations of the instrument, Mk I, II and III, have been designed, built and tested, the first two rated to descend to 9 km and the third to a full ocean depth of 11 km. During a deployment of the instrument, vertically and horizontally spaced hydrophones continuously record the ambient noise pressure time series over a large bandwidth (5 Hz – 40 kHz), returning the power spectral density, vertical and horizontal coherence as a function of depth. Deep Sound Mk I and Mk II have been deployed down to 9 km depth in the Mariana Trench and Mk I has descended three times to 5 km, 5.5 km and 6 km in the Philippine Sea. The data reported here

examines the depth-dependence of the power spectrum, vertical coherence and directionality of rain and wind noise in the Philippine Sea. Acoustic estimates of rainfall rates and wind speeds are made from the surface to 5.5 km and 6 km respectively and compared to surface meteorological measurements. The depth-dependence of the accuracy of these estimates is relatively small and found to improve with depth. A coherence fitting procedure is employed to return ambient noise directionality and provide information on the spatial variability of an overhead rainstorm. With moderate 7-10 m/s winds, downward propagating noise from directly overhead dominates the noise field directionality from the surface to 6 km. Using the wind generated surface noise and the depth dependence of the spectral slope over the band 1 – 10 kHz, the frequency dependence of the absorption due to sea water is estimated and used to infer a mean water column value of pH.

I. Introduction

Deep ocean trenches are perhaps the least explored and least understood regions of the world's oceans, due to the technical difficulty of deploying cabled instruments such great distances and designing instruments to withstand the massive pressures at such great depths. The deepest known spot in the ocean, the Challenger Deep in the Mariana Trench, is 10.9 km deep and only a handful of scientific instruments have made measurements at the bottom (Mantyla and Reid, 1978; Kyo *et al.*, 1995; Bowen *et al.*, 2009; Murashima *et al.*, 2009) while only a single manned vehicle dive has been made to full ocean depth (Walsh, 2009).

Similarly, acoustic measurements of ambient noise and the depth dependence of ambient noise in the deep ocean are few, and have been made on sparse arrays with bandwidths limited to the low frequency regime of 1 – 500 Hz (Morris, 1978; Weston, 1980; Marshall, 2005; Gaul *et al.*, 2007). In certain cases, the depth dependence of deep ocean noise levels has been inferred from sensors displaced 30 nautical miles from each other (Perrone, 1970). As a result, the understanding of noise levels, the depth dependence of power spectral density, vertical and horizontal coherence and vertical and horizontal directionality of ambient noise in the deep ocean is limited.

The recent development of glass spheres rated to descend to 9 km depth (Pausch *et al.*, 2009) and now to full ocean depth (12 km) has enabled the development of deep ocean probes, such as Deep Ocean Vehicle (DOV) Patty, a water sampler rated to full ocean depth built by Kevin Hardy for the lab of Dr. Douglas Bartlett at Scripps Institution of Oceanography, DOV Michelle, a still camera system capable of taking flash photographs at a depth of 9 km, also built by Mr. Hardy (Hardy *et al.*, 2002) and

the full ocean depth video camera systems designed by National Geographic Society engineer Eric Berkenpas. Data has yet to be published from these instruments.

Chapter II of this dissertation describes an un-tethered free-falling acoustic recorder designed to profile the ambient noise field in the ocean down to depths of 9 km. This system, called “Deep Sound”, has two vertically spaced hydrophones, which continuously record the ambient noise pressure time series over the 5 Hz – 40 kHz band as it descends to a pre-programmed depth, drops a ballast weight and returns to the surface where it is located with the aid of an on-board strobe light, radio beacon and global positioning system beacon. An external temperature and pressure sensor estimate the platform’s depth and speed in real time, and can be used to estimate the local sound speed. The instrument housing is made of two glass hemispheres containing the data acquisition, data storage, system control and power management electronics as well as a rechargeable lithium-ion battery pack. The on-board data acquisition system is centered on a 4 channel simultaneous sampled analog-to-digital converter running at 204.8 kS/s with a 24 bit dynamic range, controlled by a central processing unit (CPU), which runs a full operating system. Although this hardware and software set up is optimized for profiling the water column’s acoustics over a broadband, Deep Sound is essentially a deep-sea data-bus, that is configurable for other analog oceanographic sensors and other modes of deployment with no physical modifications. A universal serial bus (USB) connection is accessible from outside the sphere through a bulkhead connector through which control software can be uploaded and data can be downloaded. Deep Sound’s foot print and weight are small enough such that it can be easily deployed and recovered

off of a small boat. This platform opens the ocean's deep trenches to scientific study without the need for winches, wires or large oceanographic research vessels.

Two subsequent versions, the Mk II and Mk III of Deep Sound have been built. Along with general hardware speed, memory and energy efficiency improvements, both systems were upgraded to record ambient noise on four hydrophones, three vertically spaced with a fourth spaced in the horizontal, providing measurements of vertical and horizontal coherence. Deep Sound Mk II has an added conductivity sensor while Mk III has a full conductivity, temperature and pressures sensor suite as well as a in-situ sound velocity meter. Mk II has pitch, roll and yaw sensors for removing instrument motion from estimates of noise directionality. Mk III has angular and linear accelerometers coupled with 3 axis magnetometers, which enable inertial navigation calculation to be made, allowing the instrument itself to serve as a current profiler. Additionally, Mk III is housed inside a full ocean depth (12 km) rated glass sphere.

These three instrument platforms have been designed and built in the laboratory and tested in the waters surrounding the Scripps pier in La Jolla, CA. The Mk I and Mk II have been successfully deployed in the field during two experiments. In May, 2009, Deep Sound Mk I was deployed to depths of 5000 m, 5500 m and 6000 m in the Philippine Sea during the North Pacific Acoustic Laboratory's PhilSea09 experiment. In November of the same year, the Mk I and Mk II were deployed in the Mariana Trench, both to 9000 m. Deep Sound Mk II and Mk III's first attempt at reaching the full depth of the Mariana Trench was postponed due to Typhoon Muifa, in July 2011.

The remainder of the dissertation discusses the data collected during the three deployments in the Philippine Sea, one of which studied the depth dependence of rain

noise (Chapter III) and the other two which studied the depth dependence of surface generated wind noise (Chapter IV).

Using Cox's (Cox, 1973) relationship between coherence and directionality for plane wave noise fields in the ocean, the noise directional density function is computed as a function of depth. In general, single parameter models of noise coherence have been used to model vertical directionality in the ocean (Cron and Sherman, 1962; Linnette and Thompson, 1964; W. S. Liggett and Jacobson, 1966) and in some cases these models have been based on physical parameters (Talham, 1964). The model of noise directionality used here is a sum of spatially (angularly) discrete step functions where the amplitude of each step function is the intensity of noise arriving at the sensors at each discrete angular wedge. These amplitudes are free parameters, found by fitting the measured coherence to the model by a least-squares constrained minimization routine, and are able to represent an angularly discretized version of any arbitrary noise directionality.

In Chapter III, rainfall rates are estimated from spectral noise levels using established algorithms (Bom, 1969; Nystuen *et al.*, 1993; Ma and Nystuen, 2005; Anagnostou *et al.*, 2008) and compared with rainfall rates measured on the surface. The estimates were found to be accurate down to depths of 5.5 km, the maximum depth reached by Deep Sound. The vertical directionality shows the spatial variability of the noise produced by the rainfall on the ocean's surface and the distance from the receiver to the storm can be estimated by the angle of arrival of the noise.

The depth dependence of the noise directionality during moderate winds is discussed in Chapter IV. Downward propagating noise dominates the directionality over

the entire water column, in agreement with previous studies (Fox, 1964; Axelrod *et al.*, 1965; Kennedy and Goodnow, 1990). This noise is used to estimate wind speeds using established algorithms (Vagle *et al.*, 1990) and the estimate is found to improve as depth increases.

Using the surface generated winds as a constant source of ambient noise, a relationship between depth, spectral slope over the wind noise band and the frequency variation of the sound absorption is developed. Sound absorption between 1 – 10 kHz is driven by viscous and chemical relaxation (Francois and Garrison, 1982a; b) and is a strong function of pH (Mellen *et al.*, 1983; Duda, 2009). A simple best-fit inversion of the measured frequency variation of sound absorption over the wind driven noise band was used to estimate the mean water column pH at 7.9, in reasonable agreement with in-situ measurements in the Philippine Sea (Chen and Huang, 1996)

II. Deep Sound: a free-falling sensor platform for depth-profiling ambient noise in the deep ocean

II.1 Abstract

Ambient noise in the deep ocean is traditionally monitored using bottom-mounted or surface suspended hydrophone arrays. An alternative approach has recently been developed in which an autonomous, untethered instrument platform free-falls under gravity from the surface to a pre-assigned depth, where a drop-weight is released, allowing the system to return to the surface under buoyancy. Referred to as Deep Sound, the instrument records acoustic, environmental and system data continuously during the descent and ascent. The central component of Deep Sound is a Vitrovex glass sphere, formed of two hemispheres, which houses data acquisition and storage electronics, along with a microprocessor for system control. A suite of sensors on Deep Sound continuously monitor the ambient noise, temperature, salinity, pressure and system orientation throughout the round trip from the surface to the bottom. In particular, several hydrophones return ambient noise time series, each with a bandwidth of 30 kHz, from which the noise spectral level, along with the vertical and horizontal coherence, are computed as functions of depth. After system recovery, the raw data are downloaded and the internal lithium ion batteries are re-charged via throughputs in the sphere, which eliminates the need to separate the hemispheres between deployments. In May 2009, Deep Sound descended to a depth of 6 km in the Philippine Sea and successfully returned to the surface, bringing with it a unique data set on the broadband ambient

noise within and below the deep sound channel. The next deep deployment is planned for November 2009, when Deep Sound will descend almost 11 km, to the bottom of the Challenger Deep at the southern end of the Mariana Trench. If successful, it will return with continuous acoustic and environmental recordings taken from the sea surface to the bottom of the deepest ocean on Earth.

II.2 Introduction

Deep Sound, shown in Fig. II.1, is an autonomous, untethered, free-falling instrument platform designed to descend under gravity from the sea surface to a depth of 9 km. After releasing an expendable, cast-iron drop weight, it then returns to the surface under buoyancy. The descent and ascent rates are similar at about 0.6 m/s. A Vitrovex glass sphere, with external and internal diameters, respectively, of 43.2 cm and 39.6 cm, and 3.6 cm thick, houses data acquisition, data storage and power management electronics, along with lithium ion batteries.

Outside the sphere, hydrophones mounted in vertical and horizontal alignments detect the ambient noise field continuously throughout the descent and ascent. Additional sensors are mounted on Deep Sound for continuous monitoring of temperature, depth, salinity (hence sound speed), as well as the pitch, roll and yaw of the platform itself. All the data recorded by the system during the deployment are downloaded after recovery of the system via a USB data link passing through the Vitrovex sphere. Another throughput allows the batteries to be re-charged without their removal from the sphere.

Figure II.1: Deep Sound Mk. I, photographed during a tethered engineering test in 100 m water off the coast of La Jolla, southern California.

A high-density polyethylene (HDPE) casing not only protects the sphere but also provides a mounting structure for the hydrophones, along with the environmental and system sensors. To aid deployment and recovery of Deep Sound, a titanium bail is attached to the HDPE casing; and a high-intensity strobe light, a radio beacon and an Argos GPS antenna all help to locate the system when it returns to the surface.

During deployment, acoustic data, environmental data and system data, such as internal temperature, remaining battery life and system orientation, are centrally processed on an embedded microprocessor, which lies at the heart of the instrument's electronics. This processor also triggers the burn wire switch, based on incoming depth data. In the event that the burn wire is not triggered at the pre-set depth, a number of fail-safe mechanisms are built into the system to ensure that the drop weight is indeed released.

Two versions of Deep Sound, designated Mk. I and Mk. II, have been built and successfully tested in the field. The Mk. II has several improved features over the Mk. I, including four hydrophones instead of two, and a silent solid state memory rather than the original, mechanically noisy hard disk. To date, the deepest descent has been achieved with the Mk. I version, which reached a maximum depth of 6 km in the Philippine Sea in May 2009 and returned to the surface after a six-hour round trip.

II.3 The Deep Sound Channel and Ambient Noise

Deep Sound was developed in order to profile the ambient noise in the ocean from the surface to the greatest depth, which is approximately 11 km in the Challenger Deep at the southern end of the Mariana Trench. Much of the noise in the ocean is generated by acoustic sources near the sea surface, including surface ships and bubbles created by breaking waves (Wenz, 1962). A sound ray from a surface source penetrates down into the ocean, following a path which is curved due to refraction arising from the depth-varying sound speed.

Figure II.2: Sketch of a deep-ocean sound speed profile showing the sound channel axis, two conjugate depths and the critical depth.

In deep water, the primary factors affecting the speed of sound are temperature and pressure. A schematic of a deep-water sound speed profile is shown in Fig. II.2. With increasing depth, the temperature decreases giving rise to a corresponding decrease in the speed of sound. Eventually, however, the effect of pressure becomes dominant, causing the sound speed to increase with further increases in depth. The net effect is a sound speed profile which exhibits a pronounced minimum, as illustrated in Fig. II.2. In temperate waters, the sound speed minimum occurs at depths of approximately 1000 m and 700 m, respectively, in the Atlantic and Pacific Oceans.

The sound speed profile acts like a lens, causing sound rays to bend towards regions of lower sound speed. As a result, a deep-water sound speed profile forms a waveguide, known as the deep sound channel, trapping rays around the minimum, or channel axis. It is possible to propagate sound through the deep sound channel over thousands of kilometers (Ewing and Worzel, 1948; Munk *et al.*, 1995), since the attenuation is minimal in the absence of acoustic interactions with the sea surface and sea bed.

Points with the same sound speed on either side of the channel axis are referred to as conjugate depths, and the surface conjugate depth is known as the critical depth (Fig. II.2). According to Weston (Weston, 1980), at upper and lower conjugate depths, the ambient noise fields have similar properties; and below the critical depth, the noise from surface sources is thought to decay to a negligible level. In equatorial and temperate waters, the critical depth is in the region of 5 km. At such great depth, it is difficult to confirm Weston's predictions, due to the difficulty of deploying conventional cabled and moored arrays in such a hostile environment. Consequently, the available data on the depth dependence of deep water ambient noise are sparse (Morris, 1978; Gaul *et al.*, 2007).

Deep Sound has the capability of descending well below the critical depth, recording the ambient noise field continuously as it progresses. The raw acoustic data collected by the system may be processed to yield the ambient noise spectrum level as a continuous function of depth over a frequency band from 3 Hz to 30 kHz. A depth profile of the vertical coherence of the ambient noise over a similar bandwidth may also be obtained, thus providing a measure of the vertical directionality of the noise as a

function of depth and frequency. Such information is needed in order to test the validity of the various deep-water ambient noise models that now exist, including Weston's.

II.4 Design Criteria for Deep Sound

In order to operate at the greatest depths for periods of several hours, Deep Sound had to meet a number of demanding design criteria. First and foremost, it had to be capable of withstanding enormous pressures, up to the equivalent of 1,100 atmospheres, encountered at the bottom of the Challenger Deep. In both the Mk. I and Mk. II versions of Deep Sound, a Vitrovex glass sphere was selected as the pressure casing. The sphere also provides the main source of buoyancy. For ease of deployment and recovery, the system had to be small and light enough for two people to man-handle over the side of a boat using a small davit (Fig. II.1). Since the two versions of Deep Sound that have been built are similar to one another, the Mk. I will be described first, followed by a brief account of the modifications that were introduced into the Mk. II.

A. Deep Sound Mk. I

The Vitrovex glass sphere, with a maximum depth rating of 9 km, is actually comprised of two hemispheres with flat, polished surfaces of contact. No O-rings are necessary to seal the join, which is kept watertight by hydrostatic pressure. The hemispheres are kept in register with Henkel adhesive and a single wrap of 3M Scotchrap 50, with a vacuum pulled on the sphere through one of its ports. Besides the vacuum port, the sphere has seven ports for electrical bulkhead connectors and a further feedthrough for the internally housed pressure sensor. The bulkheads connect the

external sensors to the internal data acquisition hardware, as well as providing interfacing for data downloading and battery recharging.

For protection and handling, the sphere is encased in a high-density polyethylene (HDPE) hard hat, to which is bolted a titanium bail and an HDPE frame. Two HDPE arms extend away from the frame (Fig. II.1) and hold the two hydrophones out of the wake of the main body of the instrument. The hydrophones are vertically aligned with a separation of 0.5 m. The overall footprint of the instrument is 0.6 m x 0.6 m, with a height of 1 m, and a total mass in air of 68 kg. The buoyancy is 215 Newtons, which provides a steady ascent rate of 0.6 m/s; and a 21 kg cast-iron drop weight provides a matching descent rate of 0.6 m/s. At this speed, the round trip from the surface to a depth of 9 km takes 8 hours and 20 minutes.

Data acquisition, data storage, power management and burn-wire control are coordinated by an Arcom Apollo EBX motherboard with a low-powered, fanless Intel Pentium M CPU. The two simultaneously sampled channels of acoustic data are acquired through a National Instruments PCI-4462 analogue-to-digital converter with 100 kHz acoustic bandwidth and 24 bit dynamic range. The pressure and temperature data are recorded, respectively, via serial and USB ports. The Windows XP Embedded operating system and software run from a 2 GByte compact flash card, while data storage is provided by a USB-connected 150 GByte hard disk.

An OceanServer Technology BA95HC power management unit comprised of four lithium ion batteries powers the motherboard and the individual components of Deep Sound. The appropriate voltages for each component are provided by ATX DC/DC and Vicor Power DC/DC converters, while battery condition is monitored by the

main system via a serial port controller. The battery pack is rated at 95 Watt-hours, which allows Deep Sound to operate continuously for 9.5 hours. Power is isolated by another DC/DC converter and channeled by the parallel port to the burn wire. A separate circuit with an independent timer, a 9V battery and an isolated DC/DC converter provides back-up power to the burn wire in the event that the main system software or hardware fail. The expendable burn wire is fabricated from SevenStrand Sevalon 250WN nylon coated, stainless steel fishing line.

After the glass sphere has been assembled, an external magnetic switch is used to boot the system. Once running, an external computer can network with Deep Sound through an Ethernet bulkhead connector or by using a wireless ad-hoc connection. Data may be downloaded by networking a hard disk to the system through a USB bulkhead connector. The system may be shut down from a remotely networked computer or the power can be cut with the magnetic switch.

The two acoustic sensors used in Deep Sound Mk. I are Hi-Tech HTI 94 SSQ hydrophones mounted on the HDPE casing with 0.5 m vertical separation. Each of the phones, independently calibrated over a frequency band from 2 Hz to 30 kHz, shows a flat frequency response of approximately -165 dB referenced to 1 micropascal. The phones are also calibrated over pressures up to 600 bar, corresponding to a maximum ocean depth of 6000 m. Hi-Tech Inc. specifies the maximum operating depth of their HTI 94 SSQ phone as 6096 m, but our own independent tests, using the pressure chamber at Deep Sea Power and Light, show that the HTI 94 SSQ functions satisfactorily under much greater pressure, equivalent to a depth of 12 km. Little change in the calibration occurs with increasing pressure.

The operating depth of Deep Sound is determined using a Paroscientific Pressure Sensor 9000-20K, which is mounted inside the glass sphere and measures hydrostatic pressure through a titanium bulkhead. Sea water temperature is measured with a Seabird SBE 38 Digital Oceanographic Thermometer, which is mounted external to the sphere and is rated to a maximum depth of 10.5 km. Every half second, temperature and depth are recorded and, from both measurements, sound speed is estimated.

An Ocean Server compass interfaced to the motherboard via a USB connection is used to measure the pitch, roll and yaw of the platform. These data are useful in the diagnosis and correction of undesirable system motions during the descent and ascent.

To aid in locating and recovering the instrument after it returns to the surface, three Novatech systems are mounted on the HDPE casing above the glass sphere: an ST-400AR Xenon Flasher, an RF-700AR Radio Beacon and an AS-900A Argos Beacon. The xenon flasher is a high-intensity strobe light that has proved to be invaluable for visual sighting during a night-time recovery. The radio beacon broadcasts an intermittent tone, allowing a shipboard radio detection finder to determine the bearing to the instrument. The Argos beacon uses GPS satellite navigation to determine the instrument's position coordinates (latitude and longitude), which are then transmitted to an online server. Each of these systems has a pressure switch to ensure operation only when Deep Sound has returned to the surface. The Novatech systems all have the same type of pressure housing, which is rated to a maximum depth of 7.5 km by the manufacturer. However, in our own independent pressure tests at Deep Sea Power and Light, the RF-700AR Radio Beacon and antenna module were subjected to pressures as high as 1,100 bar (equivalent to a depth of 11 km) without failure.

B. Deep Sound Mk. II

The design of the Mk. II version of Deep Sound is similar to that of the Mk. I but with the following improvements.

A Kontron 986LCD-M/mITX motherboard with a low-power, fanless Intel Celeron CPU is used, because it has half the power consumption of the original Arcom unit. For data storage, a silent 128 GByte solid-state memory chip replaces the mechanically noisy hard disk. In place of individual temperature and pressure sensors, Deep Sound Mk. II has a Falmouth Scientific Standard 2 Micro conductivity, temperature and depth (CTD) sensor, with a depth rating to 9 km, which returns salinity in addition to temperature and depth measurements.

Deep Sound Mk. II has four acoustic channels, with the HTI 94 SSQ hydrophones arranged in an 'L' shape. Three of the phones are aligned in the vertical and two in the horizontal, with one phone common to both configurations. The spacings between the phones are adjustable, ranging from 0.3 m to 1 m. The horizontally aligned phones yield the horizontal coherence of the ambient noise, which is related to the horizontal directionality, while the additional phone in the vertical provides enhanced angular resolution as well as returning information on the spatial homogeneity of the noise.

II.5 The Deployment Phase

Deep Sound Mk. I and Mk. II both run National Instruments LabView software to co-ordinate operations during deployment. After the instrument is powered up using the magnetic switch, a remotely networked computer sets various deployment

parameters. Prior to use, the LabView program is assigned depths at which to start and stop recording, and a depth at which to drop the ballast weight. Sample rates, dynamic range and data acquisition parameters are adjustable through this program. Visual displays of the real time output of the hydrophones, along with battery life and system temperature, show the operator that the various components of the instrument are functioning correctly.

Two count-down timers are activated on start-up: one, with a length that is adjustable in the LabView program, and the other, on an independent circuit, with a length that can only be changed by separating the glass spheres and adjusting a variable resistor. Both timers are fail-safe devices. If either timer reaches zero, the burn wire will be activated and the ballast weight dropped, allowing the system to return to the surface under buoyancy.

Once deployed in the water, the data acquisition system remains idle until reaching the start depth, as determined by the pressure sensor. At this point, continuous data recording during free-fall begins. When the instrument reaches the pre-assigned drop depth, a voltage is activated on the burn wire, which oxidizes to the point of mechanical failure in less than one minute. The weight then falls away and the instrument begins to ascend, while continuing to acquire acoustic, environmental and system data. Near the surface, when the third pre-assigned depth is reached, the data acquisition software shuts down and the system returns to idle. Upon arrival at the surface, independent pressure switches activate the xenon strobe, the radio beacon and the Argos beacon.

The Deep Sound LabView program incorporates the incoming data into real-time decision making, above and beyond the routine deployment procedures. The main purpose of the decision-making function is to avoid the loss of Deep Sound due to errors that may occur in individual system components. Battery life and system temperature (inside the glass sphere) are monitored and if a low-battery threshold is crossed, or the system begins to overheat, data acquisition is terminated and the remaining power applied to the burn wire. In the event of a software or hardware error, such as a data buffer overflow, full data storage, or a non-responding peripheral, operations cease and the burn wire is activated. Descent and ascent rates are continuously monitored and if significant changes are detected, or if the instrument hits the sea bed before reaching the pre-programmed ballast-weight drop depth, the burn wire is activated.

The Lab View program is easily altered, allowing Deep Sound to be deployed in a variety of modes without opening the glass sphere or modifying the control hardware. For example, with the descent-speed monitoring disabled, Deep Sound could sit on the sea bed for a specified time before starting its return to the surface; or, to conserve power and extend the deployment time, Deep Sound could be programmed to record data on a duty cycle. Outside the sphere, the acoustic channels are modular, capable of supporting any type of sensor with a bandwidth up to 100 kHz in place of the hydrophones. Indeed, the design philosophy underlying Deep Sound has been the development of a deep-diving platform with software and hardware architectures that provide flexibility in terms of data acquisition, mode of deployment, and sensor payload.

II.6 Deep Sound Mk. I in the Philippine Basin

The first deep deployments of Deep Sound were made in May 2009 during the North Pacific Acoustic Laboratory (NPAL) experiment in the Philippine Basin. Operating from the R/V Kilo Moana, three descents were made to depths of 5,100, 5,500 and 6,000 m. On each occasion, the system descended to maximum depth, released the

Figure II.3: a) The depth versus time profile of Deep Sound Mk. I for its deepest deployment in the Philippine Sea experiment. b) The measured sound speed profiles from the descent and ascent.

ballast weight and successfully returned to the surface. Acoustic and environmental data were recorded continuously during each of the round trips. Fig. II.3 shows the depth versus time trajectory of the system and the measured sound speed profiles for the third and deepest drop.

During the descent and ascent, Deep Sound measured the ambient noise field on the two vertically separated hydrophones over a frequency band extending to 30 kHz. Although both the sensors were placed outside the wake produced by the main instrument housing, one of the phones was always in the wake of the other, with the result that excess flow noise appeared on the trailing hydrophone. By comparing the spectra from the two acoustic channels, the effect of the flow on the output of the trailing phone becomes apparent, as illustrated in Fig. II.4. At frequencies below 1 kHz, the trailing phone shows a spectral level some 10 dB above that of the leading phone,

Figure II.4: Ambient noise spectra from the Philippine Basin deployment, taken while Deep Sound Mk. I descended from a depth of 5667 m to 5679 m. The higher level of the spectrum from the trailing hydrophone is due to flow noise from turbulence generated by the leading phone.

although above 10 kHz the excess decreases to about 5 dB. In this particular case, the system was descending and the top phone exhibited the excess noise. A similar excess-noise phenomenon occurs in the ascent but with the lower phone returning the higher spectral level.

Since returning from the Philippine Sea, the Mk. I and Mk. II systems have been modified by fitting open-pore foam flow shields around the hydrophones. These tailor-made flow shields are highly effective at reducing the turbulence-induced noise to negligible levels across the whole frequency band shown in Fig. II.4. In effect, the flow shields trap still water around the phones, keeping the turbulent flow at a distance from the active faces of the sensors.

II.7 Future Deployment and Development of Deep Sound

Since the successful deployment of Deep Sound Mk. I to a depth of 6 km in the Philippine Sea, the Mk. II version, with four acoustic channels, has been tested in the shallow ocean off the coast of La Jolla, southern California. Both systems are now ready for the next deep deployment, which is scheduled for November 2009 in the Challenger Deep at the southern end of the Mariana Trench. The ocean at this location is the deepest in the world at just under 11 km. The Vitrovex glass spheres in both systems are rated by the manufacturers to 9 km! Following a cautionary plan, the Mk. I. and Mk. II systems will first be deployed within specifications, to a maximum depth of 9 km. Assuming a successful return to the surface, the batteries of Mk. I will be re-charged, taking a little less than 3 hours, and the system sent down again, but this time to within 100 m of the bottom. Thus, the maximum deployment depth in this deepest of deep descents will be

around 10,800 m, corresponding to a round trip travel time of 10 hours. One or more hydrophones near the surface will listen for the sound of an implosion, which, if it were to happen, would be useful for failure diagnosis.

A third version of Deep Sound, the Mk. III, is currently in the planning stage. This new instrument will use a Vitrovex glass sphere of diameter 0.43 m, with a depth rating of 11 km, significantly greater than that of its predecessors. This improved depth capability, along with our independent pressure tests of the HTI 94 SSQ hydrophones and the Novatech instrument housings to an equivalent depth of 12 km, will give Deep Sound Mk. III a full ocean depth capability. Other modifications will include the addition of high-precision, very-low drift tri-axial accelerometers, which will be used for inertial navigation of the system. The intention is to provide a current-profiling capability by monitoring the motion of the platform due to advection by local currents during its descent and ascent through the water column.

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III. The depth-dependence of the power spectral density and the vertical directionality of rain noise in the Philippine Sea

III.1 Abstract

Deep Sound is a free-falling instrument platform designed to record the ambient acoustic noise field from the ocean surface to a depth of 9 km. It was first deployed in May 2009 during the Philippine Sea Experiment and made three round trips to depths of 5,100, 5,500 and 6,000 m. During the first of these deployments, a rainstorm passed over the experiment site and the high bandwidth (5 Hz – 40 kHz) power spectrum and vertical coherence of the rain-generated noise were profiled on the ascent from 5,100 m, 1,150 m below the critical depth, to 700 m, 100 m above the sound channel axis. The relationships between the power spectral density, depth and rainfall rate are presented. A coherence fitting procedure was used to retrieve the vertical directionality of the noise as a function of depth and rainfall rate. For frequencies below 100 Hz, the ambient noise field was not significantly influenced by the rain noise and the depth dependence of the noise level decreases with depth. Above 1 kHz, the vertical directionality of the noise is sharply peaked, providing an evolving estimate of the horizontal distance between the rainstorm and Deep Sound as the storm passed overhead.

III.2 Introduction

Relatively little is known about the ambient acoustic noise field in the deep ocean. Measurements are scarce due to the challenge of deploying conventional cabled acoustic arrays to great depths. From the few such arrays that have been deployed, the reported data have been focused on low-frequency acoustics, generally below 500 Hz, and on a limited number of sensors placed around the channel axis or the critical depth (Morris, 1978; Marshall, 2005; Gaul *et al.*, 2007). The goal of these measurements has been to understand how locally generated surface noise and distant shipping noise mix as a function of depth. To the authors' knowledge, no measurements of ambient noise in the deep ocean trenches have been reported and only a handful of vehicles and instrumentation have been built to withstand the great pressures encountered in these regions (Kyo *et al.*, 1995; Bowen *et al.*, 2009; Murashima *et al.*, 2009; Walsh, 2009).

The acoustic recording platform Deep Sound is a free-vehicle (no tether) designed to profile the ambient noise field from the ocean surface to a depth of 9 km. It descends under gravity and, at a pre-assigned depth, releases a drop weight, which allows it to return to the surface under buoyancy. Two vertically aligned hydrophones return wide bandwidth (5 Hz – 40 kHz) time series, from which the power spectra, cross-spectral density and vertical coherence of the ambient noise, which may include components due to shipping, wind and rain (Barclay, 2009), may be computed. A complete description of Deep Sound's design and functionality is presented in the first section of this paper.

The data presented here are taken from Deep Sound's maiden deep-sea trials, which took place as part of the Philippine Sea Experiment in May 2009. A rainstorm

happened to pass over the experiment site during the first of three deployments, allowing continuous recordings of undersea rain noise to be made from a depth of few hundred meters down to 5 km. From the noise time series acquired by the pair of vertically separated hydrophones, the vertical coherence of the noise was computed over the entire bandwidth, from which the vertical directionality of the noise field was estimated using the well-established integral relationship that exists between spatial coherence and directionality (Cox, 1973).

Several models have previously been used to predict the functional form of a smoothly varying vertical noise directional density function to within a single parameter (Cron and Sherman, 1962; Linnette and Thompson, 1964; W. S. Liggett and Jacobson, 1966) or multiple physical parameters (Talham, 1964). However, with a spatially variable rainstorm overhead, an irregular and quite peaky form of the noise directional density function might be expected. In order to accommodate this behavior, a generalized multi-parameter form of the noise directionality, which allows the coherence from any discretely sampled angular function to be calculated, is used in a data-fitting procedure.

Due to its vertical motion through the water column, Deep Sound samples the ambient noise sequentially with depth. This makes it difficult to separate intrinsic depth variations in the noise levels and the directionality from effects due to the temporal and spatial variability of rainfall. However, direct measurements of rainfall rates were made on board the ship that deployed Deep Sound, which helped in distinguishing rain noise effects in the acoustic data. As a check on the Deep Sound data, the measured rainfall rates were used as an input to an empirical model (Ma and Nystuen, 2005) for the

intensity of rain noise just beneath the surface (< 100 m) of a deep ocean. For frequencies above 100 Hz, the sound levels predicted by the model were found to be comparable with the deep measurements returned by Deep Sound. At lower frequencies, the ambient noise was free of surface generated rain noise, showing spectral levels that decreased with increasing depth.

Noise due to splash and bubble formation by small raindrops at 15-25 kHz, and medium raindrops at 1.5 – 10 kHz (Medwin *et al.*, 1992), was observed over the entire water column. The vertical coherence of the rain noise is used to estimate a directional

Figure III.1: Deep Sound prior to attaching the drop-weight (black vertical cylinder at left), in preparation for deployment in the Philippine Sea. The two hydrophones, aligned vertically, are mounted on arms attached to the foreground corner of the instrument. The glass sphere containing the electronics is within the orange HDPE “hard hat”, on top of which are mounted the three recovery antennas.

density function, which shows a maximum at an elevation angle related to the rainstorm's horizontal distance from the instrument. The evolution of the relative position of the storm can be inferred as the vertical noise directionality changes.

III.3 Deep Sound

Deep Sound, shown in Fig. III.1, is an autonomous, un-tethered, free-falling instrument platform, designed to descend from the sea surface to a pre-programmed depth, which may be as great as 9 km, at which point a disposable iron weight is dropped, using a burn-wire release, and the platform returns to the surface under its own buoyancy. Two hydrophones, mounted with vertical spacing of 0.5 m, measure the ambient noise fluctuations during the descent and ascent, from which the vertical noise coherence and directionality are computed. Additional sensors measure sound speed, depth, and the platform's pitch, roll and yaw.

The central component of Deep Sound is a pressure chamber comprised of a Vitrovex glass sphere, actually two hemispheres in contact at the equator and kept in place by a weak vacuum, which is rated to withstand the hydrostatic pressure at 9 km. The sphere, with an outer diameter of 43 cm and thickness of 1.8 cm, houses four lithium ion batteries and a data acquisition system, along with data storage and power management electronics. The external sensors and the burn-wire are connected to the interior by four electrical bulkheads penetrating the sphere. Three additional bulkheads are used to download data to an external computer via an Ethernet link, to configure the instrument's data acquisition software, and to recharge the batteries. Data acquired

during a deployment may also be downloaded via a wireless connection. A magnetic reed switch is used to boot and power down the system.

High-density polyethylene (HDPE) is used to protect the sphere and provide the mounting structure for the hydrophones, the environmental sensors and recovery beacons, while a titanium bale facilitates deployment and recovery. Overall, the instrument stands one meter tall with a depth and width of 0.65 meters. The platform weighs 68 kg in air and, with the assistance of a davit, is readily deployable from a small boat. With the addition of the iron drop weight, the platform descends to depth at a steady rate of 0.6 m/s; and once the weight is released, buoyancy returns the system to the surface at a steady ascent rate of 0.6 m/s.

Data acquisition and storage, instrument configuration, power management and drop weight activation are all controlled by software running on a low-powered, fanless CPU mounted on a small form-factor motherboard. Two channels of acoustic data are simultaneously sampled, each at a frequency of 204 kHz, with a dynamic range of 24 bits. The operating system and software run from a 2 GB compact flash drive, while incoming data are stored on a 150 GB hard disk. The data are downloaded onto a laptop computer once the system has returned to the surface and is back on board ship.

The four lithium ion batteries power the data acquisition electronics with a lifetime of 95 Watt-hours, which provides 9.5 hours of continuous data acquisition. The battery pack is managed by a controller, through which the CPU monitors the charge state, allowing the pack to be safely recharged from an external DC power supply. The burn wire is manufactured from plastic coated steel fishing wire and, primarily, is powered through the motherboard's parallel port. For redundancy, a 9V battery on an

independent timer and separate circuitry provides back up power to the burn wire, in the event of a main system software or hardware failure. It is, of course, essential for the burn wire to release the drop weight, since the system must return to the surface if the data stored on the hard disk are to be recovered.

Deep Sound has two Hi-Tech Inc. (HTI) 94 SSQ hydrophones external to the sphere, with a vertical spacing of 0.5 m. The phones are each mounted on a horizontal arm that places it away from the turbulent flow of the body of the platform. The nominal sensitivity of the phones is -165 dB referenced to $1 \text{ V}/\mu\text{Pa}$ over the range 2 Hz to 40 kHz. Each phone is calibrated independently over frequency and over pressures from 0 - 600 bar (0 – 6,000 m of ocean depth). Although the manufacture reports the depth rating of the 94 SSQ as 6,096 meters, sensitivity tests using a high-pressure chamber showed that the phone could function at depths of 12 km with less than a 3 dB change in response.

Several environmental sensors are mounted on Deep Sound. The temperature of the seawater surrounding the system as it moves through the water column is monitored by an externally mounted thermistor, which, along with measurement electronics, is connected to the data acquisition system via a serial port. The glass sphere is fitted with a small titanium pressure port, allowing the external hydrostatic pressure to be measured by an internally mounted instrument. Both pressure and temperature are recorded at a rate of 1 Hz, thereby sampling the water column every 0.6 m. During deployment, the incoming environmental data are used to estimate depth and ascent or descent rate in real-time.

A system sensor, in the form of a solid-state, flux-gate compass, is also on board, providing the pitch, roll and yaw of the instrument platform as it descends and ascends through the water column. Three recovery beacons, a xenon flash strobe, a radio frequency (RF) beacon and a Global Positioning System (GPS) beacon, help in locating the system when it returns to the surface. The RF beacon can be detected provided the instrument is within the line of sight of a ship-mounted detector, which corresponds to a distance of 11 km; the GPS beacon uses overhead satellites to calculate its own coordinates, which it then relays to an online server; whilst the strobe excels when it comes to night-time recovery.

Deep Sound is configured and operated with software written using National Instrument's LabView program. Once the system is powered up, the software can be launched and configured via a wirelessly networked external computer. Operating parameters such as sampling rates, the depth to begin recording acoustic data, the depth at which to drop the ballast weight, and the depth to stop recording data are set via this wireless link. Before deployment, real time visualizations of incoming acoustic data, environmental data, CPU temperature, and remaining battery life are shown on the external computer screen, allowing the user to confirm the operation of each element of the system.

Once the system is configured and the checks are complete, Deep Sound is deployed in the ocean, entering a free fall and recording data until the pre-assigned depth is reached, at which point the ballast weight is dropped and the system begins its return to the surface. The iron ballast weight is suspended by the plastic-coated, steel fishing wire with a small segment of the sleeve removed, exposing the steel core to

seawater. To initiate the drop, a voltage is applied across the wire and a grounding pin, also exposed to seawater, which causes rapid oxidization of the wire and mechanical failure in less than a minute. After dropping the weight, as the instrument ascends to the surface under buoyancy, data continue to be recorded. Once the platform arrives at the sea surface, the data acquisition is terminated and the strobe, RF beacon, and GPS recovery systems are activated.

Although reaching the pre-programmed depth will activate the burn wire, this condition may not be achieved if, for example, the ocean were shallower than expected. To ensure that it returns to the surface, several levels of redundancy are built into the Deep Sound: the descent speed is monitored and if the system slows or stops by encountering the bottom before reaching the pre-assigned depth, the weight will be dropped; low-battery and high-system-temperature thresholds are set and, if crossed, the system will cease recording data and use its remaining power to activate the burn wire; external hardware and the controlling software are monitored for errors and, in the event of a data-buffer overflow, or full data storage, or unresponsive peripheral devices, the burn wire will be activated. In addition to these measures, a software timer with an adjustable length begins counting down as soon as the data acquisition software is launched. A second hardware timer, set to 12 hours by a variable resistor, begins when the instrument is powered up, and uses a separate 9 V battery to activate the burn wire. If either of these timers expires, the ballast weight is dropped.

III.4 The Philippine Sea Experiment

Deep Sound's first sea trials in the deep ocean were conducted during the North Pacific Acoustic Laboratory (NPAL) Philippine Sea Experiment (PhilSea09) in May 2009. The experiment site was the northern Philippine Basin, located south-east of Taiwan, as shown in Fig. III.2. This basin has a relatively flat topography with an average depth of 5,500 m.

During PhilSea09, several acoustic instruments were deployed for studying propagation and scattering in this energetic deep-water environment (Worcester *et al.*, 2010). PhilSea09 was a short-term, pilot study and an engineering test for a large-scale, year-long experiment planned for the same region to investigate the effects of fronts, eddies, internal tides and small-scale oceanographic variability on acoustic propagation, as well as to characterize the ambient noise field. The main purpose of the pilot study was to study temporal variability in long-duration acoustic transmissions between a 225-325 Teledyne Webb Research Corporation swept-frequency source and two receiving arrays, the Deep Vertical Line Array and the towed Four Octave Research Array. Deep Sound was included in the experiment to provide “snapshots” of the broadband ambient noise profile over the full ocean depth.

Figure III.2 The Philippine Sea, with the Deep Sound rainfall experiment site depicted by the black circle at $21^{\circ} 13.05' \text{ N}$, $125^{\circ} 57.32' \text{ W}$. The other two deployment locations of Deep Sound during the PhilSea09 are identified by the black squares.

Deep Sound operations were conducted from the R/V Kilo Moana. The ship's catamaran configuration proved to be ideal for the recovery of Deep Sound from the stern of the vessel. After positioning the ship such that the instrument was directly between the two pontoons, a tag and hoist line were attached to the titanium bail and the system was lifted onto the deck with little risk of damaging the fragile hydrophones against the hull.

Over the course of four weeks at sea, three Deep Sound deployments were made to depths of 5,100 m, 5,500 m and 6,000 m, at the locations shown in Fig. III.2. Each deployment lasted approximately five hours and returned complete acoustic profiles from the surface to the programmed depths. Two recoveries were made at night, where the strobe proved to be invaluable in locating the instrument, while the third was made during daylight using the RF Beacon to provide the ship's first point of contact. In each deployment, the recovery site was less than 3 km from the deployment location.

The first deployment was on Julian Day 106, on which occasion the instrument descended to 5,100 m and returned to the surface over the course of 260 minutes (4h 20 m). The deployment and recovery positions were $21^{\circ} 13.055' \text{ N}$, $125^{\circ} 57.325' \text{ E}$ and $21^{\circ} 13.536' \text{ N}$, $125^{\circ} 57.684' \text{ E}$, respectively, corresponding to a lateral drift during the descent and ascent of approximately 1 km. During the deployment a rainstorm passed over the area. The rainfall rate was measured on board the ship, drifting approximately 8 km away from the instrument's drop site. The method of measurement was crude, involving a bucket with a known cross-sectional area, a graduated cylinder and a stopwatch. The accumulated volume of water in the bucket was measured every 15 minutes over the course of the deployment. Qualitative observations of raindrop size and rain type (drizzle, light and heavy rain) were made in a notebook and photographs were taken of the sea state. The wind speed was continuously monitored and recorded by a ship-mounted anemometer.

The rainstorm overlapped with Deep Sound's deployment for 2 hours and 45 minutes, beginning 20 minutes into the instrument's descent. Drizzle fell for an hour at a rate of 0.2 mm/hr, and 90 minutes into the deployment a heavier fall rate was measured

at 2 mm/hr, climbing to 12 mm/hr over the following 60 minutes. This was followed by a 15-minute pause, then by light rain with occasional squalls. Rainfall rates varied between 0.8 – 3.2 mm/hr for the remainder of the deployment. Fig. III.3 shows the measured rainfall rate superimposed on the instrument's depth versus time profile.

During the entire deployment, winds were measured at 9-11 knots with the occasional squall of 12-15 knots. Some white cap coverage was observed, corresponding to a Beaufort wind force scale 4 sea state. Local shipping activity was actively monitored from the bridge of the R/V Kilo Moana by radar and radio contact, but no vessels were detected during the deployment.

Figure III.3: The depth of Deep Sound versus time (left axis, solid line) and the observed rainfall rate at the surface (right axis, dashed line) during the deployment.

On board Deep Sound, the local external temperature and pressure were measured, from which the depth and sound speed were estimated using the Fofonoff and Millard algorithms (Fofonoff *et al.*, 1983), assuming a constant value of salinity of 34.64 taken from the World Ocean Atlas (Antonov, 2010). The estimated sound speed profiles on descent and ascent are shown overlaid in Fig. III.4. The sound speed minimum (sound channel axis) was at 856 m during Deep Sound's descent and 805 m on ascent, although in both cases the minimum is fairly broad, making precise identification difficult. The surface conjugate depth, where the sound speed at depth is equal to that at the surface, was at 3,950 m. The two profiles were measured over the course of the

entire deployment of 4 hours 20 minutes and their relative agreement is indicative of the stability of the deep ocean environment on this time scale.

Figure III.4: The sound speed profiles measured by Deep Sound during the descent and ascent, with the sound channel axis (800 m) and critical depth (3,950 m) depicted by the dashed lines.

III.5 Rain Noise – Power Spectra

During the deployment of Deep Sound, the pressure time series from the two vertically separated, calibrated, broadband (5 Hz – 40 kHz) hydrophones were recorded using a sampling rate of 204.8 kHz. To produce a spectrogram, these time series were split into contiguous segments approximately 20 s long, each of which was further divided into 40 sub-segments of 0.64 s duration, with no overlap. A 2^{17} point FFT was

applied to each sub-segment, from which a power spectrum was formed with a frequency cell width of 1.56 Hz, and these power spectra were ensemble-averaged to obtain the spectrum of the original 20 s segment of the time series. Spectrograms were then constructed, as illustrated in Fig. III.5 for the lower hydrophone, in which the spatial (depth) resolution is the descent (or ascent) rate of Deep Sound times the total FFT time, which is approximately equal to $0.6 \times 20 = 12$ m. Since each vertical slice in the spectrogram represents the ensemble-averaged spectrum, as measured at a particular time and depth, the figure shows the ambient noise field as it evolves in both time and depth during the descent and ascent.

The onset of the rainstorm can be seen in the spectrogram around 20 minutes after deployment, when the instrument was at a depth of 800 meters. The level of high frequency noise between 3 – 12 kHz rises abruptly, indicating the addition of rain noise to the ambient noise field. This initial rain noise level, corresponding to the observed rainfall rate of 0.2 mm/hr, persists until 70 minutes into the deployment, at which point the first of three periods of increased rainfall appears in the spectrogram, marked as Event 1 (E1) in Fig. III.5. This event lasted approximately 10 minutes. The second and

Figure III.5: Spectrogram showing the evolution of the noise field versus time (bottom axis) and depth (top axis). Labels E1 - E5 depict elevated background noise due to increased rainfall rates.

third periods of increased rainfall (E2 and E3) are both 15 minutes in duration and centered, respectively, at the 100 minute and 125 minute marks of the spectrogram. Elevated noise levels in the 5 – 20 kHz band occur during these periods in the spectrogram. Event 3, the third and loudest of these intense rainfall periods, corresponds with the 12 mm/hr rainfall rate measurement made on board the ship, and coincides with Deep Sound's arrival at 5,000 m, where the drop weight was released and the ascent began.

The ascent phase of the deployment begins at the 130-minute mark in the spectrogram. There is an increase in noise levels across all frequencies, but particularly below 1 kHz. This additional noise is due to turbulent flow across the hydrophone. The two hydrophones are mounted with vertical spacing on horizontal arms that hold them away from the main instrument housing of Deep Sound (Fig. III.1). Although these arms remove the phones from any turbulent vortices that may be shed by the bulk of the instrument, the trailing phone, being in the wake of the leading phone, returns increased noise levels. On the descent, the top mounted phone is influenced by the turbulent flow created by the bottom phone and vice versa on the ascent. As the spectrogram in Fig. III.5 was calculated using data collected from the bottom-mounted hydrophone, an increase in the low-frequency noise, associated with turbulent flow, appears as the instrument ascends to the surface.

However, the higher frequency rain noise remains unmasked by this locally generated flow noise and can be readily distinguished during the remainder of the deployment. By the 150-minute mark, the heavy rainfall had diminished, as evident in the spectral levels as well as in the measured rainfall rate. For the remainder of the

deployment, the rainfall rate was between 0.8 – 3.2 mm/hr and the acoustic levels show similar consistency, with the exception of 5-minute squalls appearing as vertical stripes in the spectrogram (E4, E5).

A single spectrum, shown in Fig. III.6, reveals further evidence that the enhanced ambient noise levels are due to noise caused by rain falling on the surface of the ocean. This spectrum was computed from the pressure time-series recorded on the top-mounted hydrophone as the instrument ascended from 5,134 m to 5,122 m. The spectrum has broad peaks over the 1.5 – 10 kHz and 15 – 25 kHz bands, consistent with previous observations of rain noise (Nystuen, 2005). These peaks show a distinct departure from the expected wind driven ambient noise spectral shape of $f^{-5/3}$ (Wenz, 1962).

Rain noise on the ocean surface is comprised of two parts: the impact noise of the drop on the surface and the formation and ringing of bubbles entrained by the drop (Franz, 1959; Medwin *et al.*, 1992; Nystuen and Medwin, 1995). In general, the sound of bubble formation dominates the underwater noise created by rainfall on the ocean and the spectral properties of this noise component depend on the bubble size and the drop size. The enhanced spectral energy over the broad frequency band from 1.5 – 10 kHz is associated with the impact splash of medium (1.2 – 2.0 mm) or large (2.0 – 3.5 mm) raindrops, as well as the resulting turbulent entrainment of bubbles of irregular size. The spectral peak between 15 – 25 kHz corresponds to predictable uniform bubble entrainment by small (0.8 – 1.2 mm) drops (Pumphrey *et al.*, 1989). As these bubbles are all roughly the same size, the associated spectral peak is narrower in frequency than that from the irregularly sized bubbles entrained by medium and large drops.

Figure III.6: Ambient noise spectrum, recorded at 5 km depth during an 11 mm/hr rainfall. The uniform slope of the Knudsen spectrum is shown for comparison.

The two peaks in the spectrum shown in Fig. III.6 offer acoustic evidence for the presence of medium or large raindrops as well as small raindrops. This conclusion is corroborated by the measured rainfall rate of 12 mm/hr, as well as visual observations of drop size from the deck of the ship. The observed spectral level from 5,130 m depth of 68 dB re $1\mu\text{Pa}^2/\text{Hz}$ at 5 kHz for the rainfall rate of 12 mm/hr is comparable with previous measurements from sensors placed at shallow depths in lakes (66 dB re $1\mu\text{Pa}^2/\text{Hz}$) (Bom, 1969) and shallow water (63 dB re $1\mu\text{Pa}^2/\text{Hz}$) (Nystuen *et al.*, 1993); but it is somewhat higher than the empirical prediction for a shallow sensor in deep

water (59 dB re $1\mu\text{Pa}^2/\text{Hz}$), obtained from the equation (Ma and Nystuen, 2005; Anagnostou *et al.*, 2008)

$$I_{5\text{kHz}} = aR^b \quad , \quad (\text{III.1})$$

where R is the rainfall rate in mm/hr, $10\log_{10}(I_{5\text{kHz}})$ is the sound pressure level in dB re $1\mu\text{Pa}^2/\text{Hz}$ at 5 kHz, $a = 10^{4.25} = 1.78 \times 10^4$, and $b = 1.54$.

The evolution of the passing rainstorm can be observed by plotting the spectral levels that were recorded as Deep Sound ascended from depth to the surface, as shown in Fig. 7. Octave band averaging shows the relative contribution of the rain sound to the noise field for different frequency ranges. The instrument's ascent from 5,000 m to 4,000 m occurs during a weakening of the storm from a 12 mm/hr to a 0.6 mm/hr rainfall rate. This corresponds to a significant reduction in spectral levels in the bands spanning 2 – 32 kHz, while the bands below 1 kHz decrease only very slightly. The bands below 100 Hz remain unchanged by the variable rainfall rate, indicating that the spectral levels at these frequencies are independent of the rain noise. For frequencies greater than 1 kHz, the vertical structure in Fig. III.7 is due to changing source levels associated with the varying rainfall conditions.

Figure III.7: Octave-band-averaged ambient noise spectral levels during Deep Sound's ascent.

From the depth of 3,000 m upwards, the rainfall rate was observed on the surface to remain relatively constant, despite passing squalls. The depth average between 1,000 – 3,000 m of a band 100 Hz wide and centered at 5 kHz yields an estimated noise spectral level of approximately 61 dB re $1\mu\text{Pa}^2/\text{Hz}$, while the rainfall rate varied between 0.8 – 3.2 mm/hr. This spectral level is approximately 20 dB higher than predicted for this range of rainfall rates by the empirical relationship in Eq. (III.1), although it falls

within the limits of variability of previously reported measurements (Ma and Nystuen, 2005).

This difference between the empirical relationship and the measured spectral level at 5 kHz could be due to the large depth at which the acoustic measurements were taken when compared to the depths for which Eq. (III.1) was established. In the case of Ma and Nystuen (Ma and Nystuen, 2005), the acoustic recorders were placed no more than 98 m below the surface, while the levels reported here were obtained by averaging over the depths of 1,000 – 3,000 m. At greater depths, acoustic sources covering a larger area of the ocean's surface are sampled. Due to the spatial variability of the rainfall, the acoustic sampling is averaging over several squalls or patches of heavy rain that may not have been measured by the rain gauge, which, of course, samples at only a single point on the surface.

III.6 Vertical Coherence and Directionality

The coherence function relating two noise time series, $x_1(t)$ and $x_2(t)$, is defined as

$$\Gamma(\omega) = \frac{\overline{X_1(\omega)X_2^*(\omega)}}{\sqrt{\overline{|X_1(\omega)|^2}\overline{|X_2(\omega)|^2}}}, \quad (\text{III.2})$$

where ω is angular frequency, $X_k(\omega)$ is the Fourier transform of $x_k(t)$, $k = 1$ or 2 , the over bar denotes an ensemble average, and the asterisk is for complex conjugation. In effect, the coherence function is the cross-spectral density of the two time series normalized to the geometric mean of their power spectra. In the case of vertically

separated hydrophones, as in Deep Sound, the coherence function is related to the vertical directionality of the noise, as discussed a little later.

By using an ensemble averaging procedure similar to that described above in connection with the power spectra, the coherence function was computed from the noise time series observed at the two vertically aligned hydrophones on Deep Sound as it descended and ascended through the water column. For the coherence computations, however, the FFT length was half that used for the power spectra: at 2^{16} it corresponds to a frequency cell width of 3.125 Hz. The depth resolution remains the same as with the power spectra at 12 m. In effect, the reduced FFT length doubles the number of terms in each ensemble average, which leads to smoother coherence curves.

As shown in Fig. III.8, the real and imaginary parts of the coherence function are dominated by rain noise in the 1 – 10 kHz band. Above 10 kHz the curves have an oscillatory structure but the coherence is weak. The spike in the coherence at 93.3 Hz is an artifact due to the acoustic noise created by the system's hard disk, which spins at a known rate of 5,600 rpm while acquiring data.

A. Plane-wave noise

The oscillatory structure of the coherence curves in Fig. III.8 can be used to infer the vertical directionality of the noise field. Noise in the deep ocean can be modeled as a superposition of uncorrelated plane waves propagating randomly in all directions (Cox, 1973). Such a plane-wave noise field is spatially

Figure III.8: a) The real and b) the imaginary parts of the vertical coherence of ambient noise at 5 km depth during an 11 mm/hr rainfall.

homogeneous, that is, its second-order statistical measures, including the power-spectral density, the cross-spectral density and the normalized cross-spectral density (the coherence function), are independent of the absolute position at which they are measured. Of course, the coherence, although independent of position in the field, does depend on the orientation of the two sensors as well as their separation, d .

For the case of vertically aligned sensors, Cox(Cox, 1973) has derived the following expression for the coherence function:

$$\Gamma(\bar{\omega}) = \frac{1}{2} \int_0^\pi F(\omega, \theta) e^{-i\bar{\omega} \cos \theta} \sin \theta d\theta, \quad (\text{III.3})$$

where $i = \sqrt{-1}$, and $F(\theta)$ is the directional density function, a dimensionless measure of the noise power per unit angle incident on the receivers from elevation angle θ , as measured from the zenith. The normalized angular frequency, $\bar{\omega}$, is defined as

$$\bar{\omega} = \frac{\omega d}{c}, \quad (\text{III.4})$$

where c is the speed of sound in the medium and d is the separation of the sensors. In general, the coherence function in Eq. (III.3) is complex but for the special case in which the directional density function is symmetrical (even) about the horizontal, the imaginary part of $\Gamma(\omega)$ is easily shown to be zero and the coherence function is real. If the directional density function is independent of ω , then the coherence function depends only on $\bar{\omega}$ rather than ω and d individually, in which case plots of $\Gamma(\omega)$ versus $\bar{\omega}$ will all collapse onto the same curve, regardless of the separation of the sensors.

When the two sensors are coincident, the noise between them is fully coherent, a condition which is characterized by a coherence function of unity. It follows from Eq. (III.3), with $d = 0$, that

$$\frac{1}{2} \int_0^\pi F(\omega, \theta) \sin \theta d\theta = 1 \quad , \quad (\text{III.5})$$

which is a normalization condition on the directional density function, $F(\omega, \theta)$.

B. Curve-fitting for the directional density function

To recover the vertical directionality of the rain noise from the Deep Sound data, the directional density function is assigned a functional form involving certain unknown parameters, the coherence function is then computed from Eq. (III.3) and the result compared with the experimentally determined coherence function. The parameters in the directional density function are then adjusted, and the iteration continues until a best fit to the data is obtained.

Since the rain noise is broadband, it is reasonable to assume that the directional density function is independent of frequency. It is represented as a piecewise continuous function, constructed as a linear combination of boxcar functions, each spanning a discrete angular segment within the polar-angle range $0 \leq \theta \leq \pi$.

Consider the n^{th} noise segment with intensity A_n lying between the polar angles $\alpha_n - \delta$ and $\alpha_n + \delta$, then the directional density function due to this solitary contribution is

$$F(\alpha_n) = \left. \begin{array}{ll} A_n & , \quad \alpha_n - \delta < \theta < \alpha_n + \delta \\ 0 & , \quad \text{elsewhere} \end{array} \right\} \quad (\text{III.6})$$

and, from Eq. (III.3), the coherence associated with this noise component is

$$\Gamma_n(\bar{\omega}) = \frac{A_n}{\bar{\omega}} \exp[-i\bar{\omega} \cos \alpha_n \cos \delta] \sin[\bar{\omega} \sin \alpha_n \sin \delta] \quad (\text{III.7})$$

Apart from $\bar{\omega}$, this expression depends only on the elevation angle α_n (the angular direction from which the noise is arriving), the angular width of the segment, 2δ , and the intensity of the incoming noise, A_n .

Now a linear combination of noise segments is constructed, spanning the entire polar-angle interval $0 \leq \theta \leq \pi$:

$$F(\theta) = \sum_n A_n [u(\alpha_n - \delta) - u(\alpha_n + \delta)] , \quad (\text{III.8})$$

where $u(\dots)$ is the Heaviside unit step function. The representation in Eq. (III.8) could be thought of as a discrete version of the actual directional density function, as sampled at each α_n with an angular sampling interval of 2δ . Since the angular interval $[0, \pi]$ is fully occupied by the segments, it is apparent that α_n scales with δ according to the relation $\alpha_n = (2n - 1)\delta$. Obviously, δ governs the angular resolution of the model, while the intensities A_n are to be determined from the fitting procedure. The total coherence arising from the summation in Eq. (III.8) is

$$\Gamma(\bar{\omega}) = \sum_{n=1}^N A_n f(\alpha_n), \quad (\text{III.9})$$

where $N = \pi / (2\delta)$ and

$$f(\alpha_n) = \frac{1}{\bar{\omega}} \exp[i\bar{\omega} \cos \alpha_n \cos \delta] \sin[\bar{\omega} \sin \alpha_n \sin \delta], \quad (\text{III.10})$$

The directional density function in Eq. (III.8) must satisfy the normalization condition in Eq. (III.5), which leads to the following constraint on the intensities:

$$\sum_{n=1}^N A_n \sin \alpha_n = \frac{1}{\sin \delta} \quad (\text{III.11})$$

Eq. (III.9) provides the basis for deriving the unknown intensities, A_n , that characterize the directional density function. In essence, Eq. (III.9) is evaluated for a given set of A_n and compared with the coherence data. The values of the A_n are then adjusted to minimize the difference between the modeled and measured coherence, either by brute force or using a constrained minimization algorithm.

C. Turbulence fluctuations

It is implicit in Eq. (III.3) that the noise field is spatially homogeneous, consisting entirely of independent, acoustic plane waves. The noise fields observed with Deep Sound, however, do not wholly satisfy this condition because the trailing hydrophone lies in the wake of the leading phone and is therefore subject to turbulent-flow pressure fluctuations in addition to the plane-wave acoustic noise from the rainstorm. The effect of the wake turbulence on the lower hydrophone can be seen in Fig. III.5: the spectral levels on the descent are low compared with those on the ascent, which are enhanced by the turbulent flow.

To establish the effect of turbulence on the cross-spectral density and the coherence function, let the total noise recorded at each hydrophone be written as the sum of an acoustic component, $x(t)$, and a turbulent fluctuation, $n(t)$, as follows,

$$s_k(t) = x_k(t) + n_k(t) \quad , \quad (\text{III.12})$$

where the subscript $k = 1$ or 2 identifies the hydrophone in question. From the definition in Eq. (III.2), the coherence between the two signals is

$$\Gamma_{12}^{(s)}(\omega) = \frac{\overline{[(X_1(\omega) + N_1(\omega))][X_2^*(\omega) + N_2^*(\omega)]}}{\sqrt{[(X_1(\omega) + N_1(\omega))^2][(X_2(\omega) + N_2(\omega))^2]}}, \quad (\text{III.13})$$

where the upper case letters are the Fourier transforms, with respect to time, of their lower case counterparts. The superscript (s) in Eq. (III.13) identifies the coherence as being that due to the combined effect of the acoustic and turbulence fluctuations.

Assuming that the turbulence fluctuations at the two hydrophones are uncorrelated with each other and with the acoustic noise, the coherence function in Eq. (III.13) reduces to

$$\Gamma_{12}^{(s)}(\omega) = \frac{\overline{X_1(\omega)X_2^*(\omega)}}{\sqrt{[X_1(\omega)]^2[X_1(\omega)]^2 + [X_1(\omega)]^2[N_1(\omega)]^2 + [X_2(\omega)]^2[N_2(\omega)]^2 + [N_1(\omega)]^2[N_2(\omega)]^2}}, \quad (\text{III.14})$$

Since Deep Sound descends and ascends at a steady speed, it is reasonable to assume that the level of turbulent flow noise at each of the hydrophones remains constant over time. Moreover, the acoustic noise is taken to be statistically stationary over the averaging time used to compute the coherence. Under these conditions, the turbulence spectrum may be expressed as a fixed fraction of the acoustic noise spectrum,

$$[N_k(\omega)]^2 = \varepsilon_k(\omega)[X_k(\omega)]^2, \quad (\text{III.15})$$

in which case it follows that the coherence in Eq. (III.14) reduces to the form

$$\Gamma_{12}^{(s)}(\omega) = \frac{1}{\sqrt{[1 + \varepsilon_1(\omega)][1 + \varepsilon_2(\omega)]}} \frac{\overline{X_1(\omega)X_2^*(\omega)}}{\sqrt{[X_1(\omega)]^2[X_2(\omega)]^2}}. \quad (\text{III.16})$$

The last term in this expression is just the coherence of the acoustic noise, $\Gamma_{12}(\omega)$, and therefore the coherence of the acoustic plus turbulence fluctuations in Eq. (III.16) may be written as

$$\Gamma_{12}^{(s)} = G_{12}(\omega)\Gamma_{12}(\omega) \quad , \quad (\text{III.17})$$

where

$$G_{12}(\omega) = \frac{1}{\sqrt{[1 + \varepsilon_1(\omega)][1 + \varepsilon_2(\omega)]}} \quad (\text{III.18})$$

is a frequency-dependent scaling factor. If either of the $\varepsilon(\omega)$ is much greater than unity, implying that turbulence noise is dominant at one or both hydrophones, the function $G_{12}(\omega)$ approaches zero and the observed coherence, $\Gamma_{12}^{(s)}(\omega)$, is negligibly small. For lesser values of the $\varepsilon(\omega)$, representing reduced levels of turbulence noise, the observed coherence will be a scaled version of the coherence due to the acoustic noise alone, in which case the important properties of $\Gamma_{12}(\omega)$, such as zero crossings, should be recoverable.

III.7 Rain Noise – Vertical Coherence and Directionality

A. Coherence

With the aid of the curve-fitting model described above, the intensity of the incoming noise at each elevation angle was determined by comparing the measured with the modeled coherence. The angular resolution of the discrete directional density function used in the model was 18° ($\delta = 9^\circ$). Fig. III.9 shows the best-fit coherence curves from the model superimposed on the real and the imaginary parts of the vertical

coherence, as computed from the pressure time series recorded by Deep Sound at a depth of 4,900 m. It can be seen that the model matches the coherence data reasonably well over most of the frequency band up to 20 kHz. At higher frequencies, the model predicts a weak coherent structure but this is not apparent in the data, even after extensive ensemble averaging.

Several effects of turbulent flow over the hydrophones are evident in Fig. III.9. Below 30 Hz, the measured coherence goes to zero whilst the real part of the modeled coherence approaches unity. This disparity is due to the masking of the rain noise field by two flow-noise components: the first arises from the motion of Deep Sound through the water column, which creates a turbulent flow around each of the hydrophones; and, as already discussed, the second is associated with the turbulent wake of the leading hydrophone, which engulfs the trailing hydrophone. At frequencies below 30 Hz, the net effect of these two turbulent flow mechanisms is to raise the incoherent noise parameters $\varepsilon_1(\omega)$ and $\varepsilon_2(\omega)$ to levels such that the observed coherence [see Eq. (III.17)] is essentially zero.

Figure III.9: a) The real and b) the imaginary parts of the measured (black curve) and best-fit (red line) vertical coherence at 5 km depth.

At higher frequencies, in the band 30 – 500 Hz, the rain noise is more intense but similar turbulence processes are present, although they become less pronounced with increasing frequency (McGrath *et al.*, 1977; Finger *et al.*, 1979). At the lower end of the band, the incoherent noise parameters $\varepsilon_1(\omega)$ and $\varepsilon_2(\omega)$ overpower the rain noise, becoming less significant at intermediate frequencies, and having a negligible effect above 500 Hz. Between 500 Hz and 10 kHz, where there is a well-defined oscillatory structure in the coherence data, the modeled and measured coherence in Fig. III.9 show satisfactory agreement.

B Directionality

The direction of arrival of the noise created by the rainstorm is available from the same fitting procedure that yielded the coherence curve in Fig. III.9. Again, an angular resolution of 18° ($\delta = 9^\circ$) was used to obtain the directional density function, shown in Fig. III.10, of the received noise at a depth of 5,000 m, approximately 1,000 m below the critical depth. Most of the noise is downward travelling and concentrated in a lobe about 20° wide, centered at 55° above the horizontal.

Fig. III.11 shows the directional density function of the noise versus depth, computed for the 120-minute ascent from 5,100 m to 800 m, close to the sound channel axis. In computing this figure, the same FFT lengths were used as for the power spectra; and, as previously, the depth resolution in the figure is 12 m, corresponding to a time resolution of approximately 20 s.

Figure III.10: Vertical directional density function derived from the best-fit to the noise coherence data recorded at 5 km depth during an 11 mm/hr rainfall.

At all depths, the arrival angles of the noise, as measured from the vertical, lie within a 70° cone, with essentially no noise arriving from below the horizontal ($\theta = 90^\circ$). The pre-dominantly vertical directionality of the noise field depicted in Fig. III.11 is consistent with a localized surface source in the form of a rainstorm; and it is in agreement with observations by previous authors (Fox, 1964; Axelrod *et al.*, 1965; Kennedy and Goodnow, 1990) made above and below the critical depth.

By its nature, rain noise in the ocean is highly variable in time, since both the density and distribution of the sources, which are related to the rainfall rate and storm size, respectively, are constantly changing. The resultant variability in the sound intensity is illustrated in Figs. III.5 and III.7. As Deep Sound descends or ascends at a

Figure III.11: Vertical noise directional density function as it evolves versus depth (left axis) and time (right axis) during Deep Sound's ascent.

steady rate through the water column, it is inevitable that the noise directionality observed at different depths corresponds to different observation times. However, changing rain conditions on the surface can be correlated with the rainfall observations made on board ship. Indeed, several moments of intense rainfall, as well as the relative location of the storm, can be seen in Fig. III.11.

The directionality plots in Figs. III.10 and III.11 show the peak of the noise, as measured at a depth of 5,000 m, arriving at an angle of about 50° from the vertical. This peak in the directional density function is associated with the storm event marked as E4 in Fig. III.5, for which the shipboard measurements returned a rainfall rate of 11 mm/hr. Although the storm cannot be located in azimuth, due to the axial symmetry of the

vertically aligned hydrophones, it is clear from the acoustic data that the rainfall was not directly overhead. A geometric estimate of the storm's horizontal displacement from Deep Sound is approximately 6 km.

As the instrument ascends to 4,500 m (12 minutes later), the peak at $\theta = 25^\circ$ in the directional density function in Fig. III.11 indicates that the storm has moved more directly overhead. Furthermore, the spectral intensities for high frequency bands in Fig. III.7 show a dramatic increase, which is associated with this storm. By the time Deep Sound has reached 4,200 m, the intensities in Fig. III.11 are relatively weak in all directions, corresponding to the 15-minute pause in the rainfall rate observed on the ship, and consistent with the reduced spectral levels shown in Figs. III.5 and III.7. At 3,800 m the directionality in Fig. III.11 becomes strongly orientated to directly overhead during a brief 5-minute squall, designated E5 in Fig. III.5.

The measured rainfall rates throughout the remainder of the ascent stayed below 3 mm/hr, and the directionality during this time, from 3,000 m upwards, remains remarkably constant. However, intense squalls were observed on the surface, with corresponding features appearing in the directional density function (Fig. III.11) and the octave band intensities (Fig. III.7). Other short durations of increased rainfall are also weakly visible in Fig. III.5 as narrow vertical stripes.

In the low-frequency octave bands, below 500 Hz, the spectral levels versus depth shown in Fig. III.7 do not show the same variation due to the storm as the bands at higher frequencies, whose changing spectral levels have already been attributed to the rainfall rate. In the lowest frequency band, 25 – 50 Hz, the noise level is more or less independent of depth from the sound channel axis at 800 m down to 5,100 m, well

below the critical depth. Over the same depth range, the noise level in the next frequency band, 50 – 100 Hz, decreases monotonically by about 5 dB. Similarly, the noise levels in the octave 100 – 200 Hz show no variation due to the small squalls, although the spectral level does begin to increase during the heavy storm below 4,800 m, presumably due to the relatively low-frequency impact noise created by the splashes of larger drops.

Although the coherence of the acoustic noise below 500 Hz is to some extent masked by an unknown “red” spectrum associated with turbulent-flow noise, some qualitative conclusions can be drawn concerning the directionality of the acoustic noise in this low-frequency region. It is well established (Cox, 1973) that, with vertically aligned sensors, the real and imaginary parts of the coherence function, as given by the expression in Eq. (III.3), represent, respectively, the symmetric (even) and asymmetric (odd) components of the directional density function about the horizontal. Now, in Fig. III.8, the imaginary component of the coherence is zero below 300 Hz, whilst the real part is zero below 30 Hz but non-zero at higher frequencies.

According to Eq. (III.17), the real and imaginary parts of the coherence function would be scaled by an equal, albeit unknown, factor due to turbulence. The fact that the real part of the coherence in the 30 – 300 Hz band is non-zero suggests that this unknown scaling factor is not an unduly small number. This being the case, it is reasonable to conclude that the imaginary part of the coherence in this band is zero, not because of uncorrelated turbulence fluctuations at the sensors, but because the noise field is symmetrical about the horizontal.

An obvious property of a noise field that is symmetrical about the horizontal is that it contains upward as well as downward traveling waves. This is in contrast to the higher-frequency (above 1 kHz) rain noise from the localized storm system, which is entirely downward traveling, with essentially no upward propagating components. Of course, the symmetrical noise could have been propagating horizontally, which would be consistent with measurements of the vertical directionality of low-frequency noise reported by previous authors (Fox, 1964; Cron *et al.*, 1965; Anderson, 1979; Baggeroer *et al.*, 2005).

III.8 Concluding Remarks

Deep Sound is a free-falling instrument platform capable of making broadband (5 Hz to 40 kHz) ambient noise measurements in the deep ocean down to depths as great as 9 km. On reaching a pre-assigned depth, a weight is dropped and the platform returns to the surface under buoyancy. It made its first open-ocean descents, in the Philippine Sea, in May 2009 to depths of 5.1, 5.5 and 6.0 km, and recorded the ambient noise field on two vertically aligned hydrophones throughout the water column, from the sea surface down to within 200 m of the bottom.

On one of the deployments, the noise from a local rainstorm was recorded during the descent and the ascent of Deep Sound. Rainfall rates between 0.2 and 11 mm/hr were measured on board ship, and features related to the changing storm conditions are present in the ambient noise spectra between 500 Hz and 40 kHz. At lower frequencies, the noise spectra appear to be unaffected by the rain, showing a tendency to decrease monotonically with increasing depth from the sound channel axis down to 5,000 m, over

1,000 m below the critical depth. Such behavior is consistent with previous reports of the depth dependence of low frequency ambient noise in the deep ocean.

The spatial and temporal variability of the rainfall is reflected in the ambient noise spectra returned by Deep Sound. Above 500 Hz, the spectra vary significantly with depth, showing sporadic bursts of relatively high intensity sound, which correlate with the periods of high rainfall rate measured on board ship. Even at a depth of 5 km, the effect of the heavier rain was to raise the noise spectral level by as much as 20 dB. Although little is known about rain noise at such a depth, the enhanced spectral levels returned by Deep Sound are comparable with an existing empirical power-law relationship, formulated for a shallow hydrophone in deep water, for the spectral level of rain noise as a function of the rainfall rate.

From the pressure time series recorded by the two hydrophones on Deep Sound, the vertical coherence of the rain noise was computed over the 1 – 40 kHz frequency band. A simple curve-fitting procedure returned the vertical directional density function of the noise from the coherence function. The rain noise is strongly directional, consisting of downward traveling waves propagating at angles within a cone extending to 60° from the vertical. During periods of heavy rainfall, the directional density function shows a strong lobe centered at an angle that depends on depth as well as the horizontal distance between the storm and Deep Sound. At a depth of 5 km, this rain-noise lobe is about 45° from the vertical, from which the storm is estimated to have been located at a distance of 6 km from the instrument. Fortuitously, the storm passed more or less directly over Deep Sound and, as it approached, the peak in the noise directional

density function showed a corresponding movement towards the vertical, providing a continuous measure of the lateral position of the storm in relation to Deep Sound.

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IV. The depth-dependence of wind generated ambient noise and vertical coherence and an estimate of ocean acidity from noise in the Philippine Sea

IV.1 Abstract

Deep Sound is a high-bandwidth (5 Hz – 40 kHz) acoustic profiler, designed to record ambient noise pressure time series on two vertically spaced hydrophones. The instrument descends under gravity, un-tethered, and returns to the surface under buoyancy by dropping a ballast weight once a pre-programmed depth is reached. In May 2009, Deep Sound was deployed three times in the Philippine sea to depths of 5000 m, 5500 m and 6000 m, and the power spectral density and vertical coherence were computed as a function of depth for each deployment. During the first deployment, a rainstorm passed overhead while during the other two deployments, on Julian Days 110 and 119, steady 9 m/s and 10 m/s winds blew, creating Beaufort Force 5 and Force 6 seas. During these deployments, the ambient noise levels and vertical coherence were depth independent, with only small changes in the first 1000 m from the surface. The vertical directionality of the wind generated ambient noise field was determined using a best-fit coherence model and was found to be dominated by downward propagating noise at all depths. Acoustic wind speed estimates were made from noise levels and showed improving accuracy with increasing depth. Using the wind generated surface noise, an estimate of the acoustic absorption was made over the band 1 – 10 kHz and used to determine a best-fit mean water column value of pH=7.6.

IV.2 Introduction

Few measurements of the depth dependence of ambient noise in the deep ocean environment have been made, mainly due to the difficulty and expense of deploying long, multi-channel cabled acoustic arrays to great depths. The measurements that do exist rely on a small number of independent hydrophones, at a limited number of depths, generally in the sound channel axis and near the critical depth, and have focused on frequencies below 500 Hz (Perrone, 1970; Morris, 1978; Marshall, 2005; Gaul *et al.*, 2007).

As the depth of a noise measurement increases, the area of the local surface noise, suitably modeled by an infinite sheet of homogeneously distributed sound sources, also increases. Using deep-water acoustic measurements to infer information on physical processes at the surface allows a larger spatial area to be sampled at once, which may be beneficial in narrowing estimates on temporally and spatially variable processes such as rainfall rates through splash and bubbles noise (Medwin *et al.*, 1992) and wind stress and gas exchange through breaking wave noise (Farmer and Vagle, 1988). The depth dependence of noise in the deep ocean provides insight on how locally generated surface noise mixes with distantly generated propagating noise of ships, by comparing noise levels below the critical depth, where no distantly generated propagating noise is thought to be present, with noise levels within the deep sound channel.

Recently, the development of glass spheres able to withstand the high-pressures of full ocean depth (Pausch *et al.*, 2009) have enabled the design of deep ocean vehicles

able to descend into the hadal zone (Barclay, 2009) and providing a simple and inexpensive alternative to the few past and existing remotely operated vehicles able to collect in situ data in the deep ocean trenches (Kyo *et al.*, 1995; Bowen *et al.*, 2009). Deep Sound is a free-falling, free-ascending acoustic recording platform designed to profile the ambient noise field on two vertically spaced hydrophones, with a bandwidth of 5 Hz – 40 kHz, from the surface to a depth of 9 km.

The data reported here were taken from two deployments of Deep Sound in the Philippine Sea in May 2009, where ambient noise recordings were made from the surface down to a depth of 5500 m and 6000 m respectively. During both drops, near constant wind speed conditions of 9 m/s and 10 m/s were measured on the surface, and a complete snapshot of the depth dependence of the wind generated surface noise was acquired.

The small depth variation of the power spectral density and the vertical coherence show the noise field to be dominated by the locally generated wind noise during both deployments. The vertical noise directionality is inferred using a simple coherence-fitting model (Barclay, 2011) and is found to be near constant with depth, supporting the finding that the local surface noise is the largest component of the ambient noise field at all depths.

Ambient noise measured near the surface has been the basis for reliable estimates of wind speed in numerous studies (Evans *et al.*, 1984; Lemon *et al.*, 1984; Vagle *et al.*, 1990; Vakkayil *et al.*, 1996; Zedel *et al.*, 1999). The empirical relationships linking wind speed to ambient noise include a depth dependent correction factor to account for the depth variation in ambient noise caused by refraction and attenuation of the surface

generated noise. Deep Sound's measurement of ambient noise profiles during periods of relatively stable wind speed and direction, allow the accuracy of the 'universal' WOTAN (Weather Observations Through Ambient Noise) noise-to-wind speed relationship to be evaluated as a function of depth, and determine the importance of accurately calculating the depth dependent correction factor. A reasonably good agreement is found between estimate wind speeds and measured wind speeds at all depths, with increasing accuracy on the estimate as a function of depth.

Active acoustic measurements of absorption have had a renewed interest because of the connection between the acidity of the ocean and the absorption of sound below 10 kHz (Hester *et al.*, 2008; Duda, 2009). Hydroxide OH^- and carbonate CO_3^{2-} ions are involved in pressure-sensitive reactions, which modify the phase lag between pressure and velocity in sound waves and cause the relationship between ion concentrations and energy loss (absorption). An increase in global-mean ocean acidity reflects an increased ocean uptake of atmospheric CO_2 and may disrupt the marine ecosystems (Feely *et al.*, 2004; Orr *et al.*, 2005). Long range active (Jin and Worcester, 1989) and passive (Kibblewhite *et al.*, 1976) methods for measuring absorption have focused on low frequencies over long acoustic paths. By assuming that the sea surface with a uniform wind stress acting on it serves as a constant source of ambient noise, a small depth variation in the spectral slope over the 1 – 10 kHz noise band was used to make an accurate estimate of the viscous and chemical absorption of sound in seawater and provides a new technique for estimating pH in the ocean.

IV.3 Deep Sound

Deep Sound is an un-tethered, free-falling acoustic profiler which descends to a pre-assigned depth, drops a disposable weight and returns to the surface under its own buoyancy. The ambient noise pressure time series is continuously recorded on two hydrophones with a vertical separation of 0.5 m, from which the power spectral density, the vertical noise coherence and the vertical noise directionality are computed.

The instrument consists of a single glass sphere, which houses the data acquisition electronics and provides the necessary buoyancy. The calibrated hydrophones have a nominal sensitivity -165 dB referenced to 1 V/ μ Pa and are mounted outside the sphere, along with sensors for measuring pressure and temperature, from which the instrument's depth and the local sound speed are computed. The acoustic signals from the two hydrophones are sampled at 204.8 kS/s with a dynamic range of 24 bits across 4V peak-to-peak.

Deep Sound is deployed at the surface and free-falls at a rate of 0.6 m/s until the pre-assigned depth is reached, at which point a ballast weight is dropped using a burn wire exposed to sea-water, which oxidizes rapidly when a voltage is applied between the wire and another sea-water exposed grounding pin. The instrument ascends to the surface at 0.6 m/s where it is recovered with the aid of a xenon flash strobe, a radio frequency beacon and a Global Position System beacon. Deep Sound has been described in greater detail in previous publications (Barclay, 2009; Barclay, 2011)

IV.4 The Philippine Sea Experiment

The data reported in this paper was collected during The North Pacific Acoustic Laboratory (NPAL) Philippine Sea Experiment (PhilSea09) in May 2009, which took place in the northern Philippine Sea. Located south east of Taiwan, the basin has a flat topography with an average depth of 5500 meters, as shown in Fig. IV.1.

PhilSea09 was planned as a short-term, pilot study and engineering test in preparation for a large scale, year-long experiment which occurred in 2010 in the same region and which studied the effects of fronts, eddies, internal tides and small scale oceanographic variability on acoustic propagation as well as the characteristics of the ambient noise field in this energetic deep-water environment (Worcester *et al.*, 2010). During PhilSea09, propagation experiments between a stationary source and two receiving arrays, the towed Four Octave Research Array and the moored Deep Vertical Line Array (Worcester *et al.*, 2009), were conducted over four weeks. Deep Sound was included in the experiment to provide snapshots of the ambient noise profile across the full ocean depth. Equally, this experiment served as an engineering test and as Deep Sound's first open ocean sea-trials.

Deep Sound was deployed and recovered using from the R/V Kilo Moana, a catamaran with an ideal configuration for small instrument recovery. The ship was able to reverse onto the instrument, placing it directly between its two pontoons, where a hoist line was attached with no risk of damaging the fragile hydrophones against the ship's hull.

Figure IV.1: The Philippine Sea, with the Julian Day 110 experiment site indicated by a black square at $21^{\circ} 16' 58''$ N, $126^{\circ} 21' 19''$ E and the Julian Day 119 deployment site indicated by a black triangle at $22^{\circ} 13' 34''$ N, $126^{\circ} 13' 48''$ E. The third site, indicated by the black circle, was the site of a Deep Sound rainfall experiment.

During the experiment, Deep Sound was deployed from the R/V Kilo Moana on Julian Day (JD) 106 to 5100 m, on JD 110 to 5500 m and on JD 119 to 6000 m at the locations shown in Fig. IV.1. Each deployment lasted approximately five hours and captured profiles of the noise to the assigned depths.

The deployment on JD 106 had the fortune of occurring during a rainstorm, and the depth dependence of the rain noise and its vertical directionality have been reported (Barclay, 2011). The two remaining drops, discussed in this paper, were during periods

of moderate winds with no observed precipitation. During the deployments, the R/V Kilo Moana's minimized its contribution to the ambient noise field by steaming to a distance of 7 miles and shutting down its depth sounder, sonar, propellers and engines, with the exception of a single generator. Constant watch was kept on the bridge for local shipping traffic and no nearby ships were sighted by radar or radio during either deployment.

Wind speed and direction were measured using two ship-mounted RM Young 05106 anemometers, located at a height of 20 meters above the sea surface, and mounted on the port and starboard side of a mast, directly above the ship's bridge. These measurements are corrected to reflect true wind speed and direction by subtracting the velocity of the ship from the wind velocity and are reported once a minute. As the ship was drifting during the deployment, this correction is minimal. Precipitation, air temperature and humidity were also recorded at the same location. No ship measurements of precipitation were made during the two deployments on JD 110 and JD 119 were full ocean depth profile measurements of wind generated ambient noise.

The deployment on JD 100 was at the location $21^{\circ} 16' 58''$ N, $126^{\circ} 21' 19''$ E where the depth of sea floor was 5680 m. The instrument descended to 5500 m and returned to the surface in 305 minutes (5h05mins). The mean wind speed calculated from the two anemometers is plotted along with Deep Sound's depth as a function of time in Fig. IV.2. Over the 5-hour deployment the wind speed drops from 9 m/s to 7 m/s at a constant rate.

On JD 119, Deep Sound was deployed 106 km south-southeast from the JD 110 drop location, at $22^{\circ} 13' 34''$ N, $126^{\circ} 13' 48''$ E, where the ocean depth is approximately

6200 m. The instrument descended to 6000 m and re-ascended in 330 minutes (5h30mins) during which a steady 10 m/s wind was recorded at the surface, shown in Fig. IV.3.

Qualitative observations and photographs recorded the sea state as Beaufort Force 5 and Force 6 for JD 110 and JD 119 respectively. No squalls or strong gusts were observed during either deployment period.

During Deep Sound's descent and ascent, the instrument measures the local temperature and pressure from which depth and sound speed were estimated using the Fofonoff and Millard algorithms (Fofonoff *et al.*, 1983) assuming the constant value of salinity of 34.40 at both locations, taken from the World Ocean Atlas data for salinity at 1000 m depth (Antonov, 2010). The estimated sound speed profiles for both deployments are shown overlaid in Fig. IV.4. The sound speed minimum is at 850 m and 750 m for the JD 110 and JD 119 drops, respectively, with a difference of approximately 1 m/s between the sound speed minimum measured on the descent and the same measurement made approximately 4h45 minutes later, during the ascent. The surface conjugate depth (critical depth), where the sound speed at depth is equal to that at the surface, is at 3930 m on JD 110 and 3500 on JD 119. The difference between these depths is caused by a 3 degrees Celsius change in surface water temperature between the deployment days, which causes a 6 m/s difference in surface sound speed.

Figure IV.2: (a) The depth of Deep Sound versus time during the deployment on JD 110 and (b) the wind speed recorded at a height of 20 m above the sea surface during the equivalent time.

Figure IV.3: (a) The depth of Deep Sound versus time during the deployment on JD 119 and (b) the wind speed recorded at a height of 20 m above the sea surface during the equivalent time.

Figure IV.4: The sound speed profiles measured by Deep Sound during the descent and ascent of deployments on JD 110 (dashed line) and JD 119 (solid line). The sound channel axis at 850 m (JD 110) and 750 m (JD 119) and the critical depths at 3930 m (JD 110) on and 3500 (JD 119) are indicated by the dotted lines, and labeled accordingly.

During the 5h05 minutes and 5h30 minutes of each respective deployment, the surface temperature cooled by approximately one degree, corresponding to a sound speed difference of 2 m/s. In both cases the instrument was deployed at dusk and recovered before dawn, explaining the cooling surface conditions during the measurement. At 1500 m, the sound speed profiles are nearly identical with a difference between the two deployments of 0.25 m/s, decreasing with depth to less than 0.015 m/s at 5000 m.

IV.5 Depth dependence of wind generated ambient noise spectra

During both deployments, continuous pressure time series were recorded on two vertically separated, calibrated hydrophones with a frequency response of 5 Hz – 40 kHz with a sample rate of 204 kHz. Fig. IV.5 shows two ambient noise spectra from each deployment, one computed at 1 km depth, the other computed at 5 km. The spectra were calculated from a single 20-second segment of the time series, divided up into 40 sub-segments of 0.5 seconds duration. A 2^{16} point FFT was computed from each sub-segment, and the associated power spectrum was formed with a frequency cell width of 2 Hz. The 40 power spectra were then ensemble averaged to yield a spectrum for the entire 20-second time series.

Figure IV.5: Ambient noise spectra, recorded at 1 km depth and 5 km during (a) JD 110 and (b) JD 119. The uniform slope of the Knudsen spectrum is shown for comparison.

The slopes of the four spectra shown in Fig. IV.5 agree with the Knudsen spectra ($f^{-5/3}$) plotted for comparison (Knudsen *et al.*, 1948). Both spectra have levels of approximately 75 dB at 1 kHz, 55 dB at 10 kHz which are in reasonable agreement with the Wenz (Wenz, 1962) curves for wind-dependent bubble and spray noise for a Beaufort sea state of Force 5 or Force 6. There is no immediately apparent difference between the shallow and deep spectra in Fig. IV.5.

A spectrogram with a depth resolution of 12 meters was constructed from spectra computed in the same manner discussed above, as shown in Fig. IV.6.

Since each vertical slice in the spectrogram represents the ensemble-averaged spectrum as measured at a particular time and depth, the figure shows how the ambient noise field evolves in both time and depth during the descent and ascent and both scales are shown on the upper and lower axes of the figure respectively.

The descent portion of the spectrogram was computed using the pressure time series from the lower hydrophone, while the ascent portion was computed using the upper hydrophone. The hydrophones on Deep Sound are mounted with a vertical spacing, such that when the instrument is in descent (ascent) the upper (lower) hydrophone is in the turbulent wake of the leading hydrophone. The hydrophone selection used to compute the spectrogram minimizes low-frequency contamination of the natural ocean ambient noise by turbulent flow noise.

Figure IV.6: Spectrogram showing the evolution of the noise field versus depth (bottom axis) and time (top axis) for (a) JD 110 and (b) JD 119. The descent half of the figure is computed using the bottom-mounted hydrophone while the ascent half of the figure uses the top one.

Both spectrograms from JD 110 and JD 119 have certain similarities due to the nature of the deployment. At the beginning of each drop, the R/V Kilo Moana causes the high noise levels shown during the first 200 meters of descent. During this period, the ship is steaming away from the drop site and has not yet shut down its engines.

During the descent phase there is a series of broadband, short time noise events, indicative of ‘spikes’ in the time series. Close listening to the pressure time series reveals that mechanical noise generated by the knocking of the drop weight against the instrument body has caused these spikes. During the JD 119 deployment, this occurs more frequently on the descent phase and a few times during the ascent phase. Here, upon a qualitative listening test, a loose cable is found to be knocking.

The instrument’s transition from descent to ascent occurs when a burn-wire releases a drop-weight, half way through the spectrograms in Fig. IV.6. This event causes a loud broadband noise apparent in both spectrograms.

There is a difference between the measured noise levels on ascent and on descent apparent in Fig. IV.6. This is due to laminar flow of sea-water over the hydrophone and cabling. The speed of the instrument through the water is 0.63 m/s on descent and 0.58 m/s on ascent, resulting in higher measurements of low-frequency noise levels on descent.

Both forms of flow noise, turbulent and laminar, add power to the measured ambient noise spectra for low frequencies. However, it should be appreciated that the generation of flow noise as well as the generation mechanisms of ocean ambient noise are both processes that vary on time scales shorter than the 20 seconds used to compute the power spectra shown in Figs. IV.5 and IV.6. As a result, one process cannot be said to completely mask the other.

The spectrograms in Fig. IV.6 suggest that the ambient noise levels do not exhibit significant depth dependence. Both JD 110 and JD 119 show near constant noise levels on descent and ascent, with variations near the surface. On descent, once the ship

ceases to contribute to the noise field, a small increase in noise of a few dB can be seen in the 5 – 10 kHz band as the instrument travels from 400 m to 1000 m. On ascent, a similar decrease in the same band over the same depth range is seen on JD 110, but not on JD 119. On JD 119, during the ascent from 1000 m to the surface, an increase in noise of a few dB is apparent over the band 1 kHz – 10 kHz. Aside from these slight variations, the spectrograms show a near constant noise field from the surface to the maximum depth.

The depth dependences of the specific frequency bands 50 Hz, 100 Hz, 200 Hz, 500 Hz, 1 kHz, 3 kHz, 5 kHz, 8 kHz, 23 kHz and 30 kHz with a bandwidth of 40% of the center frequency are shown in Fig. IV.7. Over the band of frequencies associated with wind drive noise, 1 kHz – 30 kHz, the ambient noise levels show depth independence during both deployments.

Both Figs. IV.6 and IV.7 show that the ambient noise spectra does not have a large depth dependence, namely the spectral shape and the spectral levels of are constant. However, depth dependence was found in measurements of the spectral slope over the wind driven noise band.

The slope was measured by extracting a section of the power spectrum attributed to wind driven noise, 1 -10 kHz, and calculating a least-square fit to functional form

$$dB_{ref1\mu Pa} = m \log_{10}(f) + b \quad (IV.1)$$

where f is the frequency referenced to 1 Hz over which the power spectrum, dB (ref $1\mu Pa$) is being fit, b is vertical offset and m is the spectral slope, in dB per decade. The fit is performed on the same spectra shown in Fig. IV.6, over the entire range of depths, with the resulting spectral slopes over the band 1 – 10 kHz plotted in Fig. IV.8. For both

deployments, the spectral slope over the wind noise band is shown to monotonically decrease in steepness by 5 dB per decade over the 5 to 6 km depth increase. The slope of the Knudsen spectra, $f^{-5/3}$ or -16.7 dB per decade, occurs at approximately 2500 m depth on JD 110 and 1000 m depth on JD 119. In both cases, the steepening of the slope is linear with small variations and the occasional outlying measurement. This result suggests that either the noise at low frequencies is increasing, or the noise at high frequencies is decreasing, with depth. Careful inspection of Fig. IV.7 confirms the later. The change in spectral levels is only a few dB over the entire 5-6 km depth, which is on the order of the scatter for each band-averaged spectral line plotted in Fig. IV.7 and therefore difficult to extract.

Figure IV.7: The 40% of center frequency band-averaged ambient noise spectral levels during Deep Sound's ascent on (a) JD 110 and (b) JD 119.

Figure IV.8: The least squares fit of spectral slope over the 1 – 10 kHz band of the ambient noise spectrum as a function of depth on (a) JD 110 and (b) JD 119.

IV.6 Depth dependence of vertical coherence

The coherence function of the ambient noise between the two vertically aligned hydrophones was computed using an ensemble averaging procedure similar to the one described in section IV.4. Fig. IV.9 shows the real and the imaginary component of the coherence calculated at 5900 m depth from a 40 second time series of ambient noise, employing 80 ensemble averages. The structure of the real and imaginary coherence is oscillatory over the band 300 Hz to 10 kHz, owing to the strong wind generated ambient noise signal at those frequencies.

Below 500 Hz the coherence is contaminated by turbulent flow noise on the trailing hydrophones. The flow noise, which is the result of two independent, uncorrelated processes on the surface of each hydrophone and therefore not spatially coherent, has a strong red spectrum, which masks the ambient noise and nulls the coherence with greater veracity as frequency decreases. Section V.C. in a previous publication (Barclay, 2011) gives a complete discussion on the effects of turbulent flow

noise on the coherence of spatially correlated noise measured on this instrument and draws the essential conclusion that flow noise acts as a frequency dependent scaling factor which does not affect measurements of coherence above 500 Hz.

Figure IV.9: (a) The real and (b) the imaginary parts of the vertical coherence of ambient noise at 5900 m depth taken on JD 119.

The depth dependence of the vertical coherence was computed using the same 20-second segments of the noise time series, with 40 sub-segment ensemble averages, used to compute the spectrograms in Fig. IV.5. The real and imaginary parts of the coherence from the ascent leg of each deployment were then plotted as a function of depth in Fig. IV.10. A vertical slice of the Fig. IV.10, consists of a curve with a decaying oscillatory form at a particular depth, as shown in Fig. IV.9. The positive peak of the coherence is shown in red, the negative peak is shown in blue and the zero crossings are green. The position of these features remain at the same frequencies for all depths, and create horizontal stripes across the plot, up to 30 kHz, at which point the coherence has decayed away. This shows that the vertical coherence due to wind

generated ambient noise is depth independent. More sensitive data processing, such as tracking the zero-crossings and coherence peaks as a function of depth, yields the same conclusion. The oscillatory structure of the coherence at between 10 – 30 kHz, which is not evident in Fig. IV.9, is apparent in Fig. IV.10.

There is some variation in the amplitude of the coherence as a function of depth. In particular, for both deployments, the first two positive and negative peaks in both the real and imaginary parts of the coherence are stronger at depths of less than 1 km, although their positions with respect to frequency do not change.

A. Computing directionality from coherence

Deep ocean noise can be modeled by a superposition of uncorrelated plane waves propagating randomly in all directions (Cox, 1973). Due to the spatial homogeneity of such a field, power-spectral density, cross-spectral density and other second order statistics are independent of their absolute position of measurement. The normalized cross-spectral density, or coherence, measured between two sensors in a plane wave noise field is therefore only dependent on the separation between the sensors, d and their orientation with respect to each other. In the case of a vertical orientation, the expression derived by Cox (Cox, 1973) gives the vertical coherence function, $\Gamma(\bar{\omega})$, as

$$\Gamma(\bar{\omega}) = \frac{1}{2} \int_0^\pi F(\bar{\omega}, \theta) e^{-i\bar{\omega} \cos\theta} \sin\theta d\theta \quad , \quad (\text{IV.2})$$

Figure VI.10: (a) The real and (b) the imaginary parts of the vertical coherence as a function of depth during Deep Sound's ascent on JD 110. (c) The real and (d) the imaginary parts of the vertical coherence as a function of depth during Deep Sound's ascent on JD 119.

where $i = \sqrt{-1}$, $F(\bar{\omega}, \theta)$ is the dimensionless, frequency dependent noise power per unit angle, incident on the two sensors at the angle θ , relative to the upward vertical and $\bar{\omega}$ is the dimensionless angular frequency, normalized by c , the local sound speed in the medium and d , the sensor separation, such that

$$\bar{\omega} = \frac{\omega d}{c} . \quad (\text{IV.3})$$

In the limiting case of two sensors with no separation d , the measured coherence across all frequencies becomes unity and the expression in Eq. (IV.2) yields

$$\frac{1}{2} \int_0^\pi F(\bar{\omega}, \theta) \sin \theta d\theta = 1, \quad (\text{IV.4})$$

which serves as a normalization condition on the directional density function $F(\bar{\omega}, \theta)$.

Eqs. (IV.2) & (IV.3) show that the directional properties of the noise field, $F(\bar{\omega}, \theta)$, can be inferred from measurements of the coherence on two vertically separated sensors. For instance, it can be easily shown that the complex coherence function can be composed into a real part, related only to the component of the directional density function that is symmetric about the horizontal ($\theta=\pi/2$), and into an imaginary part, related to the asymmetric component.

To compute the vertical noise directionality from measured coherence data, a functional form of the directional density function must be assumed, where a number of free parameters simultaneously define the distribution of noise intensity per unit angle and the shape of the coherence curve such as the frequencies of zero crossings, peaks and peak amplitudes. For a given choice of the unknown free parameters, the coherence is computed using Eq. (IV.2) and then compared to the measured coherence. The goodness of fit between the computed coherence and the measured coherence evaluates the choice of free parameters and the accuracy of the assumed directional density function, which they define. The true noise directionality can then be found by searching over the unknown parameters and minimizing difference between the measured and modeled coherence.

A convenient form of the directional density function is a piecewise continuous combination of step functions, spanning discrete angular segments, representing a discretized form of the ‘true’ continuous angular noise intensity arriving at the sensors over the polar angle range $0 < \theta < \pi$. The angular range is divided into n segments centered at $\theta = \alpha_n$, with an angular width of 2δ such that the directional density function is given by

$$F(\theta, \bar{\omega}) = \sum_{n=1}^N A_n(\bar{\omega}) [u(\alpha_n - \delta_n) - u(\alpha_n + \delta_n)] \quad (\text{IV.5})$$

where $u(\dots)$ is the Heaviside unit step function, $A_n(\bar{\omega})$ is the frequency dependent dimensionless noise intensity arriving between the angles $\alpha_n - \delta_n < \theta < \alpha_n + \delta_n$ and $N = \pi/(2\delta)$. For noise generated by a single broadband sound sources such a wind dependent ambient noise in the ocean, it is reasonable to assume that A_n and the directional density function are frequency independent.

Each term in the summation in Eq. (IV.5) has a closed form solution when substituted into the integral in Eq. (IV.2) and thus the expression for the vertical coherence using the parameterized form of the directional density function is given by

$$\Gamma(\bar{\omega}) = \sum_{n=1}^N A_n \frac{1}{\bar{\omega}} \exp[i\bar{\omega} \cos \alpha_n \cos \delta] \sin[\bar{\omega} \sin \alpha_n \sin \delta]. \quad (\text{IV.6})$$

Eq. (IV.6) depends only on the angular resolution of the discretization, determined by δ and $\alpha_n = (2n-1)\delta$, and by the dimensionless noise intensity arriving at each discrete angle, described by the A_n 's. The fit procedure, described in more detail in a previous publication (Barclay, 2011), is to select an angular resolution and search over the free parameters, A_n , to find the minimized least-squares difference between the

coherence given by Eq. (IV.6) and the measured coherence, subject to the normalization constraint,

$$\sum_{n=1}^N A_n \sin \alpha_n = \frac{1}{\sin \delta} \quad , \quad (IV.7)$$

found by substituting Eq (IV.5) into Eq (IV.4). The parameters used to compute the best-fit coherence curve give the noise directionality through Eq (IV.5).

B. Depth dependence of vertical directionality

This procedure of finding the best-fit coherence is the basis for finding the vertical noise directionality as a function of depth. Using the coherence curves computed and shown in Fig. IV.10, the directionality is determined as a function of depth. Fig. IV.11 shows the real and imaginary component of the coherence curve from a depth 5900 m shown in Fig. IV.9., with the best-fit model overlain. The modeled coherence is calculated using the spatial resolution parameters of $\delta=2^\circ$ and $\alpha=2^\circ, 6^\circ, 10^\circ \dots 178^\circ$ which involves fitting 45 free parameters, $A_1, A_2, \dots, A_{45}$. For two sensors spaced by 0.5 m with an upper bandwidth limit of 10 kHz, the angular resolution set by the width of a beam is on the order 20° at broadside (Urick, 1967), which is much larger than the resolution chosen for the coherence fit. Accordingly, the resulting directional density function from the $\delta=2^\circ$ best-fit coherence is down-sampled by integrating the dimensionless intensities over angular segments of 16° . This over-parameterization followed by down sampling of the directional density function reduces the noise on the result while providing an accurate fit to the measured coherence.

Figure IV.11: (a) The real and (b) the imaginary parts of the measured (black curve) and the best-fit (red line) vertical coherence at 5900 m depth from JD 119.

The modeled coherence is in reasonable agreement with the measured coherence over the majority of the wind generated noise band. At frequencies below 500 Hz, the fit between the model and the data is poor. In the limit of zero frequency, or alternatively, the limit of zero spacing between the sensors, the real part of the coherence (symmetric part of the directionality) is expected to become unity, while the imaginary part of the coherence (asymmetric part of the directionality) is expected to go to zero. Spatially incoherent turbulent flow noise, not accounted for in the directionality-coherence model, masks the ocean ambient at low frequencies. Flow noise has a strong red spectrum (McGrath *et al.*, 1977; Finger *et al.*, 1979) which reduces the coherence as it overpowers the ocean ambient noise as frequency decreases (Barclay, 2011). For this reason, the real part of the coherence goes to zero in the limit of zero frequency, or zero separation between sensors, and a significant difference is seen between the modeled and measured coherence.

Above 1 kHz, the modeled and measured coherence agree well. At high frequencies, above 10 kHz, the coherence has decayed away, as the spacing between the hydrophones has become large, relative to the wavelength.

The directional density function derived from the best-fit coherence at 5900 m is shown in Fig. IV.12. This shows that the majority of noise is arriving on the sensors from directly above. The directional density function was calculated as a function of depth, with a depth resolution of 50 m and an angular resolution of 16° , and plotted in Fig. IV.13.

The directionality of the noise is mostly depth independent and dominated by downward propagating noise from elevation angles between 0° and 16° . At shallow depths, below 1000 m, increased noise arriving at larger elevation angles is seen. No change in directionality is seen at the critical depth for either deployment, but in general, the noise directionality becomes increasingly peaked in the direction of directly overhead, while noise arriving from larger elevation becomes suppressed, as depth increases. The intensity for upward propagating noise is near zero, with the exception of a weak intensity at the elevation angle 180° . This corresponds to noise arriving from directly below the instrument, and is most likely due to single bounce surface noise off the sea floor. Fig. IV.13 shows that the ambient noise field during sea state Force 5 and Force 6 is dominated by wind generated surface noise over the entire water column.

Figure IV.12: Vertical directional density function derived from the best-fit to the noise coherence data recorded at 5900 m depth on JD 119.

Figure IV.13: Vertical noise directional density function as it evolves versus depth (left axis) and time (right axis) during Deep Sound's ascent on (a) JD 110 and (b) JD 119.

IV.7 Depth dependence of wind speed estimates from ambient noise

The shipboard wind speeds reported in Figs. IV.2 and IV.3 were recorded 20 meters above the water line. In order to investigate the depth dependence of the wind speed estimate from ambient noise, these measurements were translated to the standard meteorological measurement height of 10 m (Thomas *et al.*, 2005). The vertical profile of wind speed over the sea surface depends on aerodynamic sea surface roughness and the stratification of air in the boundary layer. Following the method outlined by Walmsley (Walmsley, 1988), while including the correction to potential temperature due to humidity, the wind speed, U_{10} , was computed from the air temperature, humidity and sea surface temperature and the measured wind speed, U_{20} . The air temperature and humidity were measured at 20 m above the sea surface by a ship integrated meteorological station as 26.4°C and 86% on JD110 and 21.6°C and 56% on JD 119, while the sea surface temperature was measured by Deep Sound as 27.5°C on JD 110 and 24.1°C on JD 119. U_{10} was reduced by approximately 5% from U_{20} under these conditions, in agreement with the tabulated values reported by Smith (Smith, 1988).

The height corrected wind speed measurements were then compared to wind speed estimates computed from the acoustic data. The goal of this comparison is to investigate any possible depth dependence of the estimate that may be attributed to propagation, attenuation and the change in surface area sampling with the depth of the hydrophone. Although many empirical relationships between ambient noise and wind speed have been derived (Shaw *et al.*, 1978; Evans *et al.*, 1984; Farmer and Lemon,

1984; Lemon *et al.*, 1984) the WOTAN wind algorithm (Vagle *et al.*, 1990) is followed here.

Using the same 20-second segments of acoustic data used to calculate the spectrogram in Fig. IV.6 and the coherence in Fig. IV.10, the spectral level (SSL) was computed at eight different frequency bands, $f_i = 3.0, 4.3, 5.3, 6.5, 8, 10.8, 12.5$ and 14.5 kHz with a bandwidth of 16% of the center frequency. The dimensionless sound pressure variance in a 1 Hz band, $p_o^2(f)$, was then computed with the following relationships

$$SSL_0 = \frac{1}{8} \sum_{i=1}^8 [SSL(f_i) + Q \log(f_0 / f_i)] \quad (IV.8a)$$

$$p_0 = 10^{(SSL_0 / 20)} \quad (IV.8b)$$

where $Q = -19$ dB/decade and the reference frequency f_0 is chosen to be 8.0 kHz. Note that unlike the originally reported relationship (Eq. (26) in Vagle (Vagle *et al.*, 1990)), Eq. (IV.8a) does not contain a term generally referred to as $\beta(z, f)$, describing depth dependent attenuation, refraction or surface area sampling differences.

The wind speed is estimated using the empirical relationship

$$U_{10} = \frac{p_0 - b}{s} \quad (IV.9)$$

with the reported coefficients from the FASINEX data set (Vagle *et al.*, 1990) $b = -80.94$ and $s = 52.87$.

Figure IV.14: The measured (open circles) and acoustically estimated (closed dots) wind speeds at a height of 10 meters above the sea surface versus time (bottom axis) and depth (top axis) during Deep Sound's ascent on (a) JD 110 and (b) JD 119.

Fig. IV.14 shows the wind speed estimate as a function of time and depth, during the ascent phase of both the JD 110 and JD 119 deployments. In both cases, the descent phase was corrupted during the first few hundred meters by locally generated ship noise, as well as locally generated instrument noise, as seen in Fig. IV.5, so the analysis is focused on the ascent phase of the deployment. For both deployments, the acoustic estimates of the wind speed are greater than the measured wind speed. For depths greater than 2000 m, the over-estimate is less than 1 m/s and is within the variability of the ship-mounted anemometers. At depths less than 2000 m, the difference increases as the estimate approaches the surface for both deployments. At the surface, the difference between the estimate and the data is 3 m/s on JD 110 and 5 m/s on JD 119.

It is assumed that this over-estimate is partially due to the exclusion of $\beta(z,f)$, a term describing attenuation, propagation loss and surface area sampling differences as a function of depth in Eq. (IV.8a). However, this figure does support the conclusion that the importance of such a term diminishes with depth, suggesting that the increased surface sampling area with depth nearly balances losses from refraction due to the depth dependent sound speed profile, and attenuation. For both deployments, the wind speed estimate converges with the ship mounted wind measurements as the depth increases. At shallow depths of a few hundred meters, the addition of a reasonable values of $\beta(z,f)$ between -0.4 and -1.5 dB (Vagle *et al.*, 1990) into Eq. (IV.8a) do not fully account for the difference between the estimated and measured wind speed.

It should also be noted that wind speed estimates from ambient noise are generally made on the time scale of hours, rather than seconds, as is done here. The lag

between the wind speed, surface wave conditions and acoustics may be apparent from the JD 110 deployment, where the measured wind speed drops from 9 m/s to 7 m/s over 2.5 hours, while the acoustic estimate of wind speed increases from 9 m/s to 10 m/s over the same time period. Other experiments have shown that the RMS error between acoustic estimates and surface measurements of winds speed decrease as averaging time increases from hours to days and so forth (Vagle *et al.*, 1990; Vakkayil *et al.*, 1996). The general over-estimate of wind-speed by the WOTAN algorithm on the order of 1 m/s have been reported during other experiments (Vakkayil *et al.*, 1996).

It is also possible that the wind speed measurements recorded by the anemometer were underestimated. Using a sonic anemometer, Taylor showed that the reported wind speeds by conventional anemometers on drifting ships are too low, possibly due to flow distortion (Taylor *et al.*, 1995; 1999).

IV.8 Estimating pH from the depth dependence of ambient noise

Although the spectral levels appear to be constant with depth, relatively small changes between them manifest as a steepening of the spectral slope as a function of depth as shown in Fig. IV.8. This result shows that the level of high-frequency noise decreases with depth at a greater rate than the level of low-frequency noise.

Figure IV.15: The theoretical sound absorption in sea-water with a pH of 8, a temperature of 4°C at a depth of 1 km.

The absorption of sound in seawater due to viscous relaxation and chemical relaxation of different compounds and, for each individual mechanism, has an f^{-2} frequency dependence, shown in Fig. IV.15 (Francois and Garrison, 1982a; b). Over the wind noise band of 1 – 10 kHz, the frequency dependence of the absorption is due to the mixing of the mechanism of chemical relaxation for magnesium sulfate ($f > 3$ kHz) and for boric acid ($f < 3$ kHz), which involve ionic dissociations that are activated and deactivated by the condensation and rarefaction of the medium by passing sound waves. Concentrations of both chemicals determine the level at which the sound is absorbed, which makes the process strongly dependent on the salinity, temperature and pressure in the ocean. Additionally, the concentration of boric acid in the ocean is a direct measure

of the ocean's acidity so the sound absorption between 100 Hz and 3000 Hz is dependent on the pH of the seawater.

The concentration of magnesium sulfate is independent of pH. By measuring the frequency dependence of sound absorption over the wind noise band, where absorption is driven by the pH dependent mechanism at low frequencies ($f < 3$ kHz) and by the pH independent mechanism at high-frequencies ($f > 3$ kHz), the ocean's acidity can be determined from ambient noise.

Figure IV.16: The geometry of a receiver at depth z and a source near the surface, at a depth of z' , with a negative image source placed above the surface.

Consider a single omni-directional noise source with a reference pressure p_0 , a small distance z' below the ocean's surface, as shown in Fig. IV.16, such as a bubble generated by a breaking wave. At a depth z , the pressure wave on the receiver due to the source is

$$p = p_0 \left[\frac{e^{-ikr_1} e^{-\alpha r_1}}{r_1} - \frac{e^{-ikr_2} e^{-\alpha r_2}}{r_2} \right] \quad (\text{IV.10})$$

where α is the frequency dependent sound absorption, k is the wave number and the first term gives the component of the wave from the source at a distance r_1 and the second term gives the component of the wave due to a negative image source placed at $-z'$, at a distance r_2 .

By expressing r_1 and r_2 in terms of z' , θ , the elevation angle between the source and receiver relative to the vertical and r_0 , the distance from the receiver to the midpoint between the source and the image source, the magnitude squared of the pressure in Eq. IV.10 simplifies to

$$|p|^2 = \frac{4p_0^2}{r_0^2} (k^2 + \alpha^2) z'^2 \cos^2 \theta e^{-2\alpha r_0} \quad (\text{IV.11})$$

where terms containing $(z'/r_0)^2$ have been discarded under the assumption that the source depth is small relative to the distance to the receiver.

The received intensity is calculated by integrating over a homogeneous distribution of identical sources on the entire ocean surface, expressed as

$$I = \int_0^\infty 2\pi R |p|^2 dR \quad (\text{IV.12})$$

where $R = r_0 \sin \theta$ is the radial distance along the surface and the 2π is the result of integrating over the azimuth. Substituting Eq. IV.11 into Eq. IV.12 results gives

$$I = 8\pi p_0^2 (k^2 + \alpha^2) z'^2 \int_0^{\pi/2} \cos^3 \theta \sin \theta e^{-2\alpha z' / \cos \theta} d\theta \quad (\text{IV.13})$$

which is further simplified by the substitution $y = \sec \theta$, becoming

$$I = 8\pi p_0^2 (k^2 + \alpha^2) z'^2 \int_1^\infty \frac{e^{-2\alpha y} dy}{y^5}. \quad (\text{IV.14})$$

The integral in Eq. IV.14 is then evaluated using differentiation by parts four times. When the product αz is small enough, $(\alpha z)^2$ and similar higher order terms can be discarded and the dominant terms of the evaluated integral in Eq. IV.14 give the expression

$$I = A(\omega) e^{-8\alpha z/3}, \quad (\text{IV.15})$$

where $A(\omega) = 2\pi p_0^2 k^2 z'^2$ for small α . Taking the base 10 logarithm of Eq. IV.15 gives

$$S(\omega) = 10 \log_{10} (A(\omega) e^{-8\alpha z/3}) \quad (\text{IV.16})$$

which models the power spectral density of ambient noise generated by a homogeneous distribution of near-surface sources as a function of depth and frequency.

Over the wind generated noise band, the frequency dependence of the power spectrum is given by a power law, such as the Knudsen spectrum, $f^{-5/3}$ (Kundsen, 1948) so the term $A(\omega)$ can be simplified as a combination of a source intensity, relative to a reference intensity of $1 \mu\text{Pa}^2/\text{Hz}$ and a frequency dependent term with a fixed slope relative to a reference frequency. Eq IV.16 is then becomes

$$S(\omega) = 10 \log_{10} \left[\frac{I}{I_0} \left(\frac{f}{f_0} \right)^{n_0} e^{-8\alpha z/3} \right] \quad (\text{IV.17})$$

where n_0 is the power-law coefficient which describes the frequency dependence of the wind driven band of the spectrum at the surface ($n_0 = -5/3$ for the Knudsen spectrum).

The slope of the spectrum between two frequencies as a function of depth is given by

$$Q(z) = \frac{S(f_1) - S(f_2)}{\log_{10}(f_1/f_2)} \quad (\text{IV.18})$$

Substituting Eq. IV.17 into IV.18 and simplifying give the expression for the depth dependence of the spectral slope over the wind noise band as

$$Q(z) = \frac{8}{3} \frac{[\alpha(f_2) - \alpha(f_1)] \log(e)}{\log(f_1/f_2)} z + 10n_0 \quad (\text{IV.19})$$

The value of $\Delta\alpha = \alpha(f_2) - \alpha(f_1)$ can be determined by comparing a least-squares fit line to the depth dependent spectral slope data show in Fig. IV.8 to Eq. IV.19. The slope of the line is given by the coefficient of z in the first term in Eq IV.19 and gives a direct relationship between the measured data and the frequency dependence of the absorption of the wind generated ambient noise band.

Since the pH-dependent concentration of boric acid drives the absorption at f_1 while the absorption at f_2 is due to the pH-independent concentration of magnesium sulfate, the value of $\Delta\alpha$ gives a measure of the seawater's acidity. The known value of the absorption at both frequencies was calculated (Ainslie and McColm, 1998) using the mean water column values of a sea-water temperature of 4°C and a depth of 2.5 km, the estimated value of salinity of 34.4 PSU (Antonov, 2010) and a range of pH values between 7 - 8.5 and shown in Fig. IV.17. The mean value of $\Delta\alpha = 0.652$ was determined from the JD 110 and JD 119 deployments by fitting Eq. IV.19 to the data shown in Fig IV.8. The corresponding pH was determined from Fig IV.17 to be 7.9. This value is in reasonable agreement with contemporary field measurements made in the western Philippine Sea of 7.6 (Chen and Huang, 1996).

Figure IV.17: The calculated difference between absorption at 1 kHz and 10 kHz as a function of pH (black line) with the measured value of $\Delta\alpha$ shown by the red square.

IV.9 Conclusion

Deep Sound was used to make ambient noise profiles in the Philippine Sea on from the surface to 5500 m and 6000 m over the bandwidth 5 - 40 kHz. This free falling acoustic recorder offers a simple and effective alternative to traditional cabled arrays for measuring the depth dependence of ambient noise. During both deployments, the spectral levels were found to have virtually no depth dependence once below the first few hundred meters. At all depths from the surface to the bottom, the power spectra exhibited an approximate match to the Knudsen spectra characteristic slope of $f^{5/3}$ and spectral levels in accordance with the Wenz curves for the observed Beaufort sea states 5 and 6 on JD 110 and JD 119 respectively. The measured winds on JD 110 were 9 m/s slowing to 8 m/s while on JD 119 they were a constant 10 m/s.

The vertical coherence was shown to have virtually no depth dependence as the frequencies of zero-crossings and positive and negative peaks were stationary from the surface to the bottom of both deployments. A small decrease in the amplitude of the positive and negative coherent peaks between 1 – 5 kHz is seen as the depth descends to beyond 500 m.

The directionality derived from a coherence-fitting scheme, shows a similar consistency as a function of depth. Throughout the entire water column, almost no noise is measured at upward propagating angles (elevation angles greater than 90°) with the exception of a small amount of single bounce noise arriving directly from the bottom. In the first 500 m, noise is arriving on the sensors from elevation angles from 0° to 60°, but as the instrument descend beyond 1000 m the noise directionality is dominated by

downward propagating noise arriving from directly above, within the first 16° of elevation.

The unchanging properties of the ambient noise spectrum, vertical coherence and vertical directionality over the entire water column demonstrate that the locally generated surface noise at wind speeds of 7-9 m/s and 10 m/s will dominate the noise field over all depths. No large change in ambient noise directionality was seen at the critical depth.

Wind speeds were estimated acoustically using the WOTAN algorithm (Vagle *et al.*, 1990) with the exclusion of a term, $\beta(z,f)$, accounting for attenuation and propagation loss, and the depth dependence of difference between the measure winds and the estimate was investigated. At shallow depths the modified algorithm was found to overestimate the winds by 3 - 5 m/s, partially, although not exclusively, due to exclusion of the term $\beta(z,f)$. The overestimate may have also been caused by the unusually short time scale of 20 seconds of acoustic data per wind speed estimate, as previous studies have shown that increasing the averaging time of the wind speed estimate, improves accuracy when compared to buoy or ship data (Vagle *et al.*, 1990; Vakkayil *et al.*, 1996). It is also likely that the wind speed measurements recorded by the drifting surface ship were under-estimated (Taylor *et al.*, 1995; 1999), contributing to the difference between the two measurements.

A small steepening of the spectral slope over the wind noise band of 1 – 10 kHz as a function of depth was measured during both deployments. By assuming that the wind generated ambient noise acts as a constant source at the surface, the change in spectral slope was shown to be due to the absorption by the viscous and chemical

properties of seawater. A measure of the pH was made from the frequency dependence of the absorption as a function of depth.

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V. Conclusions

Deep Sound is a new instrument platform for making measurements in the deepest trenches of the world's oceans. In two field experiments it made high-bandwidth acoustic profiles from the surface to 5 km, 5.5 km, 6 km and 9 km, resulting in the deepest measurement of ambient noise ever made, according to the open literature. The depth dependence of the power spectral density and vertical coherence of rain noise and wind generated noise on the ocean's surface was characterized over the entire water column.

A coherence fitting procedure was introduced and used to retrieve the directionality of ambient noise through Cox's relationship (Cox, 1973). The highly directional noise field due to a spatially variable rainstorm was resolved from a depth of 5 km and the rainstorm was tracked as it passed overhead. The depth dependence of the vertical coherence and directionality during moderate winds was found to be dominated by downward propagation noise at all depths.

Deep Sound was used to check the depth dependence of acoustic rainfall rate estimate algorithms and acoustic wind speed estimate algorithms and found that accurate estimates of both surface processes could be made from depths up to 6 km. These initial studies suggest that at great depths, measurements of surface processes are averaged over a larger spatial area and provide more stable estimates of their rates.

An measurement of the frequency dependence of the absorption of sound in seawater was made using ambient noise and used to estimate the mean water column pH. Further investigation into this technique is merited as the question of ocean acidification is important to the marine ecosystem (Feely *et al.*, 2004). With more

detailed modeling, it is realistic to suppose that the depth profile of pH may be extracted from the ambient noise field.

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