Deep Sound: A Free-Falling Sensor Platform for Depth-Profiling Ambient Noise in the Deep Ocean

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Introduction

Deep Sound, shown in Figure 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 the

FIGURE 1

Deep Sound Mk. I, photographed during a tethered engineering test in 100 m water off the coast of La Jolla, Southern California.

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 preassigned 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 recharged 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.

ascent rates are similar at about 0.6 m/s. A Vitrovex glass sphere, with external and internal diameters of 43.2 and 39.6 cm, respectively, 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 the ascent. Additional sen-sors are mounted on Deep Sound for continuous monitoring of temperature, depth, and 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 recharged without their removal from the sphere.

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 preset 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 6-h round trip.

The Deep Sound Channel and Ambient Noise

Deep Sound was developed 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 that is curved due to refraction arising from the depth-varying sound speed.
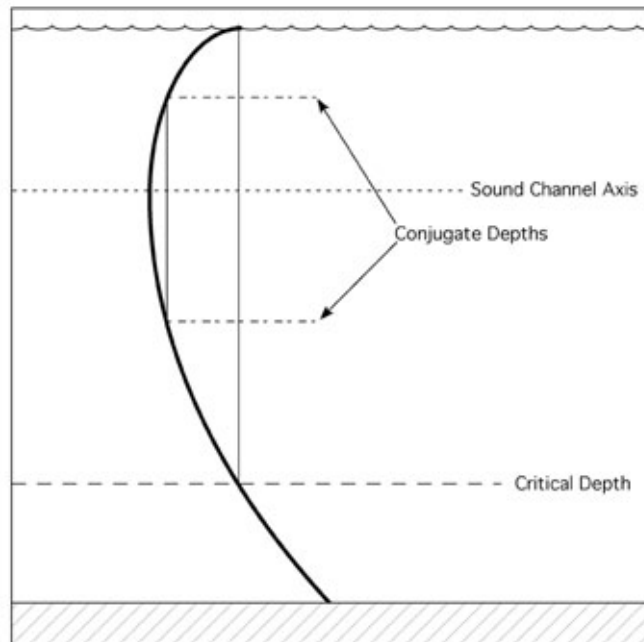
In deep water, the primary factors affecting the speed of sound are temperature and pressure. A schematic of a deep-water sound speed profile is shown in Figure 2. With increasing

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 that exhibits a pro-

nounced minimum, as illustrated in Figure 2. In temperate waters, the sound speed minimum occurs at depths of approximately 1000 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

FIGURE 2

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

the critical depth (Figure 2). According to 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 (Gaul et al., 2007; Morris, 1978).

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 to test the validity of the various deep-water ambient noise models that now exist, including Weston's.

Design Criteria for Deep Sound

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 the 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 manhandle over the side of a boat using a small davit (Figure 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.

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 an HDPE hard hat, to which is bolted a titanium bail and an HDPE frame. Two HDPE arms extend away from the frame (Figure 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 in-

strument is 0.6 × 0.6 m, with a height of 1 m and a total mass in air of 68 kg. The buoyancy is 215 N, 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 h and 20 min.

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 Wh, which allows Deep Sound to operate continuously for 9.5 h. 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 9-V battery and an isolated DC/DC converter, provides backup power to the burn wire in the event that the main system software or hardware fail. The expendable

burn wire is fabricated from Seven-Strand 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 µPa. The phones are also calibrated over pressures up to 600 bar, corresponding to a maximum ocean depth of 6,000 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 nighttime 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.

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 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 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.

The Deployment Phase

Deep Sound Mk. I and Mk. II both run National Instruments LabView software to coordinate 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 countdown 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 preassigned 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 preassigned 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 if 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 preprogrammed 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 pay load.

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 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 ballast weight, and successfully returned to the surface. Acoustic and environmental data were recorded continuously during each of the round trips. Figure 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 Figure 4. At frequencies below 1 kHz, the trailing phone shows a spectral level some 10 dB above that of 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
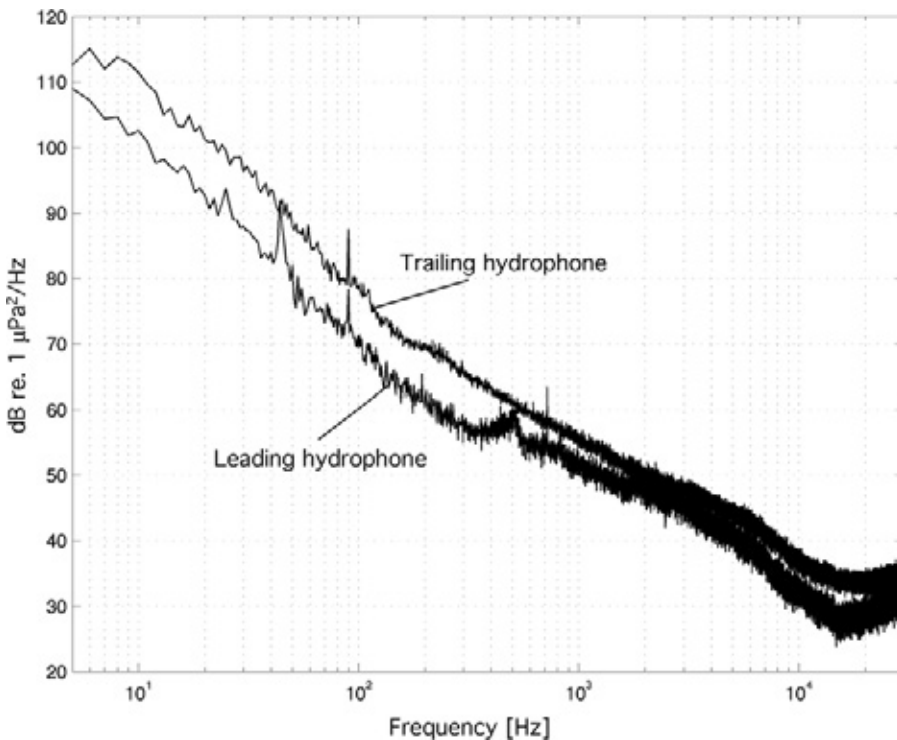
FIGURE 3

(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.
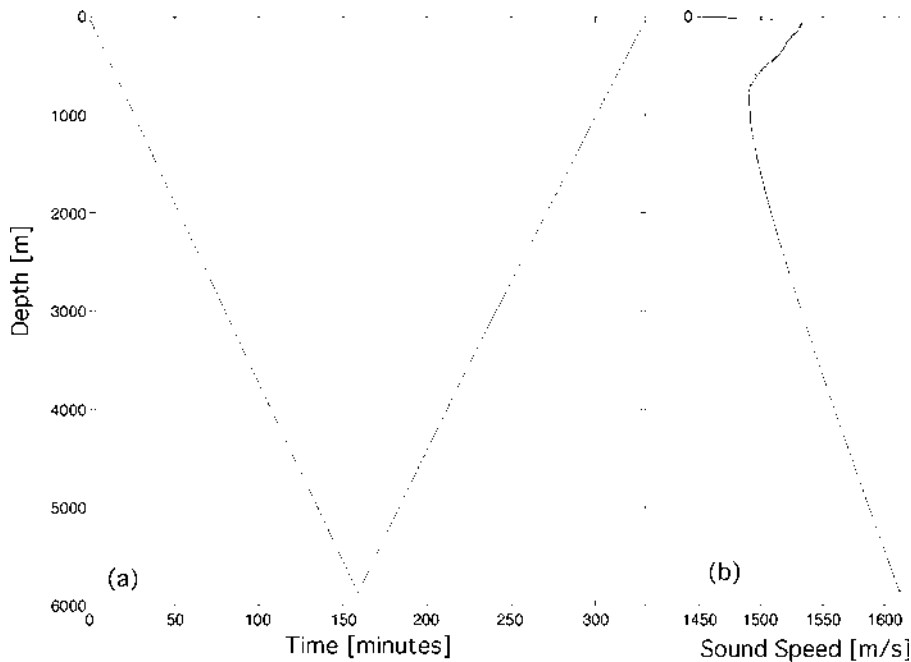
FIGURE 4

Ambient noise spectra from the Philippine Basin deployment, taken while Deep Sound Mk. I descended from a depth of 5667 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.

levels across the whole frequency band shown in Figure 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.

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 recharged, taking a little less than 3 h, 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 h. 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.

Acknowledgments

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