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SEISMOLOGY SENSORS

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Introduction

A glance at the globe shows that the Earth's surface is largely water-covered. The logical consequence of this is that seismic studies based on land seismic stations alone will be severely biased because of two factors. The existence of large expanses of ocean distant from land means that many small earthquakes underneath the ocean will remain unobserved. The difference in seismic velocity structure between continent and ocean intruduces a bias in locations, with oceanic earthquakes which are located using only stations on one side of the event being pulled tens of kilometers landward. Additionally, the depths of shallow subduction zone events, which are covered by water, will be very poorly determined. Thus seafloor seismic stations are necessary both for completeness of coverage as well as for precise location of events which are tectonically important. This paper summarizes the status of seafloor seismic instrumentation.

The alternative methods for providing coverage are temporary (pop-up) instruments and permanently connected systems. The high costs of seafloor cabling has thus far precluded dedicated cables of significant length for seismic purposes, although efforts have been made to use existing, disused wires. Accordingly, the main emphasis of this report will be temporary instruments.

Large ongoing programs to investigate oceanic spreading centers (RIDGE) and subductions (MARGINS) have provided impetus for the upgrading of seismic capabilities in oceanic areas.

The past few years has seen a blossoming of ocean bottom seismograph (OBS) instrumentation, both in number and in their capabilities. Active experimental programs are in place in the USA, Europe, and Japan. Increases in the reliability of electronics and in the capacity of storage devices has allowed the development of instruments which are much more reliable and useful. Major construction programs in Japan and the USA are producing hundreds of instruments, a number which allows imaging experiments which have been heretofore associated with the petroleum exploration industry. This contrasts sharply with the severely underdetermined experiments which have characterized earthquake

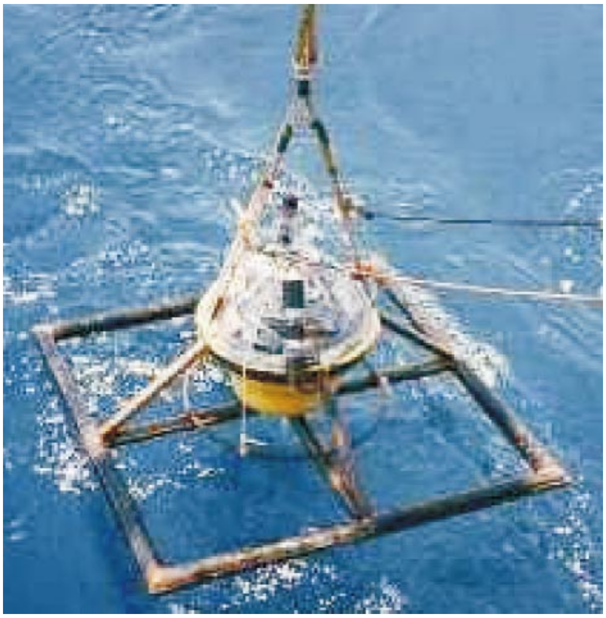

Figure 1 The UTIG OBS, a particularly 'clean' mechanical design, which has been in use for many years, with evolving electronics. The anchor is 1.2 m on each side. (Photograph by Gail Christeson, UTIG.)

Table 1 Characteristics of short period ocean bottom seismometers

Parameter	*UTIG*	*WHOI-SP*	*SIO-IGPP-SP*	*GEOMAR-SP*	*JAMSTEC-ORI*[a]
Contact/website	Nakamura/http://www.ig.utexas.edu/research/projects/obs/obs.html	Detrick/Collins http://www.obsip.org	Orcutt/Babcock http://www.obsip.org	Flüh/Bialas http://www.geomar.de	–
Seismic sensor(s)	3-component 4.5 Hz Mark Products L-15B or Oyo GS-11D	2 Hz Mark Products L-22 4.5 Hz or L-28 4.5 Hz, vertical component	2 Hz Mark Products L-22, vertical component	optionally uses Webb BB sensor	4.5 Hz vertical
Frequency response	4.5–100 Hz	2–X Hz	2–X Hz	0.05–30 Hz/0.01–X Hz	4.5–100 Hz
Nominal sensitivity	2.5 nm s^{-1}	–	–	–	–
Hydrophone	OAS E-2PD crystal	Hightech crystal	Hightech HYI-90-U	OAS E4SD or Cox-Webb DPG	–
Frequency Response	3–100 Hz	5–X Hz	50 mHz-X	0.05–30 Hz	–
Digitizer type, dynamic range, sample rates	14 bits + gain-ranging, 126 dB,112 dB re electronic noise	Quanterra Q330 24-bit,126 dB, 1–200 Hz	Cirrus/Crystal CS5321-CS5322 24-bit, 124–130 dB	oversampling, 120 dB, 25–200 Hz	–
Recording medium and capacity[b]	Disk, semi-continuous	Disk, data download through pressure case	9 Gbyte disk, data download through pressure case	1 Gbyte DAT or 2 Gbyte semiconductor memory	–
Clock type and drift[c]	10 ms	Seascan Precision Timebase < 0.5 ms d^{-1}	Seascan Precision Timebase < 0.5 ms/d^{-1}	Seascan Precision Timebase < 0.5 ms d^{-1}	–
Endurance	8 weeks–6 months	90 days, alkaline/1 year, lithium	80–180 days at 250/31.25 Hz sampling 5 days on NiCad rechargeable cells	300 days	–
Power consumption	550 mW	–	420 mW at 31.25 Hz, 1.6 W at 250 Hz for 2 channels	230–250 mW	–
Release type	Burnwire release, acoustically controlled, acoustic release, two backup timers	Burnwire, Edgetech acoustics	Double burnwire, Edgetech acoustics	Acoustic release with back-up timer	–
Mechanical configuration, launch/recovery weights	Single 43 cm diameter glass sphere, 85 kg/35 kg	63 kg/43 kg	110 kg/80 kg	Vertical cylinders, 175 kg/125 kg	Single 43 cm diameter glass sphere
Number available	37–39[d]	15 now, 40 more under construction	14 now, 74 more under construction	27 OBH + 11 OBS	100?
Total			51		

[a]Information on these instruments is incomplete.
[b]2 gigabytes is about 22 days of data sampling four channels at 128 Hz or 176 days sampling four channels at 16 Hz.
[c]1 ms d^{-1} is about 1×10 E-8.
[d]Includes instruments of the same design operated by IRD (formerly ORSTOM) and National Taiwan Ocean University.

Table 2 Characteristics of broadband ocean bottom seismometerrs

Parameter	*SIO/ONR*[a]	*WHOI-BB*	*LDEO-BB*[e]	*SIO/IGPP-BB*	*ORI-BB*[f]
Manager	*Dorman/* Sauter http://www-mpl.ucsd.edu/obs	Detrick/ Collins http://www.obsip.org	Webb/ http://www.obsip.org	Orcutt/Babcock http://www.obsip.org	–
Seismic sensor	1 Hz Mark Products L4C-3D or PMD 2123	Guralp CMG-3ESP	1 Hz Mark Products L4C-3D	Kinemetrics	PMD 2023
Frequency response	0.033–32 Hz[b]	0.033–50 Hz[b]	0.005–30 Hz[b]	0.02–50 Hz	0.033–50 Hz
Hydrophone	Cox-Webb DPG	HighTech	Cox-Webb DPG for low frequency hydrophone for high frequency	High Tech HYI-90-U or Cox-Webb DPG	–
Frequency response	0.001–5 Hz	0.033–X Hz	0.001–60 Hz	0.05–15 kHz or 0.01–32 Hz	–
Digitizer type, Dynamic range, sample rates	16-bit + gain-ranging, 126 dB, X-128 sps	Quanterra QA330 24-bit, 135 dB	nominal 24-bit ~ 135 dB, 1, 20, 40, 100, 200 sps	24-bit Cirrus/ Crystal CS 5321–CS-5322, 130 dB	20-bit
Recording medium and capacity[c]	Disk, 9–27 Gbyte	Disk, 2 Gbyte	Disk, 18 Gb, 72 Gb planned	Disk, 9 Gbyte	4 × 6.4 Gbyte disks
Clock drift[d]	< 1 ms d^{-1}	< 1 ms d^{-1}	0.5 ms d^{-1}	< 1 ms d^{-1}	–
Endurance	6–12 months	6–12 + months	Up to 15 months	6–12 months	9 months?
Power consumption	400 mW	1.5 W at 20 sps	–	–	~ 600 mW
Release type	Two EG&G 8242 acoustic releases	One EG&G 8242 acoustic relase with back-up acoustic burnwire release	Acoustically controlled burnwire?	EG&G acoustically controlled burnwire	Acoustically controlled burn-plate
Mechanical configuration, launch/ recovery weights	Fiberglass frame, aluminum pressure cases, glass flotation (ONR OBS-style)	ONR OBS-style, floating above anchor, 570 kg/ 472 kg	Aluminum pressure cases, plastic plate frame, 215/145 kg	178/138 kg	50 cm diameter, titanium sphere
Number available	14	25 under construction	64 under construction	15–20 (using recording package from SP instrument)	15
Total			~ 133		

[a]These instruments incorporate a fluid flowmeter/sampler in the instrument frame (see Tryon *et al.* 2001).
[b]Seismometers are free from spurious resonances below 20 Hz.
[c]2 gigabytes is about 22 days of data sampling four channels at 128 Hz or 176 days sampling four channels at 16 Hz.
[d]1 ms is about 1×10^{-8}.
[e]1 See Webb *et al.*, 2001.
[f]1 See Shiobara *et al.*, 2000.

seismology. One change over the past decade has been the disappearance of analog recording systems.

A side effect of this rapid change is that a review such as this provides a snapshot of the technology, rather than a long-lasting reference. The technical details reported below are for instruments at two stages of development: existing instruments (UTIG, SIO/ONR, SIO/IGPP-SP, GEOMAR, LDEO-BB) and instruments still in design and construction (WHOI-SP, WHOI-BB SIO/IGPP-BB) (see **Tables 1** and **2**; **Figures 1–6**. The latter construction project has the acronym 'OBSIP' for OBS instrument pool, and sports a polished, professionally designed web site at http://www.obsip.org.

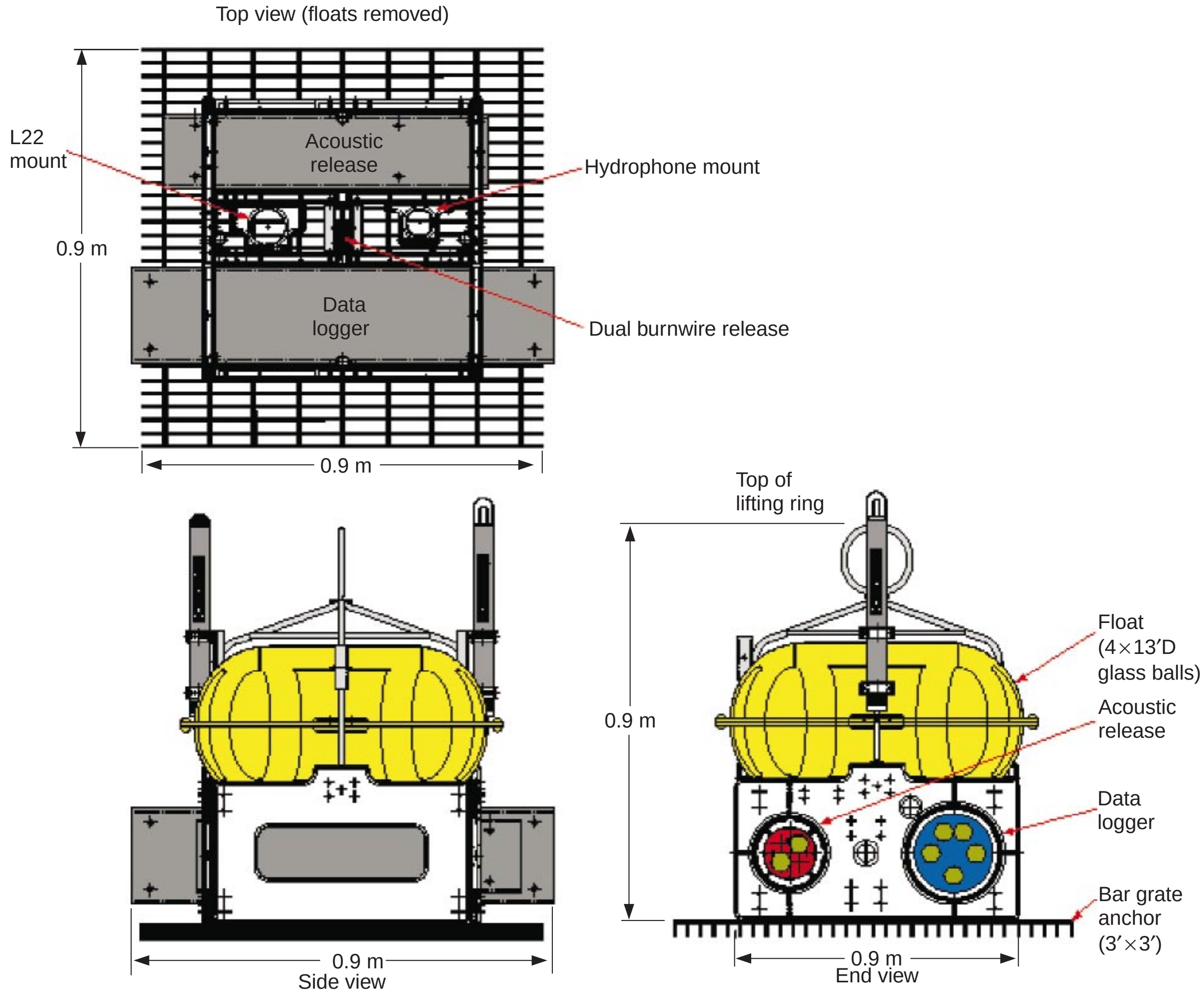

Figure 2 The IGPP-SP instrument. (Figure from Babcock, Harding, Kent, and Orcutt.)

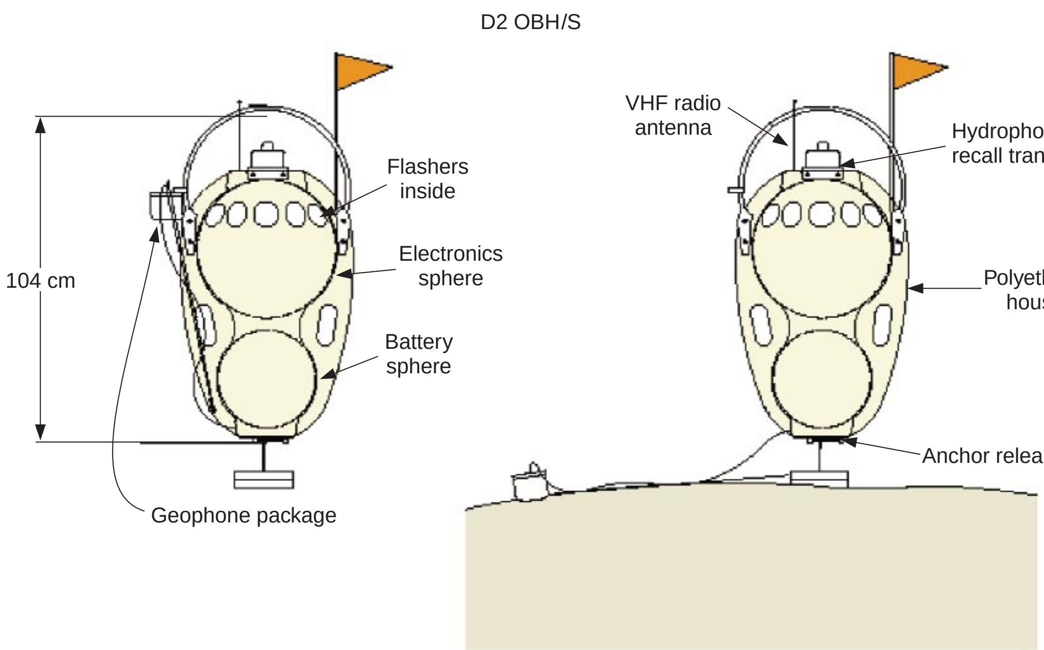

Figure 3 The WHOI-SP instrument. The change of orientation between seafloor and surface modes allows the acoustic transducer an unobstructed view of the surface while on the seafloor and permits acoustic ranging while the instrument is on the surface. (Figure by Beecher Wooding and John Collins.)

Figure 4 The GEOMAR OBH/S. The shipping/storage container is equipped with an overhead rail so that it serves as an instrument dispenser. The OBS version is shown here. (Photograph by Michael Tryon, UCSD.)

OBS designs are roughly divided into two categories which for brevity will be called 'short-period' (SP) and 'broadband' (BB). The distinction blurs at times because some instruments of both classes use a common recording system, a possibility which emerges when a high data-rate digitizer has the capability of operation in a low-power, high endurance mode.

Short Period (SP) Instruments

The SP instruments (**Table 1**) are light in weight and easy to deploy, typically use 4.5 Hz geophones, commonly only the vertical component, and/or hydrophones, may have somewhat limited recording capacity and endurance, and are typically used in active-source seismic experiments and for

Figure 5 The SIO-ONR OBSs (Jacobson *et al*. 1991, Sauter *et al*, 1990) being launched in Antarctica. The anchor serves as a collector for the CAT fluid fluxmeter (Tryon *et al.* 2001). The plumbing for the flowmeter is in the light-colored box at the right-hand end of the instrument. (Photograph by Michael Tryon, UCSD.)

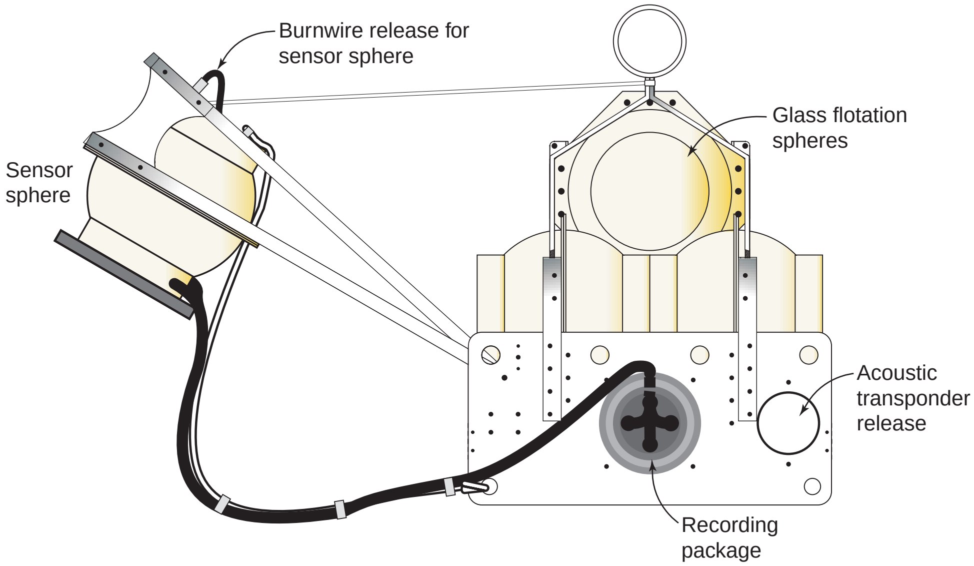

Figure 6 The LDGO-BB OBS. This is based on the Webb design in use during the past few years. The earlier version established a reputation for high reliability and was the lowest noise OBS and lightest of its time period. The main drawback of the earlier version was its limited (16-bit) dynamic range. (Figure from S. Webb, LDEO.)

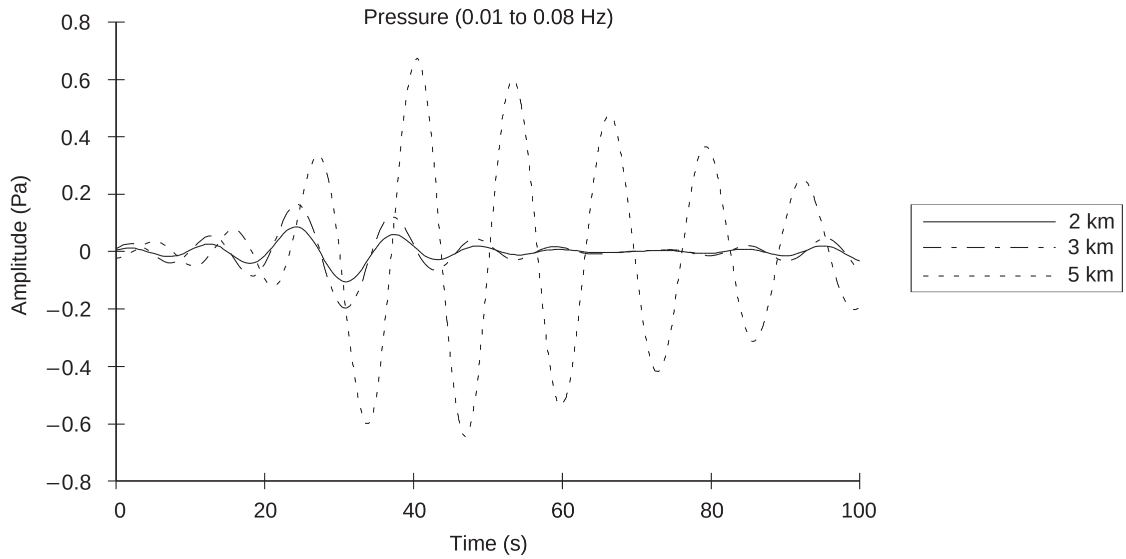

Figure 7 Synthetic seismograms of pressure at three ocean depths.

micro-earthquake studies with durations of a week to a few months. Two types (UTIG and JAMSTEC) are single-sphere instruments.

Broadband (BB) Instruments

The BB instruments (**Table 2**) provide many features of land seismic observatories, relatively high dynamic range, excellent clock stability – $< 1\,\mathrm{ms\ d^{-1}}$ drift. This class of instruments can be equipped with hydrophones useful down to a millihertz. The BB instruments are designed in two parts, the main section contains the recording package, and release and recovery aids, while the sensor package is physically separated from the main section. This configuration allows isolation from mechanical noise and and permits tuning of the mechanical resonance of the sensor–seafloor system.

Sensor Considerations

Emplacement of a sensor on the seafloor is almost always suboptimal in comparison with land stations. Instruments dropped from the sea surface can land tens of meters from the desired location. The seafloor material is almost always softer than the surficial sediments (these materials have shear velocities as low as a few tens of meters per second.

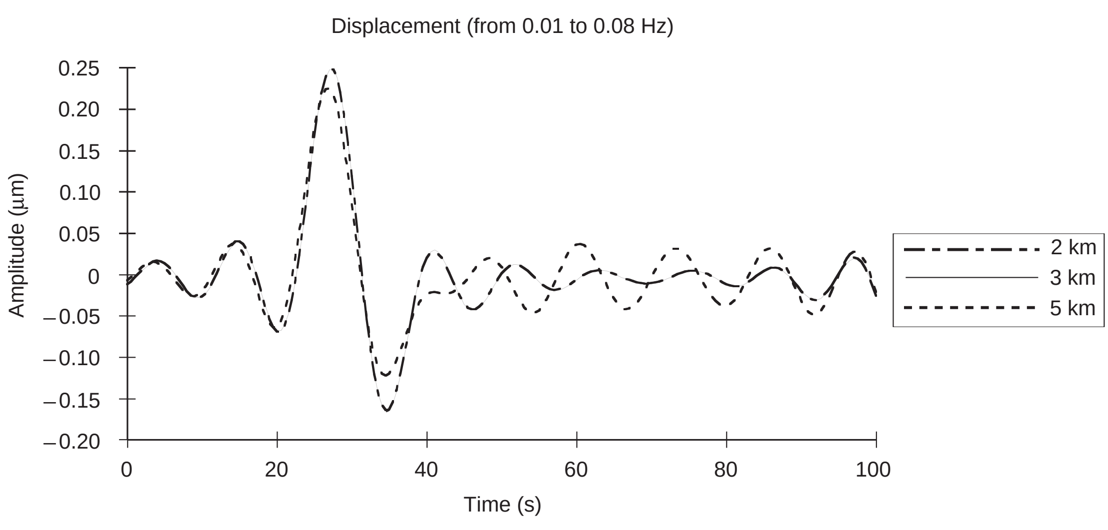

Figure 8 Synthetic seismograms of vertical motion at the same depths as **Figure 7**; note the reduction in the effects of the water column reverberations. (From Lewis and Dorman, 1998).

The sensor is thus almost always poorly coupled to the seafloor and sensor resonances can occur within the frequency range of interest for short period sensors. Fortunately, these resonances have little effect on lower frequencies. However, lower frequency sensors are affected, since a soft foundation permits tilt either in response to sediment deformation by the weight of the sensor or in response to water currents. The existing Webb instruments combat this problem by periodic releveling of the sensor gimbals. The PMD sensors have an advantage here in that the mass element is a fluid and the horizontal components self-level to within 5°.

Why not use hydrophones then? These make leveling unnecessary and are more robust mechanically. In terms of sensitivity, they are comparable to seismometers. The disadvantage of hydrophones lies in the physics of reverberation in the water layer. A pulse incident from below is reflected from the sea surface completely, and when it encounters the seafloor it is reflected to a significant degree. Since the seafloor has a higher acoustic impedance than water, the reflected pressure pulse has the same sign as the incident pulse and the signal is large. However, the seafloor motion associated with pressure pulses traveling in opposite directions is opposite in sign, so cancellation occurs. Unfortunately, the frequency range in which these reverberations are troublesome is in the low noise region. **Figures 7** and 8 show synthetic seismograms of pressure and vertical motion illustrating this effect.

See also

Mid-Ocean Ridge Seismic Structure. Seismic Structure.

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SENSORS FOR MEAN METEOROLOGY

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Introduction

Basic mean meteorological variables include the following: pressure, wind speed and direction, temperature, and humidity. These are measured at all surface stations over land and from ships and buoys at sea. Radiation (broadband solar and infrared) is also often measured, and sea state, swell, wind sea, cloud cover and type, and precipitation and its intensity and type are evaluated by an observer over the ocean. Sea surface temperature and wave height (possibly also frequency and direction of wave trains) may be measured from a buoy at sea; they are part of the set of parameters required for evaluating net surface energy flux and momentum transfer. Instruments for measuring the quantities described here have been limited to the most common and basic. Precipitation is an important meteorological variable that is measured routinely over land with rain gauges, but its direct measurement at sea is difficult because of ship motion and wind deflection by ships' superstructure and consequently it has been measured routinely over the ocean only from ferry boats. However, it can be estimated at sea by satellite techniques, as can surface wind and sea surface temperature. Satellite methods are included in this article, since they are increasing in importance and provide the only means for obtaining complete global coverage.

Pressure

Several types of aneroid barometers are in use. They depend on the compression or expansion of an