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Development and evaluations of the broadband ocean bottom seismometer (Yardbird-BB OBS) in Taiwan

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Abstract

This study focuses on developing and evaluating the broadband ocean bottom seismometer (Yardbird-BB OBS) in Taiwan. The Yardbird-BB OBS is a crucial instrument for recording seismic signals in deep-sea environments. Rigorous testing ensures optimal performance and data recording capabilities. Following assembly, the Yardbird-BB OBS undergoes a 3–6 month deployment test in the deep sea, capturing seismic signals worldwide. Data from 2016 and 2017 deployments in the Okinawa Trough analyze significant seismic events, including a magnitude 7.8 earthquake in New Zealand and a magnitude 6.3 earthquake from a North Korean nuclear test. Waveform analysis, focusing on teleseismic events and waveform quality, assesses the OBS's performance, highlighting successful automatic leveling adjustment. These high-quality recordings benefit research, aiding the study of plate tectonics, crustal age estimation, seafloor ambient noise determination, and earthquake location accuracy improvement. The study also details methods for verifying instrumental self-noise, dynamic range, digitization sensitivity, linearity error, clock drift, and data logger power consumption. Calibration procedures and evaluation methods provide insights into Yardbird-BB OBS performance characteristics, contributing to its understanding and enhancement for effective long-term underwater data recording and valuable scientific research.

Keywords Ocean bottom seismometer (OBS), Broadband, Yardbird-BB, Data logger, Earthquake

1 Introduction

Since 1991, Taiwan has progressively imported various models of OBSs with different performance capabilities from overseas (e.g., Chen et al. 1994; Liu et al. 1997; Wang et al. 1998; Wang et al. 2001; Chang et al. 2008; Lin et al. 2010). Although OBSs initially appeared to have comprehensive functionality, years of usage have revealed certain imperfections. These include the need to extend the deployment time, broaden the frequency response of seismic sensors from 4.5 Hz to below 0.01 Hz to capture tele-seismic data, and increase the instrument recovery probability, among others. Improving these aspects or adding flexible functionalities would enhance convenience during usage.

In instrument design, there are often differing perspectives between commercial company and the research institute. Ideally, instruments designed by engineers should meet the requirements of scientists. However, not all the initial instrument concepts proposed by scientists can be fully realized by a commercial company, particularly for imported equipment, as most manufacturers do not provide complete instrument design drawings. It is nearly impossible for scientists to modify the instruments themselves. If scientists want to convey their

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suggestions for instrument improvement to the original manufacturers and request design changes, they can only wait for the next generation of products to be released and then repurchase them. Consequently, the currently used instrument equipment can only be used reluctantly and lacks flexibility. Therefore, there is a definite necessity for scientists to independently develop and produce instruments.

Since 2009, the Institute of Earth Sciences, Academia Sinica (IES), has collaborated with the Taiwan Ocean Research Institute, National Applied Research Laboratories (TORI), and the Institute of Undersea Technology, National Sun Yat-sen University (IUT), to jointly develop the wideband ocean bottom seismometer (OBS) called Yardbird-20 s (Wang et al. 2011). Through numerous underwater deployment experiments, Yardbird-20 s has consistently demonstrated high stability as an instrument. Its data has been used to study regional tectonics and crustal properties (e.g., Ko et al. 2012) and develop new data processing techniques for future entry into broadband OBS preparation (Kuo et al. 2014; Kuo et al. 2015). However, Yardbird-20 s has a low-frequency cutoff of only 20 s, which can observe tele-seismic body wave but couldn't to catch surface waves. It becomes necessary to extend the frequency response of the seismic sensors to achieve a global scale of earthquake observation for improved recording of surface waves, reducing saturation problem of source determination, and more pulse-like waveforms of body waves for the purpose of picking. The developed broadband OBS, called Yardbird-BB, has undergone multiple experiments. This paper provides a detailed description of the design goals, component specifications, and calibration methods of each major component, as well as the analysis of data collected from actual deployments on the seabed to explore the research outcomes.

2 Design requirements of Yardbird-BB OBS

The primary limitation of passive source OBS lies in their power supply. Since earthquakes cannot be accurately predicted, sufficient power is necessary to extend the deployment period of OBS and collect the desired seismic data. To address this bottleneck, reducing the power consumption of the OBS itself or adopting high-performance batteries are effective methods. To minimize noise caused by seafloor currents and disturbances on the seismometers, it is recommended to separate the seismometers from the OBS platform and place them at a certain distance. The seismometers should be installed in a watertight compartment with a leveling mechanism to allow automatic adjustment of the horizontal tilt angle. The base area of the compartment should be enlarged to lower the center of gravity, and three conical supports should be added to increase the gripping force of the seismometers and enhance the quality of seismic wave detection.

The instrument's bandwidth should also meet the requirements for wideband coverage to capture seismic waves from global earthquakes for deep structural analysis. Based on these considerations, the summarized design objectives for this instrument are as follows:

- Allow deployment at depths of approximately 5000 m or more.
- Velocity-type seismometers with a sensing bandwidth of 120 s to 50 Hz, installed on a leveling mechanism with a braking device for automatic adjustment of the seismometer's leveling angle within 0.1 degree.
- Analog-to-digital converter (A/D) with a resolution of 24 bits or higher.
- Minimum sampling rate of 100 samples per second (sps).
- Capable of continuous underwater recording for a minimum of 365 days, recording three-axis seismic data along with one-axis pressure gauge data.
- The time drift of the instrument's internal clock should be within 3 s per year, correctable and adjusted using a GPS clock.
- Capable of accurately determining the instrument's underwater position using acoustic means for instrument recovery control.
- Power consumption of 0.7 watts or below to reduce the number of batteries required and weight.
- Equipped with devices such as Flash beacon, Radio beacon, orange flag, and reflective markers to facilitate instrument recovery on the sea surface.
- After the entire OBS has settled and detached from the anchor, it should float to the water surface at a speed of at least 1 m per second, reducing the time and distance required for OBS deployment and recovery.
- User-friendly interface with data format conversion capabilities, allowing recorded data to be converted into ASCII and SEED formats for ease of subsequent data processing.

Based on the above design objectives, the key facts about Yardbird-BB OBS are as follows:

- Maximum depth of 6000 m thus allowing deployment in most ocean environments with depth of no more than 5000 m.
- Three-component broadband seismic sensor with a bandwidth of 120 s to 50 Hz.

- Equipped with a freefall, self-pop up system for easy recovery via an acoustic releasing mechanism.
- Capable of temporary observation for up to 12 months.
- Includes a differential pressure gauge.
- Features a self-leveling mechanism for the seismometer.

The functional block diagram of the Yardbird-BB OBS is show in Fig. 1. To achieve power-saving functionality and reduce production costs, our team independently developed the seismometer's levellingmechanism, data logger, anchor release mechanism, and instrument platform. The detailed design of these developments was described in the following sections. Table 1 is the specifications of Yardbird-BB OBS.

3 Specifications of Yardbird-BB components

The Yardbird-BB OBS is designed for underwater deployments and uses various components and technologies to enable its recovery and data collection. Here is a summary of the key features and functionalities:

Seismometer: The Yardbird-BB OBS uses the Nanometrics Trillium Compact 120 s (TC-120 s) seismometer (http://www.nanometrics.ca). It is lightweight, consumes low power, and is designed for energy-efficient operation. While its self-noise increases at frequencies below 0.03 Hz, it does not significantly affect long-period seismic signals.

Leveling mechanism of seismometer: Due to the free-fall deployment method used for this OBS on the seafloor, and in order to adapt to various seabed conditions, ensuring that the vertical component of TC-120 s

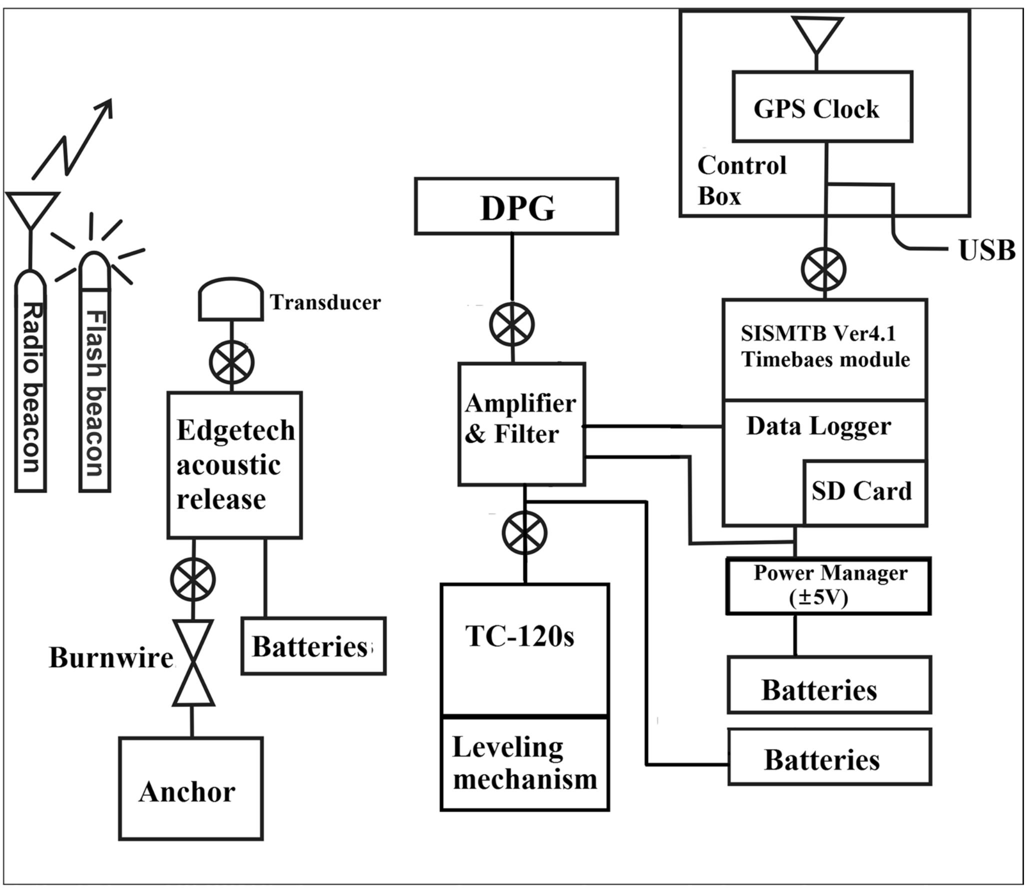

Fig. 1 The functional block diagram of Yardbird-BB OBS. The TC-120 s broadband seismometer is installed within a leveling mechanism that allows for 360-degree rotation. The leveling mechanism is automatically adjusted for tilt angle. The outputs of the TC-120 s and the differential pressure gauge (DPG) are connected to the Data Logger through an Amplifier & Filter. The Data Logger is equipped with a 64 Gb micro SD card for data storage and incorporates the SISMTB Timebase Module to ensure a clock drift of no more than 3 s within a year. Edgetech Acoustic Releases & Transducer are used for underwater instrument positioning and to release the OBS by burning the wire (Burnwire) when recovery it. Radio beacon and Flash beacon are installed to provide guidance when the OBS surfaces on the sea, facilitating instrument recovery

Table 1 The Specifications of Yardbird-BB OBS

Size (W × D × H)	0.7 × 2.3 × 09 m
Weight in air	130 kg (without Anchor),
Weight in water	39 kg (with anchor), – 17 kg (without anchor)
Pressure case	Nautilus 17" Glass sphere (with 25 kg buoyancy)
Releasing mechanism	Burn wire
Recovery control	Acoustic transponder system with communication
Recovery aids	Orange nylon flag, Radio beacon and Flash beacon
Seismometer	Trillium compact 120 s (TC-120 s, Nanometrics, CA) with an active leveling mechanism frequency range: 120 s–108 Hz Sensitivity: 754.3 V/m/s levelling works up to360 degree in tilting
Differential Pressure Gauge (DPG)	Band width: 0.01–100 Hz pressure rage: ± 7kpa
Data Logger	sampling rate: 100 Hz A/D: 32 bits (± 5 V) Time base module stability: < ± 3 s/year Media: micro SD, data format: FAT32
Power supply	116 ea. DD-size lithium battery cells
Option	Iron Anchor: Size 0.76 × 1.445 × 0.07 m, weight 66 kg

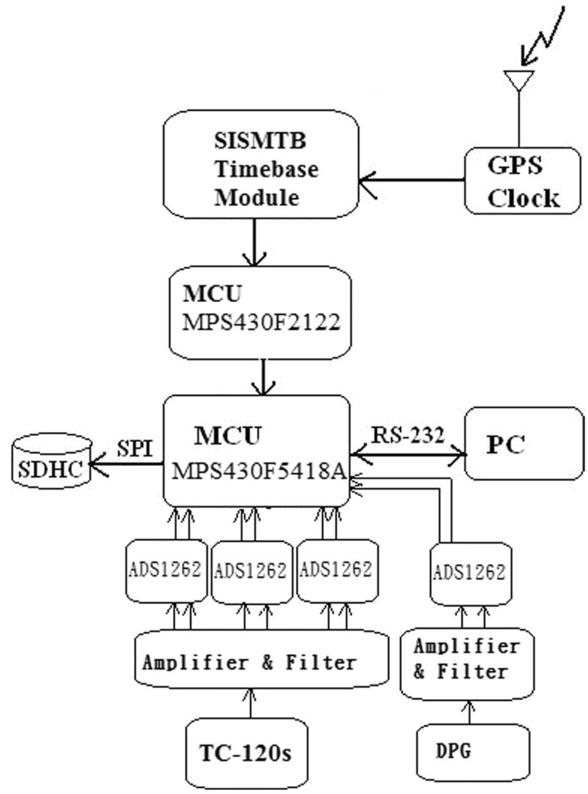

Fig. 2 The Functional Block Diagram of the Data Logger: The MPS430F2122 is primarily used to process the Seascan Clock SISMTB Ver4.1 time base module and GPS time correction, providing accurate time base signals to the data logger. Four of 32-bit A/D (ADS1262) convert the analog signals from the TC-120 s and DPG into digital format, which is then sent to the MPS430F5418A for archiving and storage on the SDHC memory card. The MPS430F5418A MCU can also be controlled externally by an PC via RS-232 communication

remains level under any circumstances, TC-120 s must be installed on a leveling mechanism and capable of automatically adjusting the horizontal tilt. While commercial products for this purpose are available, our team has chosen to develop this equipment in-house to reduce costs.

Data Logger: At present, most commercial Data Loggers have a power consumption that cannot be reduced below 0.3W, and they exhibit significant time inaccuracies when there is no GPS signal. In order to meet power-saving requirements and maintain a certain level of time accuracy, our team has independently developed our own Data Logger. This Data Logger employs four parallel-operating ADS1262 A/D chips to convert analog signals from the seismometer and DPG into digital data. The data is stored in a high-speed micro SD card. In time synchronization, the data logger utilizes the SISMTB Ver4.1 Timebases module manufactured by Seascan, Inc. [https://www.seascaninc.com/products/p/sismtb-time-base-module] to ensure accurate time information in the recorded data. The module generates frequency outputs and undergoes temperature environment tests for compensation effects, maintaining high precision. The Functional Block Diagram of the Data Logger is shown in Fig. 2.

GPS Clock Synchronization: Before deployment, an external GPS clock is used to synchronize the internal clock within the data logger. This synchronization process is repeated when the OBS is recovered to validate and correct the recorded data's time difference.

Pressure-resistant Encapsulation: The OBS components, including the data logger, batteries, and ASSY PCB, are all encapsulated inside a 17-inch VITROVEX (http://www.nautilus-gmbh.de) pressure-resistant glass sphere (called Instrument sphere). The sphere can withstand high pressures and provides buoyancy in water. It is sealed with self-dissolving adhesive tape and reinforced with stainless steel wire loops.

OBS Platform: To achieve an ascent speed of approximately 1 m/s for the OBS, it is necessary to increase buoyancy. An empty glass sphere is installed at the rear of the OBS, and a buoyant material with a density of 0.65 is added below the instrument sphere. This configuration allows the instrument to descend to the seabed in a horizontal position and during ascent, it rises vertically with the tail end facing upward to reduce resistance. Additionally, a triangular stainless steel tube is mounted at the rear to serve as a lifting point for instrument retrieval.

Weight and Anchor: The total weight of the Yardbird-BB OBS is calculated in Table 2, and the anchor weighing 58.6 kg, is positioned below the main structure side panel. The burn wire release mechanism detaches the OBS from the anchor upon activation, allowing it to float to the water surface.

OBS Release Control: The OBS release mechanism uses with the #D980709 transducer and #B980175 ASSY PCB board manufactured by ORE (http://www.edgetech.com/ore-offshore). The transducer employs binary FSK encoding and allows for underwater ranging positioning. The release is triggered by sending a command through the EdgeTech 8011 M deck unit acoustic commander.

Radio Beacon: The OBS is equipped with a radio beacon called Xeos™ XMB-11 K (http://www.seimac.com). It operates on four VHF frequencies and has an effective range of 12 km. Upon resurfacing, the beacon automatically activates and starts transmitting radio signals, facilitating swift retrieval.

Flash Beacon: The OBS also has a flash beacon called Xeos™ XMF-11 K (http://www.seimac.com). It emits flashing signals for nighttime search purposes. Like the radio beacon, it has an independent power source and activates upon resurfacing.

Table 2 Yardbird-BB OBS weight calculation

	On air (kg)	In water (kg)
Rack iron frame	8.9	7.8
PE board × 2	10.4	− 0.8
PE poles	1.6	− 0.2
Rear rack	1.2	1.0
Rear rack	0.5	0.5
Radio beacon	1.6	1.0
Flash beacon	1.7	1.0
17″ Glass ball × 2	45.6	− 50.0
Batteries	12.5	12.5
Buoyancy stuff	6.2	− 5.0
TC & gimbal	2.6	2.6
Glass ball for TC	4.0	− 4.0
Sensor Anchor	11.2	9.8
PCB & data logger	2.1	2.1
DPG	5.6	1.0
Acoustic transducer	2.5	1.7
Release	0.8	0.7
Screws	1.2	1.0
Total without anchor	120.2	− 17.4
Anchor	58.6	50.2
Total with anchor	178.8	32.8

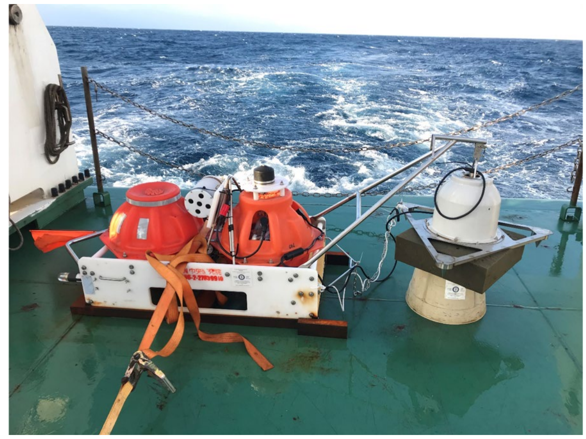

Fig. 3 A photograph of the Yardbird-BB OBS: The TC-120 s broadband seismometer is suspended in front of the instrument platform. Approximately 18–24 h after the OBS is deployed, the metal fuse wire suspending the seismometer will break, causing the seismometer to fall onto the seabed about 40 cm away from the OBS platform. This prevents vibrations caused by the impact of seabed water currents on the OBS platform from interfering with the seismometer's reception of natural seabed motion signals. The signal from the seismometer is transmitted through an underwater cable and connected to the glass instrument sphere, which contains the batteries, data logger and ASSY PCB board. Above the instrument sphere, a acoustic transducer is installed for OBS positioning and control during recovery. The DPG is installed in the center of the OBS platform to measure changes in water pressure from the seawater. Another empty glass sphere is mounted at another site of the platform to provide necessary buoyancy during OBS recovery. A Flash Beacon and an orange nylon flag bound together with a Radio Beacon are installed at the rear end of the OBS platform. When the OBS is recovery, it will be exposed above the sea surface, and the Radio Beacon will emit a specific frequency radio wave. The radio direction finder can be used to determine the direction between the OBS and the working vessel. The Flashing Beacon emits flashing signals in dim sea conditions, facilitating the retrieval operation of the OBS during nighttime

These features and technologies enable the Yardbird-BB OBS to record seismic data, resurface for retrieval, transmit radio signals, and provide accurate time information during underwater deployments. A photograph of Yardbird-BB OBS is shown in Fig. 3.

4 Evaluations methods for Yardbird BB components

To improve the performance of the OBS and mitigate potential issues such as recovery failure or incomplete data recording, it is crucial to conduct thorough testing for each component (such as the data logger, seismometer leveling mechanism, acoustic control board, internal wiring, etc.) prior to the OBS assembly. The selection of high-performance components should be done meticulously, and performance verification should be carried out during the assembly process to ensure successful recovery of the OBS after long-term underwater deployment and extraction of valuable data. In this section, a set of evaluation methods is developed for the Yardbird-BB design. Each component of the Yardbird-BB OBS undergoes performance evaluation, including self- noise level, digitization sensitivity, and linearity of the data logger, clock drift, activation time, and leveling angle of the seismometer's leveling mechanism, as well as the enable/disable/range/release functions of the acoustic control board, and power consumption. These evaluations effectively filter out components with poor performance and ensure the use of components that meet the desired specifications.

4.1 Verification method for data logger's digitization sensitivity and linearity error

The input to the data logger is a differential voltage, and what is recorded in memory is in counts. The conversion factor for physical quantities is what we refer to as digitization sensitivity. The input differential voltage has a specific range of values. To determine if there is a linear relationship, we cannot rely solely on the maximum value; we must also perform measurements at intermediate values. The data logger of Yardbird-BB OBS has four channels, namely Z, N, E, and P. The Z, N, and E channels record the output signals from the TC-120 s, with input voltage limited to ± 20 V. The P channel records the output signal from the DPG, with input voltage limited to ± 5 V. Therefore, separate processing is required when performing digitization sensitivity. The calibration procedure begins by connecting the Z, N, and E input lines in parallel to the voltage output terminal of the FLUKE726 calibrator (https://www.fluke.com/en-us/product/calibration-tools/multifunction-calibrators/fluke-726). The data logger is then activated and set to the recording mode. The calibrator is configured to output voltages of 0 V, + 5 V, + 10 V, + 15 V, + 19 V, + 19.6 V, + 19.75 V, − 5 V, − 10 V, − 15 V, − 19 V, − 19.6 V, and − 19.75 V, with each segment lasting approximately 20 s. After completion, the recording is stopped, and the SD card is removed for data conversion. The recorded values corresponding to each voltage level are averaged after subtracting the value recorded at 0 V output from the calibrator. This process yields the recorded values for each level, which are then divided by the respective input voltage values. By performing statistical averaging, the digitization sensitivity of the data logger can be determined. Multiplying this sensitivity by the difference between the voltage values at each level and the average measured values provides the linearity error of the data logger.

The calibration procedure for the P channel follows a similar approach. The P input line is connected to the FLUKE726 calibrator, which is set to output voltages of 0 V, + 1 V, + 2 V, + 3 V, + 4 V, + 4.1 V, + 4.2 V, + 4.3 V, + 4.4 V, + 4.5 V, + 4.6 V, + 4.7 V, + 4.8 V, + 4.9 V, − 1 V, − 2 V, − 3 V, − 4 V, − 4.1 V, − 4.2 V, − 4.3 V, − 4.4 V, − 4.5 V, − 4.6 V, − 4.7 V, − 4.8 V, and − 4.9 V.

Although the Data Logger's channels are named Z, N, E, and P, corresponding to the output signal of the Z, N, E components of the TC120s and the DPG, when actually deployed on the seabed, the N and E components do not align with the true North and East directions. Therefore, a more accurate practice is to rename these components as H1 and H2, respectively, when retrieving the instrument. This renaming is performed during the data format conversion process after extracting the SD card, effectively substituting N with H1 and E with H2 components.

4.2 Calibration procedures and evaluation method for instrumental self-noise and dynamic range in data loggers

To determine the smallest signal variation that a data logger can record, it is necessary to know the data logger's inherent noise level. From there, one can calculate the ratio between the minimum and maximum signals that the data logger can record. This value is referred to as the dynamic range and is typically expressed in decibels (dB). The calibration procedure is as follows:

Connect the Z + and Z−, N + and N−, E + and E−, P + and P− input lines together, then activate the data logger to enter recording mode. Record for approximately 30 s and stop recording. Retrieve the data and calculate the root mean square (RMS) value of the instrumental self-noise for each recorded channel using Eq. 1:

$$N_{RMS} = \sqrt{\frac{1}{n}(A_1^2 + A_2^2 + \cdots + A_n^2)} \tag{1}$$

where, n is the number of data points, and A_1–A_n are the noise amplitudes of the 1st to nth points.

Although the signals from Z, N, and E have been attenuated by a factor of 4 through the amplifier, it does not affect the calculation result of self-noise.

After obtaining the RMS value of the instrumental self-noise for each channel according to Eq. (2), take $\log_2$ to determine the number of bits representing the background signal noise for each channel.

$$dB_{NRMS} = \log_2(N_{RMS}) \tag{2}$$

The dynamic range of a data logger is defined as the ratio between the minimum signal N_{RMS} and the maximum signal count that the data logger can record. The calculation formula is as follows:

$$D = 20\log\left(\frac{Sensitivity \times V_{MAX}}{N_{RMS}}\right) \tag{3}$$

where the maximum voltage (Vmax) for the P channel is 5 V, and for the N, E, and Z channels is 20 V.

4.3 Method for clock drift evaluation of the data logger

After the data logger starts recording, the GPS time base signal with PPS (pulse per second), PPM (plus per minute), and PPH (plus per hour) is connected to the signal input terminal. After a period of 3 to 5 days, following the standard operating procedure, the data recording is concluded. The SeisGram2K70 software is then used to examine the time displayed by the data logger when PPM or PPH occurs after the 3 to 5-day period. This analysis helps determine the clock drift.

4.4 Method for evaluating the power consumption of the data logger

In order to determine whether the data logger meets the design requirements and to ascertain how many batteries need to be installed within the deployment period to supply power, a methodology for evaluating the power consumption must be in place.

The data logger requires a power supply of DC + 5 V and − 5 V, with the Yardbird-BB utilizing a 3.6 V lithium battery as the primary power source. To simplify the battery power supply, the Yardbird-BB's power system consists of four 3.6 V lithium batteries connected in series to provide a voltage of 14.4 V. This voltage is then converted using a voltage converter to generate the + 5 V and − 5 V power supply. The method for evaluating the power consumption of the data logger involves connecting three DC Ammeters in series. The first Ammeter is connected between the positive terminal of the 14.4 V power supply and the positive input terminal of the ± 5 V power converter. The second Ammeter is connected between the positive terminal of the + 5 V power converter and the positive voltage input terminal of the data logger. The third Ammeter is connected between the negative terminal of the − 5 V power converter and the negative voltage input terminal of the data logger. The Ammeters are used to measure the maximum current and average current during both the instrument startup and data recording phases.

4.5 Method and procedure for calibrating the tilt angle of a seismometer's leveling mechanism

The TC-120 s seismic sensor is installed on a leveling mechanism with two dynamic rotating axes, enclosed within a 7-inch glass sphere (https://worldwide.espacenet.com/patent/search/family/050345506/publication/TW201403109A?q=pn%3DTW201403109). The leveling mechanism incorporates two-axis Tilters to sense the horizontal tilt angle. An MCU within the mechanism compares the tilt angle, and if it exceeds 0.5 degrees, it drives the motor to perform the balancing action. During testing, the first step is to adjust the center point of the seismic sensor's leveling mechanism. Connect the PC to the USB-TTL232 interface, with one end of the USB cable connected to the TC-120 s leveling control board. Connect the red wire to the V point (VCC) and the black wire to the G point (GND). Connect the yellow wire to the T point (TX) and the orange wire to the R point (RX) on the yellow-orange pin terminals. Open the program YBB_Balancer_tools.exe and click on "Connect" to establish the connection. Adjust the TC-120 s to the horizontal position and click on "Zero Offset" to reset the zero point. Click "Stop" to halt the program and complete the zeroing process. Disconnect the cables. When the G and 3 pins on the TC-120 s leveling control board are shorted, the TC-120 s sphere is powered, and immediate

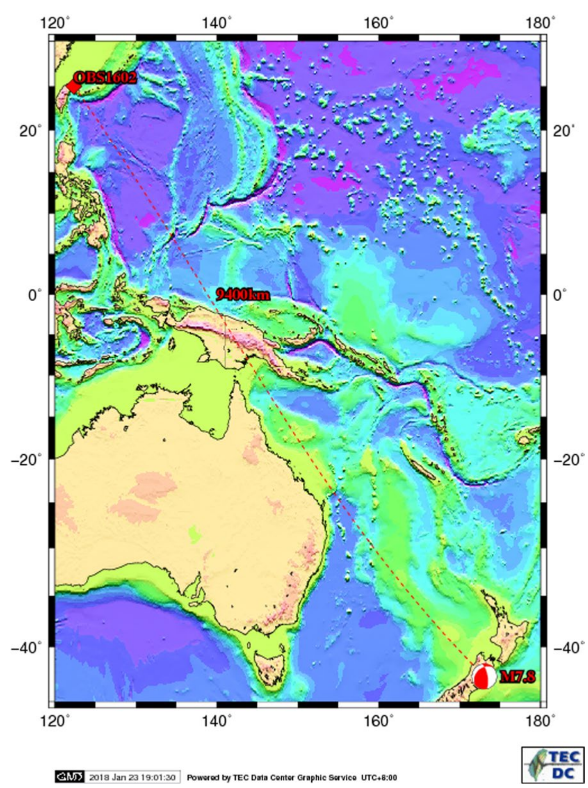

Fig. 4 The deployment location of the OBS1601station (25.0188°N, 122.3210°E, depth 1119 m) and the corresponding location map are presented for the magnitude 7.8 earthquake (42.757°S, 173.077°E, depth 23 km) that occurred on 2016/11/13 11:02:06 (UTC)

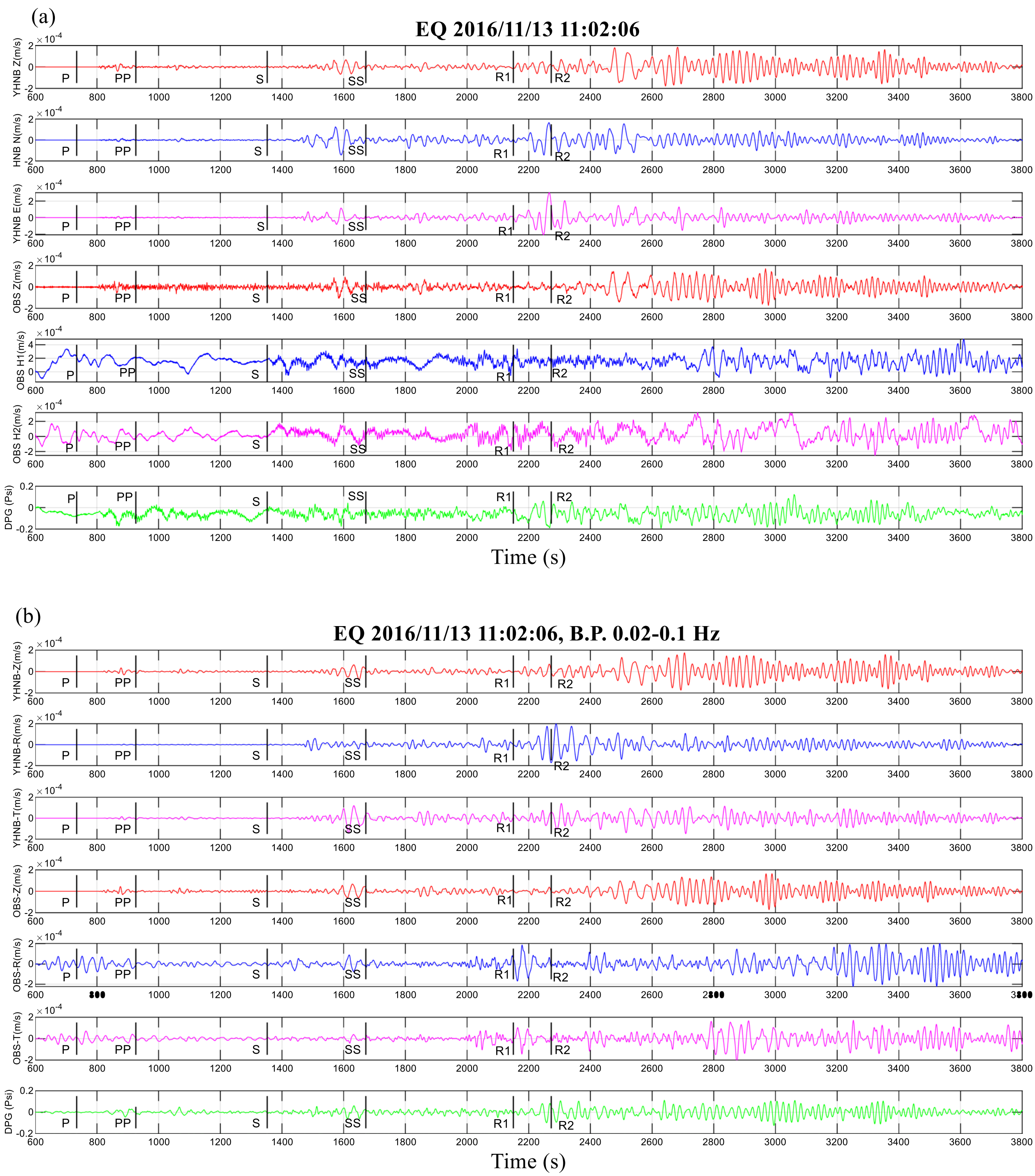

Fig. 5 The waveform records for YHNB and OBS1601 stations during the seismic event that occurred on 2016-11-13 11:02:06 (UTC), located at 42.757°S, 173.077°E, with a depth of 23 km and a magnitude of 7.8. **a** Represents the raw waveform records. From top to bottom, the traces are YHNB Z (red), YHNB N (blue), YHNB E (black), OBS Z (red), OBS H1 (blue), OBS H2 (black), and DPG (green). 600 is the time after 600 s when the earthquake occurred. **b** Shows the waveforms after applying a 0.02–0.1 Hz bandpass filter. From top to bottom, the traces are YHNB Z (red), YHNB Radial component (blue), YHNB Tangential component (black), OBS Z (red), OBS Radial component (blue), OBS Tangential component (black), and DPG (green). Where the P, PP, S, SS are the theoretical arrival times, and the intervals R1 and R2 represent the theoretical travel times of Rayleigh waves according to IASP91 (Kennett et al. 1995)

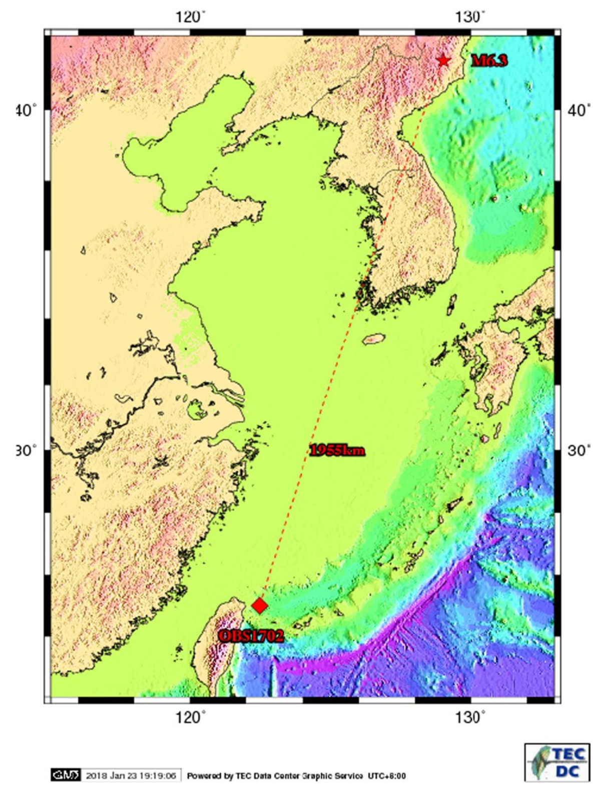

Fig. 6 The deployment location of the OBS 1703 station (122.4523°N, 24.9999°E, Depth 1415 m) and the corresponding location map are shown for the magnitude 6.3 earthquake resulting from North Korea's nuclear bomb explosion test (location: 41.343°N, 129.036°E) on 2017/09/03 03:30:01 (UTC)

balancing action can be performed. Remove the shorting pin to return to deployment mode.

Observe whether the TC-120 s performs balancing actions within 8 h of being powered on, and check if the bubble level of the TC-120 s remains within the circle. Additionally, ensure that the TC's power consumption is within 18 mA.

4.6 Method for functional evaluations of the acoustic transponder and acoustic control board

The acoustic control board features functions such as Enable, Disable, Rang, Release1, Release2, Option1, etc. To test its functionality, it is necessary to select a water area with sufficient distance and no intermediate obstacles. The evaluations method can be referenced as Lin et al. 2019.

5 Preliminary results of the instrument development

In addition to conducting performance evaluations on individual components prior to assembly, the assembled instrument undergoes a deep-sea deployment test for duration of 3–6 months to record seismic signals from around the world. This study analyzes data recorded during deployments in the Okinawa Trough in 2016 and 2017 as examples. Figure 4 illustrates the location in relation to the magnitude 7.8 earthquake that occurred in New Zealand on 2016/11/13 at 11:02:56, with a hypocenter located at 42.757°S, 173.077°E, and a depth of 23 km. The earthquake waveform is depicted in Fig. 5. The OBS1601 station was situated at25.0188°N, 122.3210°E, depth 1119 m, a distance of 9400 km from the event. Based on the waveform data, it is evident that, after undergoing 0.02–0.1 Hz band-pass filtering processing, the recorded waveforms by the OBS can clearly distinguish various seismic phases and waveform qualities. This indicates the successful automatic leveling adjustment of the seismic sensor. Another significant event analyzed is the magnitude 6.3 earthquake resulting from a nuclear test conducted by North Korea on 2017/09/03 03:30:01. The explosion occurred at a location with coordinates 41.343°N, 129.036°E, and a depth of 0 km. The OBS1702 station was located at 25.0203N, 122.4801E far from the event 1955 km away. Figure 6 shows the corresponding geographic location, and Fig. 7a displays the original seismic waveforms, including those from the YHNB station. Prior to any data processing, the P-wave recorded by the OBS is not distinctly visible. However, after applying a 0.5–1.2 Hz band-pass filter, the P-wave's position becomes evident. As the seismic source was explosive, no S-waves were generated. Despite the considerable distance from the OBS, the Yardbird-BB OBS recorded high-quality data attributed to the substantial magnitude of the earthquakes, highlighting its ability to capture tele-seismic signals.

The recorded data from these OBS deployments have various research applications, such as studying plate tectonics and estimating crustal ages (e.g., Kuo et al. 2009), determining seafloor ambient noise (e.g., Webb 1988, 2002; Collins et al. 2002; Lin et al. 2010), accurately estimating seismic wave velocity structures offshore of Taiwan (Chou et al. 2006), and improving earthquake location accuracy. These applications highlight the potential of Yardbird-BB OBS data for further analysis.

6 Conclusion

The development and evaluations of the Broadband OBS (Yardbird-BB) have been successfully conducted. Through rigorous testing and performance evaluations of individual components, the OBS assembly process ensures the selection of high-performance components and verifies their functionality. This minimizes the risk of failure to recover data or incomplete data recording during underwater deployments.

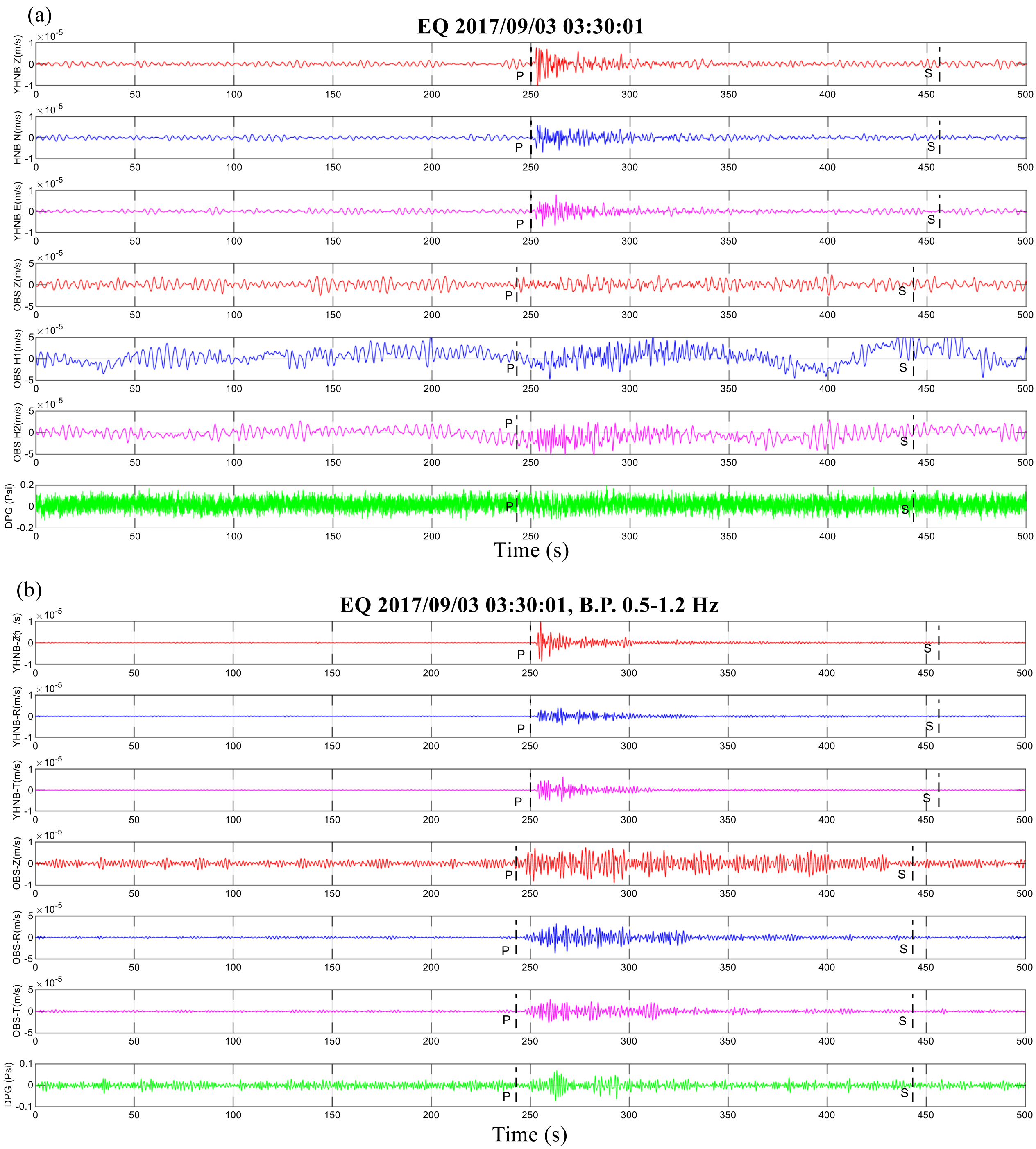

Fig. 7 The waveform records for YHNB and OBS1703 stations during the seismic event equivalent to a magnitude 6.3 North Korean nuclear test, which occurred on 2017/09/03 at 03:30:01 (UTC), located at 41.343°S, 129.036°E. **a** Represents the raw waveform records. From top to bottom, the traces are YHNB Z (red), YHNB N (blue), YHNB E (black), OBS Z (red), OBS H1 (blue), OBS H2 (black), and DPG (green). 0 is the time when the earthquake occurred. **b** Shows the waveforms after applying a 0.5–1.2 Hz bandpass filter. Where the P, S are based on the theoretical arrival times according to IASP91

The OBSs have undergone successful deployment tests in the deep sea, recording seismic signals from various sources worldwide. The analysis of recorded data from deployments in the Okinawa Trough has demonstrated the OBS's capability to capture high-quality waveforms, including various seismic phases and waveform characteristics. This indicates the effective automatic leveling adjustment of the seismometer.

The recorded data from OBS deployments have significant applications in various research fields, including plate tectonics, crustal age estimation, seafloor ambient noise analysis, and improved earthquake location accuracy. These applications highlight the potential of the Yardbird-BB OBS data for further analysis and scientific investigations.

Additionally, the evaluations have encompassed important performance characteristics of the OBSs. Methods for verifying instrumental self-noise, dynamic range, digitization sensitivity, linearity error, clock drift, and power consumption have been outlined. These evaluation methods provide valuable insights into the OBS's performance and ensure its accurate and reliable operation.

Developing instruments in-house not only allows for a thorough understanding of their performance and cost savings but also provides an opportunity to gain valuable knowledge and experience in instrument development. During the execution of seabed observation missions, it is also possible to modify or enhance the instrument's functionality, for example, by attaching an Aquadopp current meter to simultaneously observe seafloor currents (Lin et al. 2019).

Overall, the comprehensive development and evaluations conducted on the Yardbird-BB OBS contribute to its advancement as a crucial instrument for underwater seismic signal recording. The findings and methods presented in this study enhance the understanding of the OBS's capabilities, enabling its successful deployment for long-term data recording and supporting further scientific research in marine seismology.

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Author contributions
C-rL: Instrument specification formulation, instrument circuit design, instrument testing and analysis, data collection and analysis, article writing. Y-CL: Data logger design, human-machine interface programming. C-cW: Instrument specification formulation and development project management. B-YK: Instrument specification and experiment planning. H-HC: Anchor release mechanism design and engineering management. J-pJ: Instrument platform mechanism design. P-cC: Instrument operation control program design. H-kC: Instrument assembly and testing. F-SL: Instrument assembly and testing. K-HC: Instrument assembly and testing.

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Data availability
All data was archived in the IES Data Management Center (DMC). If anyone wants this data, they can request it from the IES DMC.

Declarations

Competing interests
The authors declared that they do not have any competing interests.

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