Development and operation of ICT seafloor cable seismic and tsunami observation system in the source region of the Tohoku-oki Earthquake

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Abstract

A seafloor-cable seismic and tsunami observation system is ideal for marine geophysical observation because the data can be obtained in real-time. We have developed a new compact seafloor cable seismic and tsunami observation system using Information and Communication Technology (ICT) since 2005. Our new system secures reliability by using Transmission Control Protocol/Internet Protocol technology and provides observational flexibility via observation nodes with a software-based system using up-to-date electronics technology. These features contribute to cost reduction and production sustainability. The system was installed on the Pacific Ocean floor off Sanriku, northeast Japan, in September 2015, in the source area of the 2011 Tohoku-oki earthquake. Our purpose is to better monitor seismic activity and to observe tsunami activity through spatially dense observation. The obtained high quality seismic and pressure data are stored continuously by the new system.

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Key Points:

- We developed a seafloor-cable seismic and tsunami observation system using Internet Technology for data collection and system control.
- Reliability is secured by using a redundant system which is easily constructed by using the commercially available internet technology.
- The system with three observation nodes and a total length 105 km was deployed in September 2015 and collected data immediately.

Abstract

A seafloor-cable seismic and tsunami observation system is ideal for marine geophysical observation because the data can be obtained in real-time. We have developed a new compact seafloor cable seismic and tsunami observation system using Information and Communication Technology (ICT) since 2005. Our new system secures reliability by using Transmission Control Protocol/Internet Protocol technology and provides observational flexibility via observation nodes with a software-based system using up-to-date electronics technology. These features contribute to cost reduction and production sustainability. The system was installed on the Pacific Ocean floor off Sanriku, northeast Japan, in September 2015, in the source area of the 2011 Tohoku-oki earthquake. Our purpose is to better monitor seismic activity and to observe tsunami activity through spatially dense observation. The obtained high quality seismic and pressure data are stored continuously by the new system.

Plain Language Summary

Large magnitude earthquakes and great tsunami are significant hazards in marine subduction zones. A cable seafloor observation system is essential for research and mitigation of such hazards because it can provide observation in real-time. We have developed a new compact cable seismic and tsunami observation system to increase the number of observation stations, and we introduce Internet and Communication Technology (ICT) to allow for this objective. ICT also provides the flexibility to monitor the system and change observational parameters after deployment. In 2015, our ICT cable seismic and tsunami observation system was deployed in the source region of the 2011 Tohoku-oki earthquake and data are being gathered continuously.

1 Introduction

Many destructive earthquakes have occurred at plate boundaries around Japan due to the subduction of oceanic plates, thus observation of seismic waves and tsunami on the sea floor is essential for disaster mitigation. A seafloor-cable system is a powerful tool for the study of plate subduction and earthquake generation because it performs in real-time and allows long-term sea-based observation. Therefore, seafloor-cable systems with seismometers and tsunami-meters were developed based on submarine telecommunication cable system technology, and have been used for the past 25 years around Japan (Kanazawa et al., 1997). A large-scale cable observation system with telecommunication technology (S-net) was recently deployed off northeast Japan (Mochizuki et al., 2017). A cable system with Underwater Mateable Connectors (UMCs) for seafloor sensors was also installed in the Nankai Trough (Kaneda et al., 2015; Kawaguchi et al., 2015). In Canada, cabled ocean observatories with diverse instruments were deployed (Barnes et al., 2013). Cabled array of instruments was also installed off the coast of Oregon (Smith et al., 2018). For detailed monitoring, however, a network of seismometers and tsunami-gauges distributed at high spatial density is required. Aside from the need for higher density networks, weaknesses in existing systems have become apparent: they lack sufficient flexibility of measurements after installation (Kanazawa et al., 2009), and they become more difficult to maintain as telecommunications technology advances rapidly and older parts become increasingly difficult to find.

A next generation system, called the Ocean Bottom Cable Seismometer (OBCS) system, was introduced in 2010 which used Information and Communication Technologies (ICT), i.e., Internet Protocol (IP) on the seafloor. Observation nodes (ON) of the OBCS system were downsized by introducing software which controls the system and processes the observed data. Reliability in the system was assured by redundancy, which is easily implemented using the ICT (Kanazawa et al., 2006, Yamazaki et al., 2012). The OBCS system was designed for low-cost production and installation. A smaller ON led to lower installation costs because sufficiently small ONs may be installed without cable ships. The OBCS system has dual communications capabilities: ring configuration and doubled route configuration, which are implemented as a double ring network on a single seafloor cable. (Yamazaki et al., 2012; Shinohara et al., 2014). Ethernet, the de-facto standard in ICT, is used for data transmission and monitoring of the system. The practical OBCS system was produced and deployed in the Japan Sea (Shinohara et al., 2014). It was considered a preliminary implementation because it included seismometers alone as scientific sensors and had minimum ICT functions. Expansion of the system was anticipated.

2 Development of OBCST system

We started development on an improved version of the OBCS system in 2012 that would include a tsunami-meter, and called it the Ocean Bottom Cable Seismometer and Tsunami-meter (OBCST) system (Shinohara et al., 2014; Shinohara et al., 2016a; Shinohara et al., 2016b). For the seismometers, we chose conventional force balance accelerometers which are identical to those on the OBCS system. For the tsunami meter, we chose a high-precision pressure gauge that uses a quartz crystal resonator whose frequency of oscillation varies with changes in pressure (Series 8B, Paroscientific Inc.). The control unit has a micro-processor (SH-4, Renesas Electronics Corp.) and interfaces with the digitizer for the seismometers using a Field Programmable Gate Array (FPGA). The pressure gauge senses changes in pressure using frequency of crystal oscillation. The frequency of the output signal from the pressure gauge is measured by a counting unit programmed on the FGPA. The operating system is Linux. Analog signals from the three accelerometers on a seismometer are synchronously digitized by sigma-delta A/D converters with a resolution of 24 bits and a sampling rate of 1 kHz. A time window of 1 ms is used for counting the pulses of the output signal from the pressure gauge which has a measurement resolution of <1 mm. A system block diagram of the ON of the OBCST system is shown in Figure 1.

The OBCST system implements a standard TCP/IP protocol with a speed of 1 Gbps for data transmission, system control, and system monitoring. High speed data transmission allows us to collect larger amounts of data. We used Wavelength Division Multiplexing (WDM) technology to reduce the number of optical-electro conversion modules and optical fibers. Because precision timing is critical for seismic observation, a clock signal with an accuracy of $<10^{-8}$ is delivered through a dedicated fiber to all ONs from a GPS receiver on the landing station. Precision timing is also required for the pressure gauges, which use the delivered clock signal to obtain an accurate time window for counting the pulses of the output signal. When the TCP/IP system is unavailable, the lines for clock delivery are also used for communication between the Linux system on the ONs and the landing station. If the delivery of the reference clock from the landing station have a problem, an atomic clock module with an accuracy of $< 10^{-8}$ is used instead. In addition, an IEEE-1588 standard (Precision Time Protocol) is implemented for the OBCST system to synchronize the real-time clock on the ONs to the land-based system clock driven by GPS through a TCP/IP protocol. We evaluated the clock accuracy of the implemented IEEE-

1588 (Shinohara et al., 2016a), and found a timing error through the switches of < 300 ns (Figure 2).

We produced two types of ONs for the OBCST system: Type FA and Type FB. Each type has three orthogonal accelerometers installed. The Type FA ON is equipped with a pressure gauge housed inside a canister. The Type FB ON lacks an internal pressure-gauge but has an external port for attaching an additional observation sensor. Communication and power for additional sensors connected through the external port are provided using Power over Ethernet (PoE) technology. PoE can provide ~13W of electrical power to the external sensor and Ethernet communication at 10 Mbps. Implementation of PoE is not difficult due to the adoption of TCP/IP technology for the system. Because a UMC (Underwater Mateable Connector) is used for the external port, external sensors can be replaced even after installation of the cable system. For both types of ONs, four electric lines must penetrate the pressure capsule. Our capsule has no connector, so we developed feed-through technology for the four metal conductors. The capsule for the ON has diameter of 26 cm and length of about 1.3 m (Figure 3). We selected the smallest size standard canister available for tele-communications seafloor cable systems for the pressure vessel. The choice of a small size canister reduces installation cost.

3 Installation of OBCST system to source region of Tohoku-oki Earthquake

A first-generation seismic and tsunami observation system, using optical fiber, was installed on the seafloor by the Earthquake Research Institute (ERI) of the University of Tokyo, in 1996 . This seafloor cable system was based on available telecommunications technology, and was able to continuously observe seismic waves and tsunamis in real-time. The system was installed in the source region of the 2011 Tohoku-oki earthquake which had a hypocenter located the below a landward slope of the Japan Trench. For about 30 minutes from the mainshock, the system continued to transmit seismic wave and tsunami data to ERI, until its landing station was damaged by the tsunami. Data from the seafloor system were essential for accurately estimating source faults in the area, and for evaluating the rupture process of the 2011 event (Fujii et al., 2011; Maeda et al., 2011).

The indispensable nature of real time observation on the seafloor led to the decision to restore the existing system and deploy an OBCST system for additional observation and/or replacement of the existing system addirionally. The older Sanriku cable system was restored in 2014 with the rebuilding of the landing station and reproduction of receiving units in the landing station. The OBCST system has a total cable length of 105 km and three ONs with 30 or 40 km spacing. The two ONs nearest shore are type FA, and one farthest from shore ON is Type FB. A precise pressure gauge with digital output was attached to the PoE interface on the Type FB ON at the deployment of the cable system so that all ONs had both three-component accelerometers and a pressure gauge as a tsunami-meter. A seafloor route for the new OBCST was selected with reference to the existing cable system and plans for S-net deployment. Results of a route survey in 2013 were also considered.

The OBCST system shares the landing station with the older cable system. Because one side of the cable is landed, the Ethernet channel is turned at the seaward end of the cable to make a ring configuration, from the perspective of network topology (Figure 4). A single fiber is used for each Ethernet channel by using WDM technology. The seafloor cable has six fibers. Because a fiber pair is needed for a ring configuration, we have two Ethernet channels and one clock delivery system. The clock module can receive timing information from either side. At the landing station, the data are stored in a large disk unit. Collected data are decimated at the landing station and transmitted through a land-based network for data distribution. System monitoring and control are performed from ERI. Collection of seismic and tsunami data began immediately with the deployment of the system in September, 2015 (Figure 5). The system was deployed by using a commercial telecommunication cable ship. In the region where the water depth is less than 1,000 meters, the seafloor cable and the ON (YOB1) were simultaneously buried with a depth of 1 m from seafloor during cable deployment. Positions of the stations are summarized in Table 1. After the installation of the OBCST, a Remote Operated Vehicle (ROV) dived to the seafloor at YOB3 where the Type FB ON was installed and confirmed that the UMC can be accessed on the seafloor (Figure 6).

4 Observed data from OBCST system

Seismic data from the OBCST system off Sanriku allow us to study seismic noise and calculate the spectrum of the ambient seismic noise. Spectra of each seismometers are calculated with a time window of about 262 seconds from seismic records of horizontal component just after the installation and is averaged using smoothing frequency band of 0.085 Hz. We found that the noise levels at the OBCST system are low at frequencies > 2 Hz and < 0.1 Hz (Figure 7). This level of ambient seismic noise is close to system noise level, and compares to similar noise levels for the older cable system off Sanriku. The buried ON below the seafloor (YOB1) has lower noise environment. It is known that burial of the sensor package is effective for seismological noise reduction (Sutton et al., 1981; Stephen et al., 2003; Shinohara et al., 2014). As seismic records are continuously recorded since the installation of the system, the long-term variation of seismic noise can be estimated. The seismic noise models were estimated by using the method of McNamara and Boaz (2005) from records for period of three months (Figure 8). It is found that the seismic noises are stable temporally. Although a large variation of spectrum levels for frequency of > 1 Hz by earthquakes are clearly seen, seismic noise levels at this frequency band seem to be stable. On the other hands, large temporal variations in levels for periods around a few seconds are recognized as changes of amplitude of microseisms. Reflecting a low noise environment, a number of earthquakes were clearly recorded by the OBCST system (Figure 9).

The high precision pressure gauges in the OBCST systems are crystal oscillator-type sensors that are temperature sensitive, so they also record temperature, making it possible to compare the temperature fluctuations at the seafloor sensors with those at the buried sensor (Figure 10). The seafloor sensors show small changes in temperature which may be related to changes in seawater temperature near the seafloor, while the buried sensor shows little temperature fluctuation. We also compared data for tidal changes recorded by the pressure gauges. The sensitivity of the buried pressure gauge is comparable to that of the seafloor gauges. The pressure gauges have ambient noise of less than 1 hPa, which corresponds to a change of water height of less than 1 cm. An event with a magnitude of 7.4 occurred off Fukushima on November 22nd, 2016, and generated a moderate tsunami (Figure 11). The cabled systems clearly observed the tsunami, and the collected data contributed to the estimation of a focal solution (Gusman et al., 2017). According to the analysis of Gusman et al (2017), the burial does not affect a sensibility of pressure gauge.

Temperatures at the semiconductor modules (e.g. CPU) and optical modules are continuously monitored to check system status. For example, the CPU and integrated circuits on the ON remain at low temperature (< 30 °C) and stable. The buried ON (YOB1) shows a larger temperature variation: the temperature rises a few degrees in winter. Since YOB1 is closest to land, there is a possibility that seasonal land temperature changes affect it.

An ON canister may rotate due to its cylindrical shape. Because the accelerometers on the ONs detect gravity, rotation of the canister can be estimated. We calculated roll angles of the ONs, and found that the canisters did rotate due to ground motions during local earthquakes (Figure 12), however the rotating angle was < 0.1 °.

5 Conclusions

We developed an OBCST system and installed it off Tohoku, northeast Japan. A new feature of our system is the application of ICT technology, which allows it to be more compact and less expensive. IP access and an upgrade of software in the system are also enabled. The OBCST has other new features: Giga-bit Ethernet, IEEE1588, WDM, and PoE. System reliability is achieved through redundancy, which is easily implemented using the ICT. ONs on the seafloor can be accessed through TCP/IP from land. CPU and FPGAs are implemented on the ONs which allow the measurement parameters of the sensors to be modified, and the firmware and software on the ONs to be upgraded after deployment. We installed the OBCST system in September 2015 The system has three ONs and is 105 km long. Two of the ONs have a built-in tsunami-meter, and the third has an external port to which a tsunami gauge was connected as an external sensor during deployment. The data from each ON are sent to our institute and data distribution center via a landing station using TCP/IP protocol. The data are also stored at the landing station. Seismic data from the OBCST shows that noise levels are low enough to assure meaningful seismic observation. In addition, the buried ON below the seafloor has the lowest noise environment. Water pressures are simultaneously observed by high-precision pressure gauges with a resolution of < 1 hPa, which corresponds to a change of water height of < 1 cm, and data from all the sensors are consistent. In November 2016, a moderate local tsunami was observed by the system.

Acknowledgments

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Figure 1. System block diagram of Observation Node (ON) of the developed OBCST system. Microprocessor controls all function of the ON. The Ethernet Switch is formed on a Field Programmable Gate Array (FPGA) and Power over Ethernet (PoE) can be implemented. The PoE interface can supply an electric power of approximately 12 W to additional devices. Interfaces to the Analog to Digital converter for seismic sensors and counting unit for pressure gauge are also configured on a FPGA.

Figure 2 Accuracy measurement for IEEE-1588 synchronization. IEEE-1588 (Precision Time Protocol, PTP) is implemented in the OBCST system for possibility to synchronize a real-time clock in the ON to a land-based system clock driven by GPS through TCP/IP protocol. We evaluated clock accuracy of implemented IEEE-1588, and found that an error of timing is less than 300 ns through the network switches.

Figure 3. Photograph of observation nodes of the OBCST system. Pressure vessel has a diameter of 26 cm and a length of about 1.3 m. The deployed system has two types of nodes: (1) node type FA has accelerometers and a pressure gauge and (2) node type FB has accelerometers and a PoE interface through Underwater Mateable Connector (UMC). Lower left: Type FB has a frame structure for easy access to a PoE port.

Figure 4. Network configuration for the deployed OBCST. Redundancy of communication is designed into the system to increase reliability. Precise time is delivered from the GPS clock at the landing station. Each observation node (ON) has four Ethernet ports. Two VPNs on land are

configured to transmit the data from the seafloor and to monitor and control the ONs. O/E: Optical-Electro module. VPN: Vertical Private Network.

Figure 5. Location of OBCST system installed in 2015 and previously deployed cable system from 1996. Squares and red line indicate position of observation nodes and cable route, respectively, for the OBCST system. Circles show seismometers and tsunami-meters in older system. Colored circles mark epicenters during 2018 determined by the Japan Meteorological Agency. The landing station is common to both cable systems.

Figure 6. Photograph of an observation node of Type FB on seafloor (YOB3). Remote Operated Vehicle (ROV) dived to seafloor on October 11, 2016. The YOB3 is the furthest ON from a coast where a water depth is about 1,570m. We had connected a pressure gauge with digital output to the PoE interface at the deployment. The ROV had being watched the ON on seafloor for inspection. It is difficult to bury the Type FB ON below seafloor because the ON has a frame.

Figure 7. Ambient noise power spectra of the OBCST system. Power spectra estimated using approximately 262 s records with a smoothing band of 0.085 Hz are plotted. The high noise model and low noise model of Peterson (1993) are also shown. The buried observation node has a low noise environment around a few seconds. Ambient noise levels of the OBCST system are comparable to that of the earlier system.

Figure 8. The spectrum from records of YOB2. Z component which is parallel to an axis of cylindrical pressure capsule corresponds to a horizontal component. The seismic noise models were estimated by using the probability density function of the power spectral density [McNamara and Boaz, 2005]. The data from January 1st to April 4th, 2018 were used for the estimation. Seismic noise around a few seconds have a large variation of levels.

Figure 9. Example of seismograms of an earthquake recorded by both the OBCST system and the existing system. See Fig. 5 for positions of the OBCST system and the existing system installed in 1996. Three components are shown without a filter. Note that orthogonal three components of X, Y and Z do not correspond to vertical component and two horizontal components. The origin time of the event was 06:10:50.6, February 15th 2019. A focal depth and magnitude are approximately 50 km and 3.0 by Japan Meteorological Agency. Epicenter was positioned below a deployment area of the cable systems.

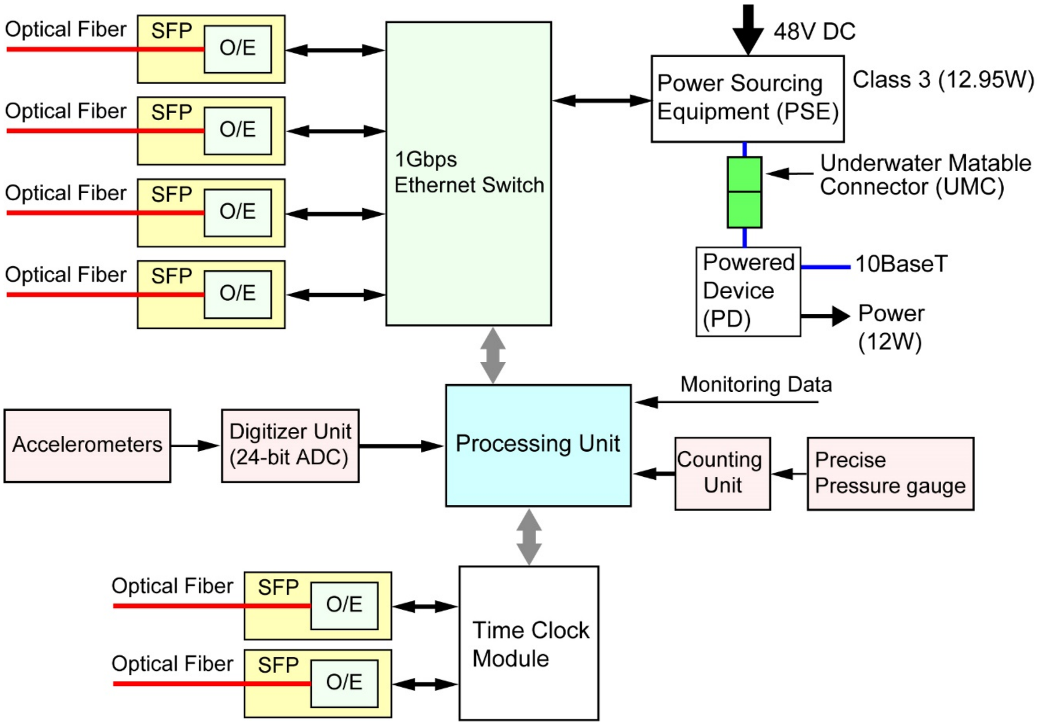
Figure 10. Records of pressure (upper) and temperature (lower) from high precision pressure gauge in each ON just after the deployment. Tide is clearly recorded at all pressure gauges. We found that temperature of the buried node (YOB1) does not have small changes. Other sensors on the seafloor have small variation of temperature due to sea water temperature changes. Water pressures are simultaneously observed by both the existing system and OBCST. It is also found that a buried pressure gauge seems to have a proper sensibility. sf: Seafloor.

Figure 11. Tsunami records from pressure gauges of the OBCST system and the earlier system installed in 1996. A recorded tsunami was generated by a large earthquake on 21st November 2016 at 20:59:47 UTC, offshore Fukushima prefecture. Japan Meteorological Agency determined a focal depth of 25 km and a magnitude of 7.4. Obtained tsunami waveforms gave

the fault slip distribution for the event. Note that the amplitude of the tsunami recorded by the buried pressure gauge (YOB1) is comparable to that recorded by pressure gauges on seafloor.

Figure 12. Rotation of the ONs calculated from accelerometer data. The pressure vessel has cylindrical shape and is not fixed on seafloor. Just after the deployment, large rotations around the axes were noted. Movements were sometimes rapid, corresponding to earthquake occurrences. However rotating angles were $< 0.1°$.

Table 1. Coordinates (WGS 84) of the Observation Nodes for the OBCST system installed in 2015. mbsl: meters below sea level.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SFP
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SFP
O/E
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Optical Fiber
SFP
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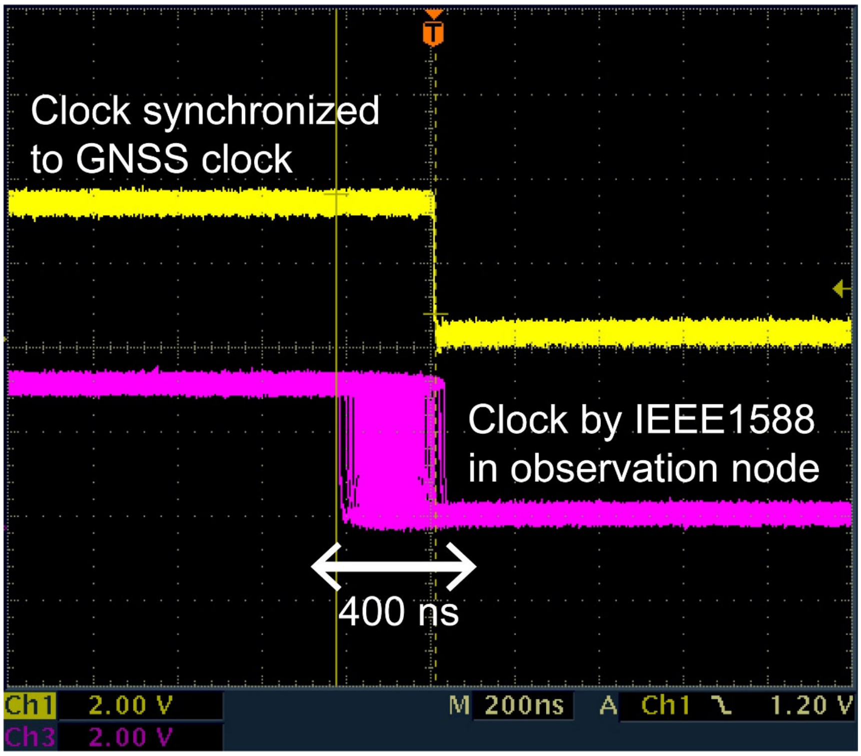
Ethernet Switch
48V DC
Power Sourcing
Equipment (PSE)
Class 3 (12.95W)
Underwater Matable
Connector (UMC)
Powered
Device
(PD)
10BaseT
Power
(12W)
Monitoring Data
Accelerometers
Digitizer Unit
(24-bit ADC)
Processing Unit
Counting
Unit
Precise
Pressure gauge
Optical Fiber
SFP
O/E
Optical Fiber
SFP
O/E
Time Clock
Module

Fig. 1.


Clock synchronized
to GNSS clock
Clock by IEEE1588
in observation node
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Ch1 2.00 V
Ch3 2.00 V
M 200ns A Ch1 1.20 V

Fig. 2.

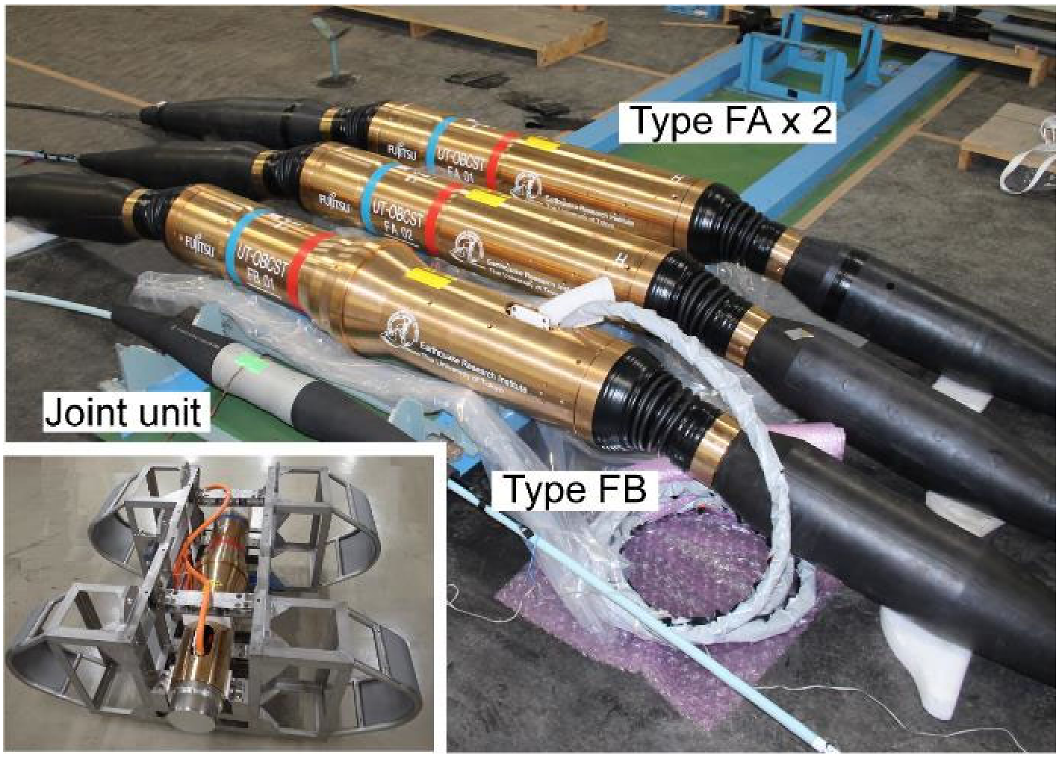
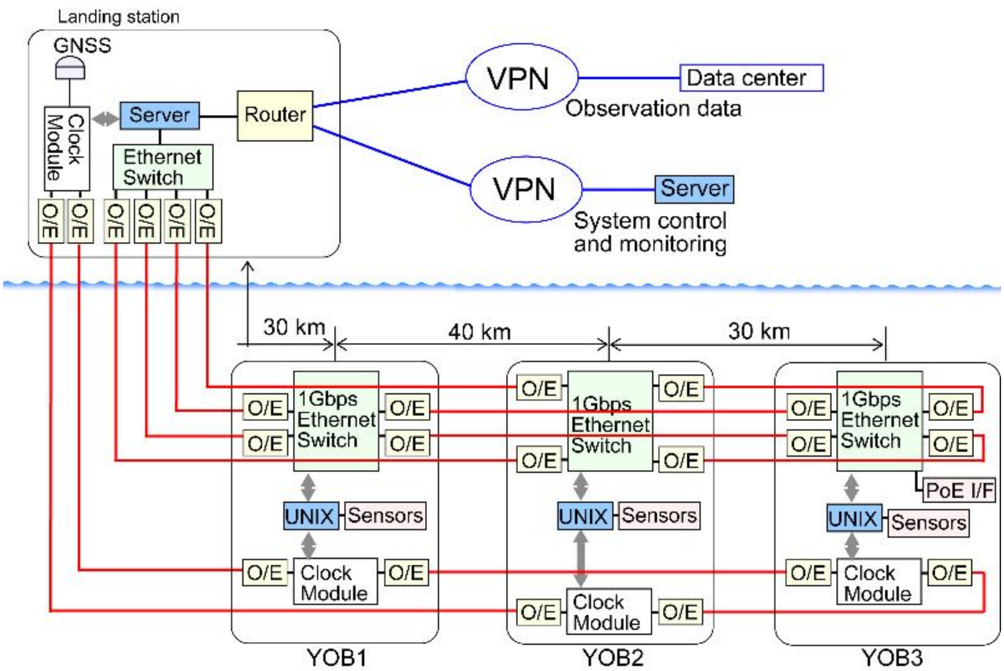

Type FA x 2
Joint unit
Type FB

Fig. 3.


Landing station
GNSS
Clock Module
Server
Router
Ethernet Switch
O/E
VPN
Data center
Observation data
VPN
Server
System control and monitoring
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30 km
1Gbps Ethernet Switch
UNIX
Sensors
Clock Module
PoE I/F
YOB1
YOB2
YOB3

Fig. 4.

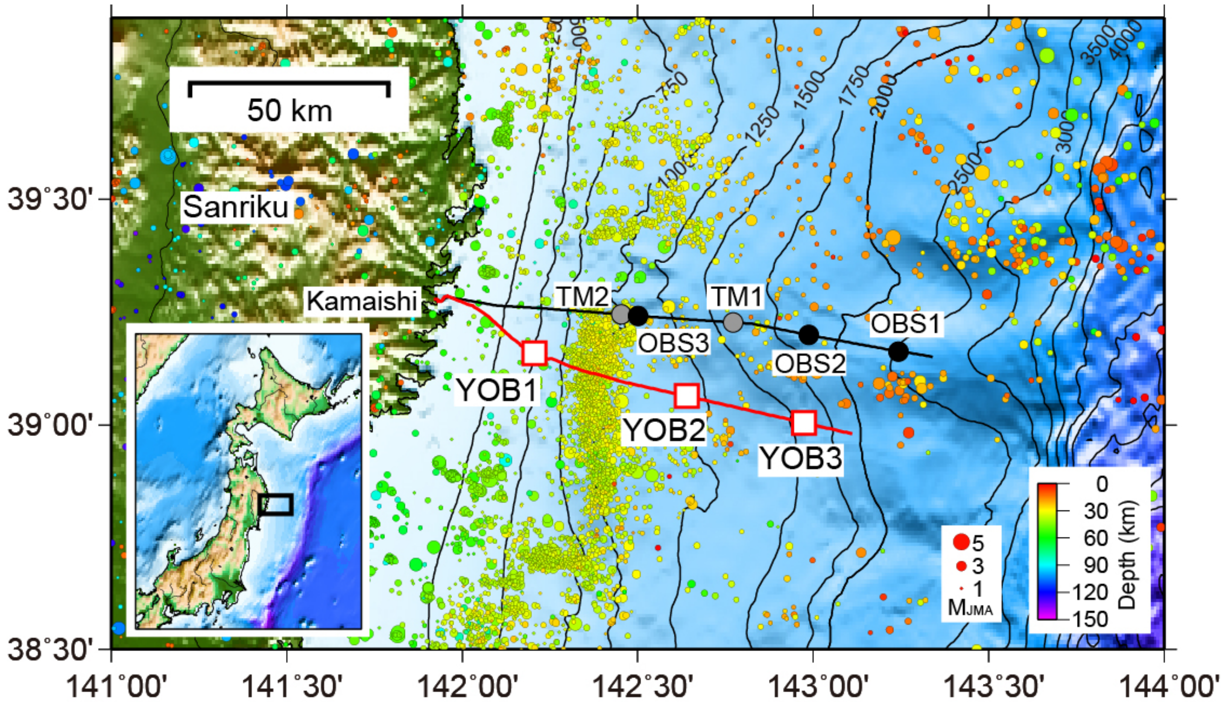
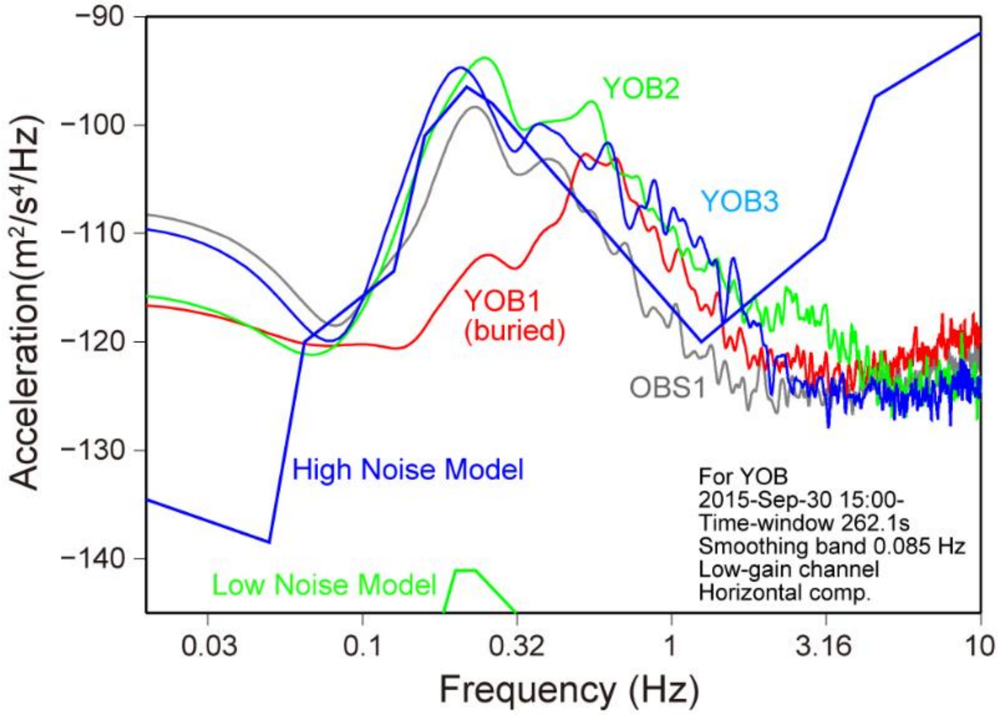

50 km
Sanriku
Kamaishi
TM2
TM1
OBS1
OBS2
OBS3
YOB1
YOB2
YOB3
0
30
60
90
120
150
Depth (km)
5
3
1
MJMA
39°30'
39°00'
38°30'
141°00'
141°30'
142°00'
142°30'
143°00'
143°30'
144°00'

Fig. 5.

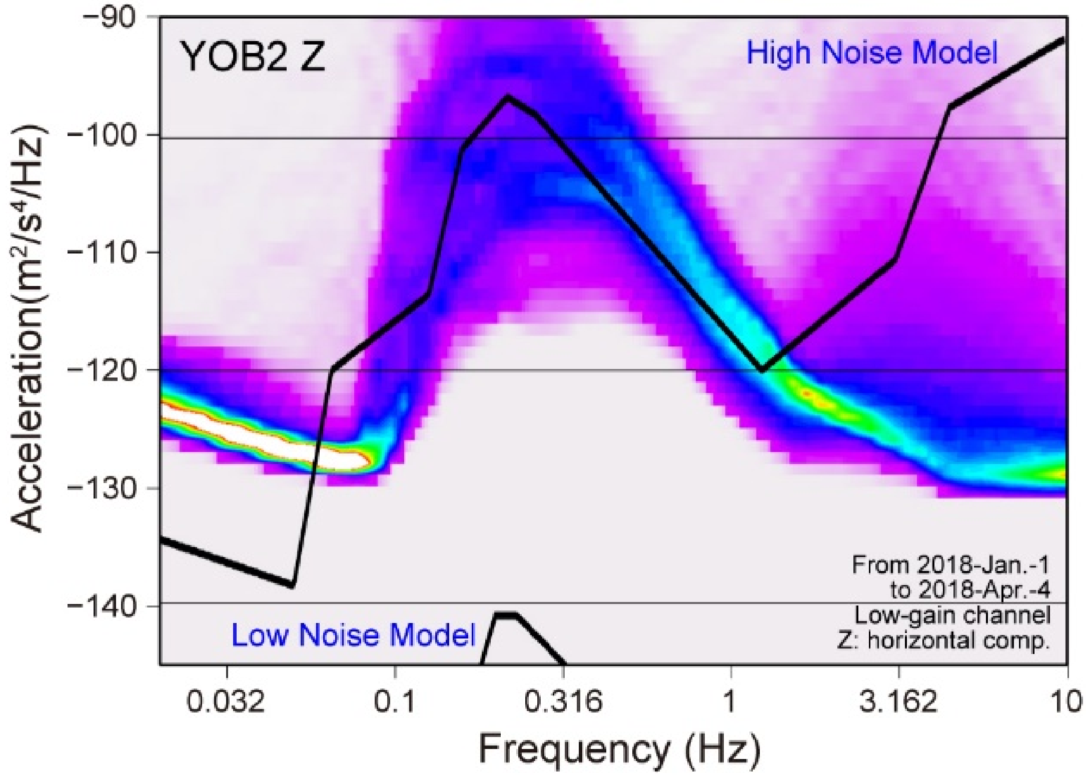

Dive 01
Time : 11:51:35
Date : 2016/10/11
Depth : +1565.6 M
Lat : 39 00.3554N
Long : 142 58.4065E
Heading : 241.4
PoE port
244.0

Fig. 6.



YOB2
YOB3
YOB1
(buried)
OBS1
High Noise Model
Low Noise Model
For YOB
2015-Sep-30 15:00-
Time-window 262.1s
Smoothing band 0.085 Hz
Low-gain channel
Horizontal comp.
Acceleration(m²/s⁴/Hz)
−90
−100
−110
−120
−130
−140
0.03
0.1
0.32
1
3.16
10
Frequency (Hz)

Fig. 7.



YOB2 Z
High Noise Model
Low Noise Model
From 2018-Jan.-1
to 2018-Apr.-4
Low-gain channel
Z: horizontal comp.
Acceleration(m²/s⁴/Hz)
−90
−100
−110
−120
−130
−140
0.032
0.1
0.316
1
3.162
10
Frequency (Hz)

Fig. 8.

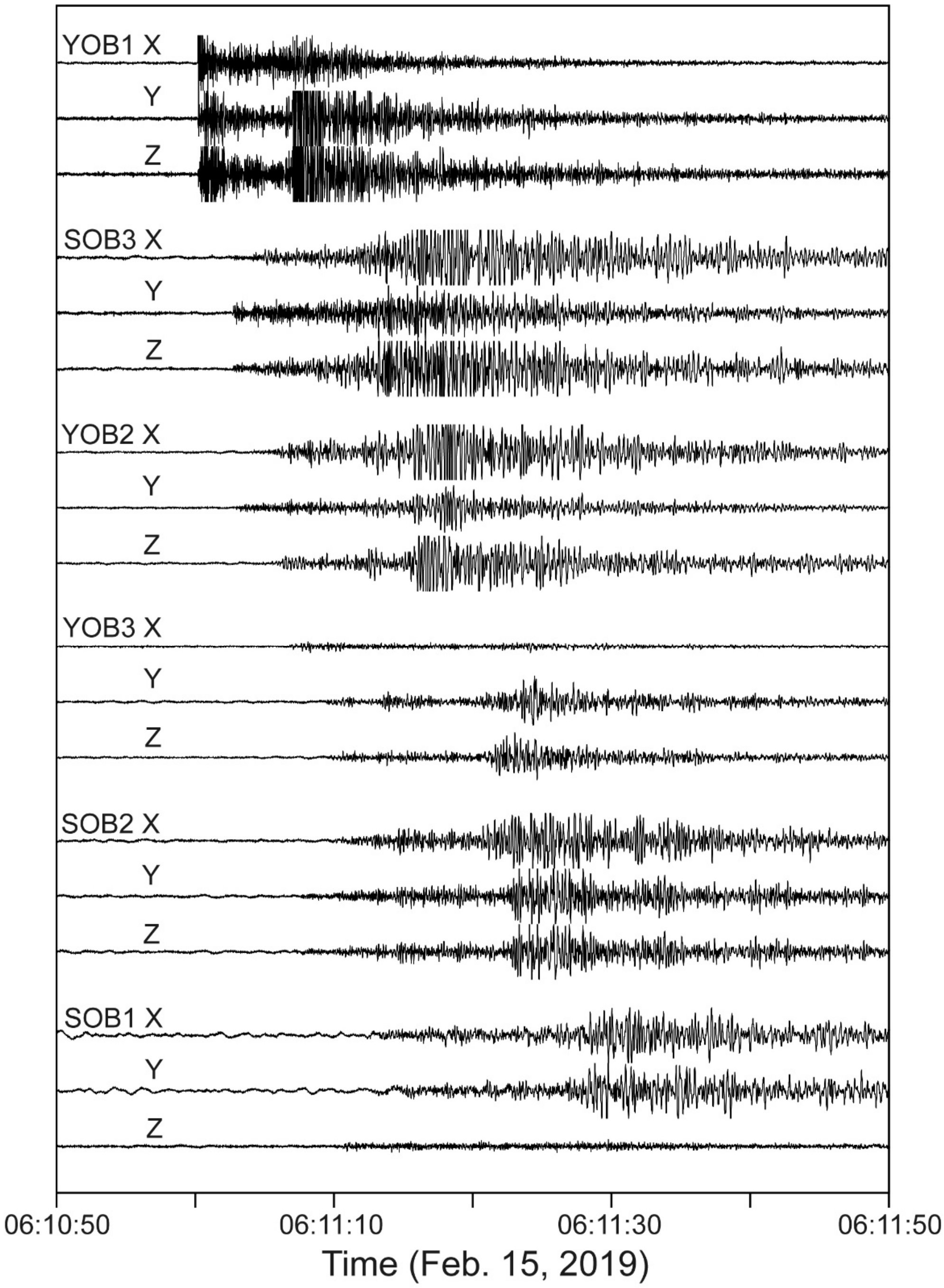
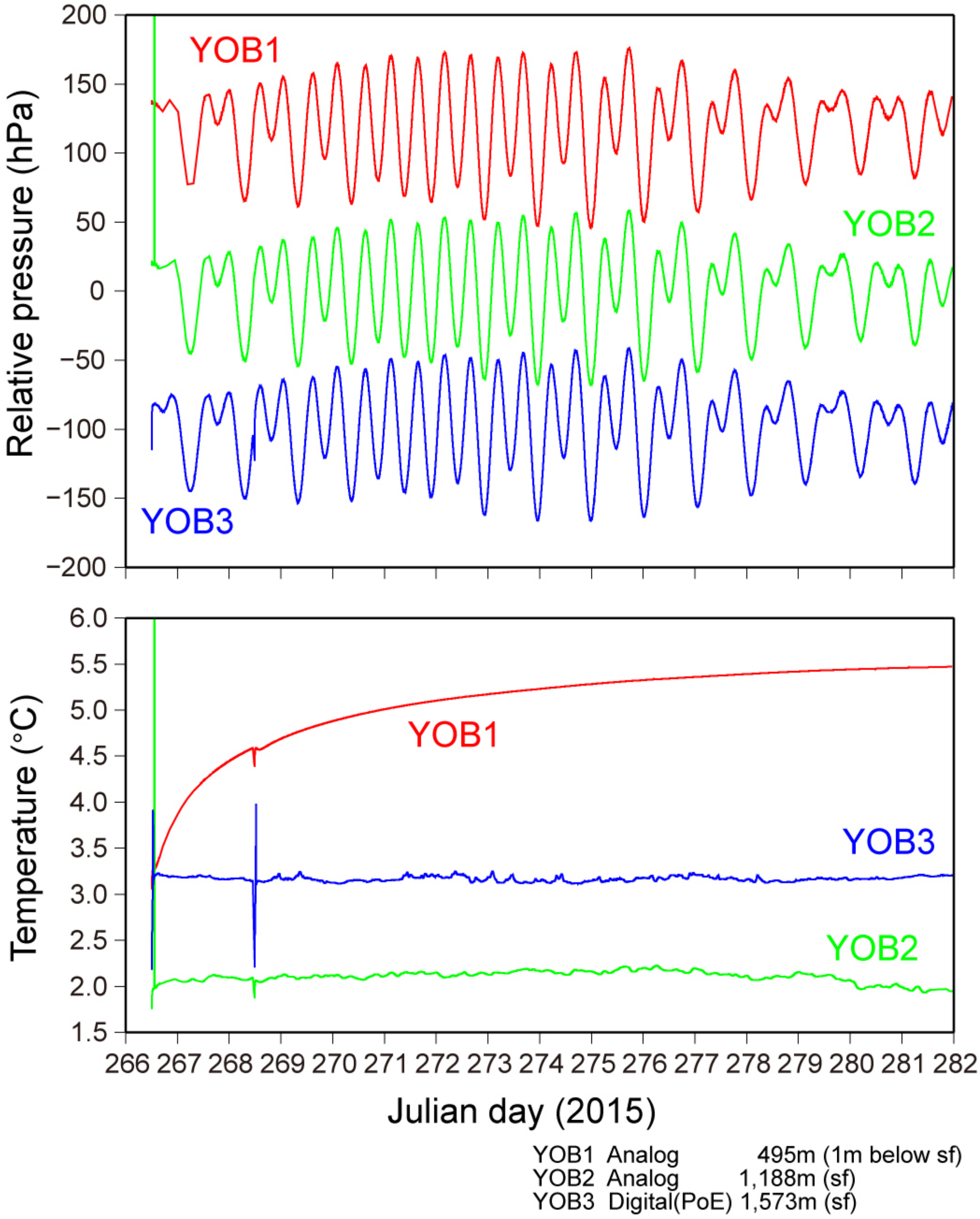

YOB1 X
Y
Z
SOB3 X
Y
Z
YOB2 X
Y
Z
YOB3 X
Y
Z
SOB2 X
Y
Z
SOB1 X
Y
Z
06:10:50
06:11:10
06:11:30
06:11:50
Time (Feb. 15, 2019)

Fig. 9.



YOB1
YOB2
YOB3
Relative pressure (hPa)
200
150
100
50
0
−50
−100
−150
−200
Temperature (°C)
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
266 267 268 269 270 271 272 273 274 275 276 277 278 279 280 281 282
Julian day (2015)
YOB1 Analog 495m (1m below sf)
YOB2 Analog 1,188m (sf)
YOB3 Digital(PoE) 1,573m (sf)

Fig. 10.

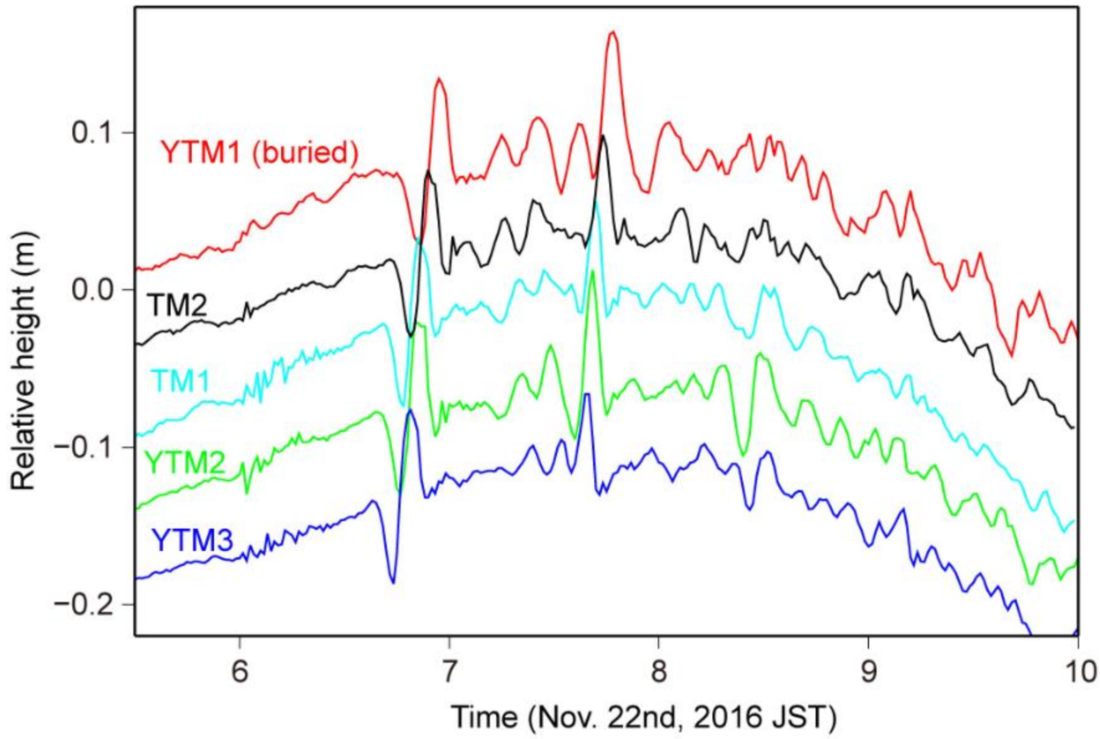

YTM1 (buried)
TM2
TM1
YTM2
YTM3
Relative height (m)
0.1
0.0
−0.1
−0.2
6
7
8
9
10
Time (Nov. 22nd, 2016 JST)

Fig. 11.

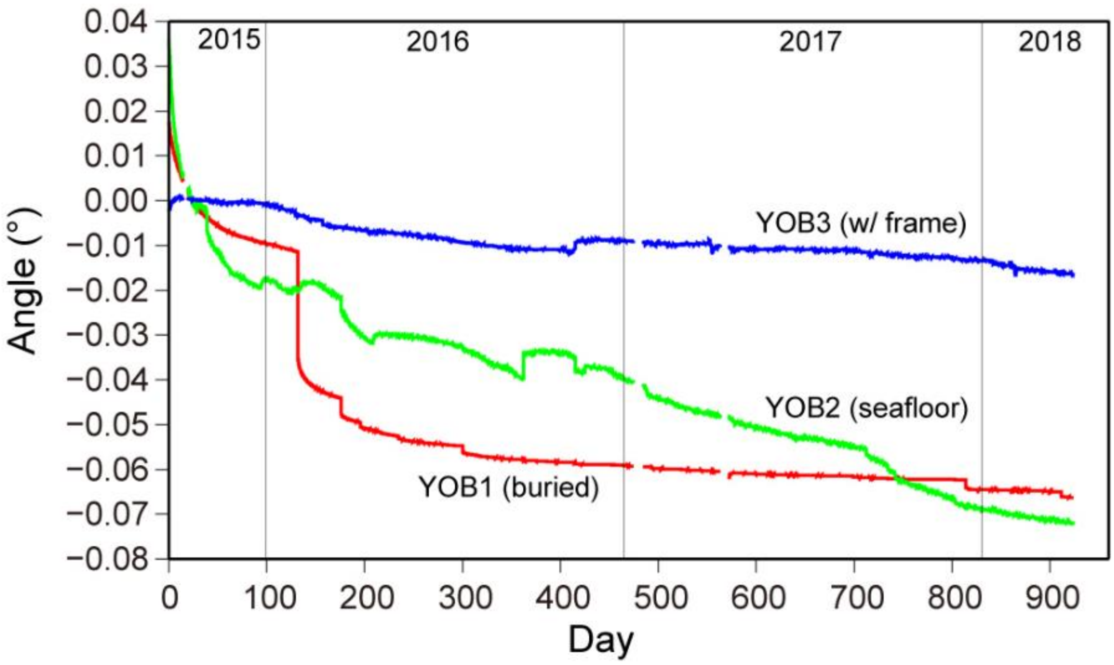

2015
2016
2017
2018
YOB3 (w/ frame)
YOB2 (seafloor)
YOB1 (buried)
Angle (°)
0.04
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03
−0.04
−0.05
−0.06
−0.07
−0.08
0
100
200
300
400
500
600
700
800
900
Day

Fig.12

Station	Latitude (° North)	Longitude (° East)	Depth (mbsl)
YOB1	39.15968	142.20556	495
YOB2	39.06454	142.63959	1188
YOB3	39.00555	142.97364	1573

Table 1.