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Development of Seismometers Sensor Network for Observation on Sea Floor —— IP goes to Oceans ——

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SUMMARY   Because large earthquakes have repeatedly occurred in
subduction zones, it is important to observe seismic activities on the sea
floor. An ocean bottom cabled seismometers (OBCS) system is the most
suitable tool for this purpose since data can be obtained in real-time. Al-
though the existing OBCS systems are useful for the study of seismic ac-
tivities, the number of stations is limited due to their cost. Therefore, lower
cost in both production and installation is desired. We have developed
a new OBCS system utilizing IP technologies. IP technologies yield the
new OBCS system that are more compact and less expensive, while a large
amount of complex hardware is used in the existing OBCS system. System
reliability is ensured by using IP network technologies that provide redun-
dancy. The new OBCS system was first installed to observe the Niigata-
Kobe tectonic zone in the Japan Sea on September 2010. Although this
first OBCS system has a total length of 25 km, it has been proven that seis-
mic data can be successfully obtained and that the new OBCS system is
effective and useful for the dense observation of seismogenic activities on
the sea floor around Japan.
key words: OBCS, earthquake

1. Introduction

The Japanese islands lie in subduction zones, where the Pa-
cific plate subducts below the Japanese islands. Because
large earthquakes have repeatedly occurred in subduction
zones, it is important to observe seismic activity on the sea
floor just above these seismogenic zones. Note that the main
purpose of this seismic measurement is not the direct detec-
tion of earthquakes but the detection of imperceptible tec-
tonic activities by which the tectonic mechanism and move-
ment can be analyzed and estimated for earthquake observa-
tions.

Ocean bottom seismometers (OBSs) were developed
for one-year observations and have been deployed in the
seismogenic zone around Japan [1]. The OBS is stand-alone
equipment, and is first dropped and placed on the sea floor.
It records seismic data internally, and after about a year
pops-up on the sea surface after which we can finally obtain
the data. Although this pop-up OBS has been widely used,
it has serious problems such as limited power, low reliabil-
ity of data recovery, and off-line observation for long-term
seismic activities.

Ocean bottom cabled seismometers (OBCS), where the
sensors are equipped in a hermetically-sealed case and these
cases are connected with cables, is the best solution to ad-
dress these problems. Note that OBCSs can be used to de-
tect the occurrence of earthquakes in real time, while OBSs
cannot. The first OBCS system, consisting of eight cabled
seismometers (CSs), was developed by the ERI (earthquake
research institute), University of Tokyo, based on a subma-
rine telecommunication cable system, and has been used
over the past 25 years in Japan [2], [3]. Although this ex-
isting OBCS system has made a significant contribution to
the study of seismic activity, the number of seismometers is
insufficient for high resolution observations of the seismo-
genic zone. The high cost is a problem that must be resolved
to consider a sufficient number of seismometers. This is the
critical problem in the existing OBCS system [4]–[6].

In addition to the problem of cost, the existing OBCS
system has become insufficient to meet today's require-
ments, particularly in flexibility of measurements after in-
stallation. A portable system is also required and is expected
to be used for the precise monitoring of seismic activity after
large earthquakes and so on.

After substantial consideration of interdisciplinary re-
search studies with engineers of various fields, such as ocean
engineering, metrology, electronic engineering, mechani-
cal engineering, and information and communication engi-
neering in particular, it was concluded that IP technologies
should be utilized for a new OBCS system, i.e., IP should
be used for OBCSs at the bottom of the ocean.

In accordance with this concept, we have developed a
new OBCS system. While a large amount of complex hard-
ware is used in the existing OBCS system, the new OBCS
system can be made compact since software processes vari-
ous measurements. Reliability of the system is achieved by
using a redundant system that is constructed with IP network
technologies.

The new OBCS system was first installed to observe
the Niigata-Kobe tectonic zone in the Japan Sea on Septem-
ber 2010. Although this first OBCS system has a total length
of 25 km, it has been proven that seismic data can be suc-
cessfully obtained and that the new OBCS system is effec-
tive and useful for a dense observation of seismogenic zones
on the sea floor around Japan.

This paper is organized as follows. Section 2 addresses
the backgrounds and objectives of the new OBCS system.
Section 3 outlines the proposed architecture and system de-

sign. Section 4 presents the details of the developed system as well as evaluation results of Linux/IP and a network. Section 5 gives the first installation of the OBCS system in the Japan Sea near Awashima Island, Niigata Prefecture. Conclusions are given in Sect. 6.

2. Backgrounds and Objectives of the New OBCS System

There are already approximately 2,000 land-based seismic observatories in Japan. On the other hand, the number of seismic observatories in the oceans is quite limited, and furthermore those OBCSs are configured in a line. Figure 1 shows existing OBCSs around Japan, where c) and e) are operated by the ERI and the others are operated by other organizations. All of these OBCSs are installed in a quite short line; hence they are not sufficient to measure seismic activities precisely on the sea floor. Note that the circles in Fig. 1 indicate areas where careful seismic observations are required.

Our objective is to develop a high density of observation points in the emerging seismogenic ocean areas that will be sufficient to achieve the same level of observation as the land-based networks. Seismic measurements in the ocean should be performed over a planar area rather than only over a line of points.

Figure 2 depicts the conceptual scheme for the new long-haul application OBCSs. CSs are equipped with optical cables and placed at 20 km intervals. Optical cab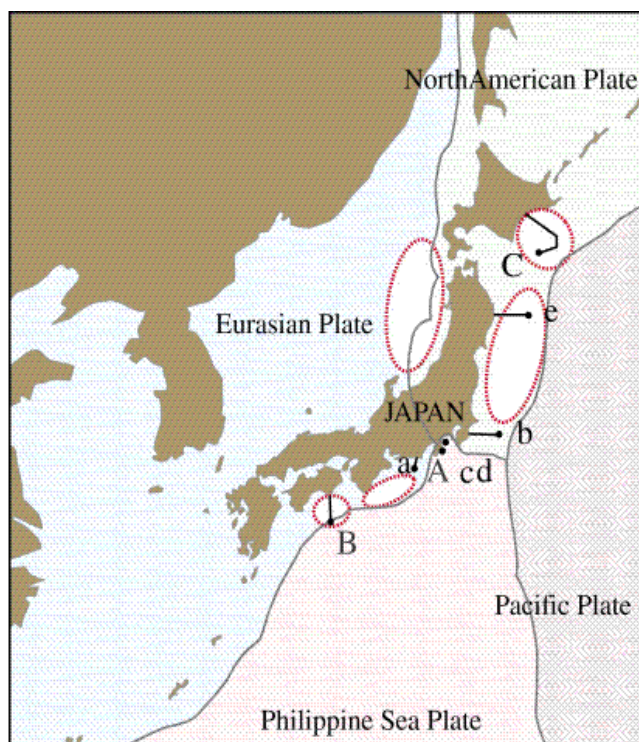les are installed for up to 900 km with a continuous "S" pattern, by which the CSs are distributed on a plane. Therefore, the seismic observatories would be on a planar level, and the density of observatories on the ocean bottom would be equivalent to that on the land. When this system is used at the maximum length, it is composed of 40 CSs and three tsunami sensors.

Objective specifications for the new OBCS are given in Table 1. The operational depth is set to 6,000 m, so the system can be used for almost all targeted areas of the ocean bottom around Japan. The accuracy of the time stamp is less than 0.1 ms, which is equal to the present accuracy. The system is expected to be in use for more than 20 years.

The most important objective of the new OBCS system is reducing the cost of both development and installation. The size of the CS is the key to achieve this requirement. A smaller CS leads to lower costs for development. When the CSs are sufficiently small, ordinary ships, rather than specialized cable ships that are used for the existing OBCSs, can be utilized to install the OBCS, and the installation costs can be significantly reduced.

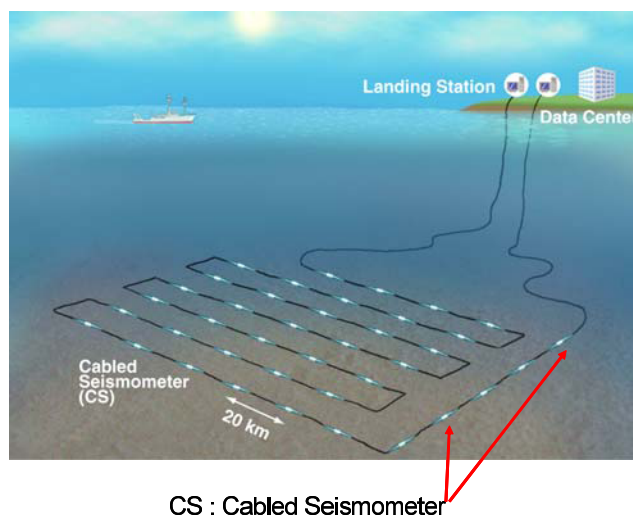In addition, measurement must be more compatible and

CS : Cabled Seismometer

Fig. 2 Concept of new OBCS system — Observation on a plane.

Table 1 Objective specifications of the new OBCS system.

Items	Specifications
Maximum cable length	900 km
Landing stations	two places; each station has power-feeding unit
Maximum operating depth	6,000 m
Interval between cabled seismometers (CS)	20 km
Sensors within CS	40 Seismometers, and 3 Tsunami sensors
Accuracy of time stamp	less than 0.1 ms
Operational lifetime	20 years (for long-haul application)
Size of CS	much smaller than conventional CS for easy handling and installation using a commercial (not specialized) work ship
Measurement	more compatible and friendly to Researchers than conventional OBCS
Cost	less expensive than conventional OBCS

Fig. 1 Existing OBCS system — Observation in a line.

user-friendly for researchers, for example, allowing changing of measurement parameters after installation. These requirements can be met by utilizing IP technologies, as described in Sect. 3.

3. Basic Architecture and System Design of the New OBCS

3.1 Network

The conceptual network configuration for the new OBCS and the terrestrial network is schematically shown in Fig. 3. This cable network adopts two dual methods, i.e., one is a ring configuration, and the other is a doubled ring configuration. A CS is equipped to a ring at 40 km intervals, i.e., a CS is installed with 20 km intervals on the ocean bottom due to the doubled ring configuration. This scheme is employed to enable both high reliability and low cost. Ethernet, which is a de-facto standard in IP area, is used as transmission system for this doubled ring configuration.

Data collected with a time stamp at each CS are transmitted using standard IP data transmission to landing stations. The two landing stations are equipped with a power supply, a storage system, and access to the Internet. When broadband is available between the landing stations and the control center (ERI), data can be directly sent to the control center. When broadband connections can not be available, which would most likely occur as the OBCS will be installed in rural areas, the data is stored at the landing stations and is accessible by researchers through the non-broadband Internet.

A GPS clock at each landing station is used as a time reference to synchronize each CS, and is fed to each CS through a dedicated line, i.e., Ethernet is not used. Methods of clock transmission have been studied, and it was found that the latest clock synchronization system over Ethernet is sufficient for OBCS [6], [7]. In particular, IEEE-1588 is useful for a land-based system clock synchronization method, as the number of cables is reduced. After evaluation of clock systems including IEEE-1588, it was, however, decided that a simple dedicated line for clock distribution should be used, because for a system in the ocean: 1) a dedicated line is not so costly, and 2) a simple configuration can realize high reliability [6], [7].

3.2 Why IP?

The existing OBCS consists of 100% hardware. All aspects of IP technologies have been studied, and it was concluded that the use of IP for OBCS is timely, when taking account of the following advantages:

1) Making OBCS compact:

Software is capable of processing various measurements, while the existing OBCS is composed of a large amount of complex hardware.

2) Making OBCS less expensive:

Use of a central processing unit (CPU) and large scale integration (LSI) can significantly reduce the number of circuits and parts.

3) Enabling IP access to OBCS:

Researchers can access OBCS via IP protocol, thus enabling quick analysis of seismogenic characteristics.

4) Enabling upgrade of OBCS:

Researchers can change measurement parameters, thus enabling detailed and investigative measurement.
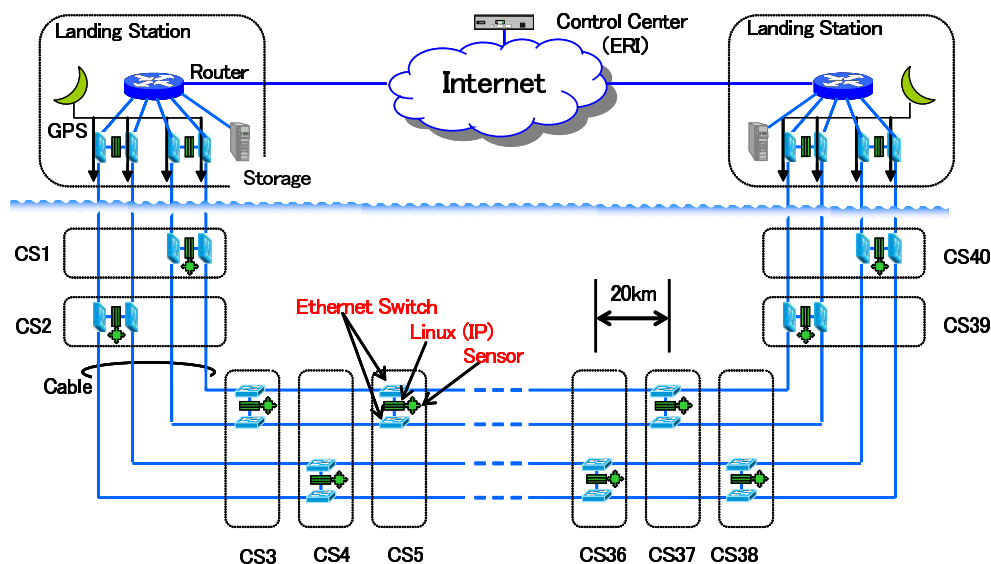

Fig. 3 Conceptual network configuration.

5) Enabling preventive maintenance of OBCS:

Software continuously monitors the status of parts, and alerts when necessary (e.g., power down of laser transmitters).

3.3 Why Linux?

There are several software platforms, i.e., operating systems (OS), as candidates for OBCS. In particular, 1) Linux, 2) conventional real-time OS, and 3) Windows embedded (known as Windows mobile) OS have been studied. Conventional real-time OS have advantages in several metrics, i.e., processing performance, proven experiments for industrial use and software stability.

However, conventional OS are not compatible with IP. At most, the objective of the new OBCS is to provide ease of access to the OBCS once installed at the ocean bottom. IP has to be supported so that researchers can access OBCS in just the same manner as they access machines at laboratories. The performance and reliability issues of Linux have been addressed and evaluated as shown in the next Sect. 3.4. It was finally concluded that Linux is mature enough and acceptable for use with OBCS.

With regard to the Windows Mobile OS, it was considered to be still pre-mature for OBCS application, since 1) performance for real-time processing is not sufficient, and 2) there is uncertainty as to the stability of the software, i.e., Windows Mobile has been version-upgraded so many times in the last few years.

3.4 Reliability and Performance Issues of Linux

One can raise reliability issues for Linux, as the software has become non-operational so many times. Therefore, the following solutions have been adopted for OBCS application;

1) Ring configuration:
   Each Linux OS can be accessed from both landing stations.
2) Restart procedures:
   The Linux OS can be restarted from landing stations through the dedicated clock line (not Ethernet lines).

Another issue for Linux or a software-based system is performance, i.e., whether or not Linux can realize sufficient real-time processing. To cope with this issue, the following two solutions were adopted:

1) Sensor data can be processed with a high priority mode (an interrupt mode is used only for sensor data).
2) Other operations, e.g. monitoring circuits, can be processed with a low priority mode (periodically processed with 1 min intervals, etc.).

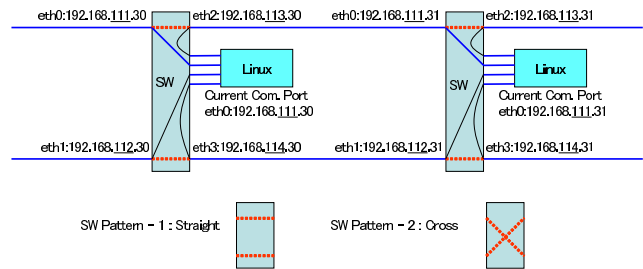An example of a developed Linux system for evaluation is presented in Sect. 4.

Fig. 4   Addressing and routing of OBCS.

3.5 Addressing and Routing of OBCS System

In order to minimize hardware circuits of CS and to realize simple configuration, layer 2 networking technology has been adopted. Furthermore, a layer 2 switching is implemented as a part of FPGA. Figure 4 shows addressing and routing of OBCS. A Linux of CS has four Ethernet ports, where a subnetwork IP address is assigned to each Ethernet port. A Linux also keeps an IP address of a current communication port. On the other hand, a layer 2 switching has two switching pattern, i.e., strait connection and cross connection. These parameters, i.e., a current communication port and layer 2 switching pattern, can be sent to CS by a dedicated control information over a clock link. Researchers will have to set these parameters carefully from a server of landing stations.

We have studied the use of commercial layer 2 switch and layer 2 networking technologies such as a spanning tree protocol, but concluded to develop the above mentioned manually controlled layer 2 networks in order to make OBCS as much as simple. For the same reason, IP version 4 private addressing has been adopted, since there is no reason to use IP version 6.

A Linux may freeze or hang up due to unexpected errors or so. A communication through Ethernet line can not be effective in that case. In order to restart a Linux, a control signal is sent over a clock link. So, the clock link conveys clock signals as well as control information such as layer 2 switching parameters and a restart signal to each Linux. Clock links are also duplicated so that signals can be sent to CS from both landing stations.

3.6 Reliability of the Entire OBCS System

Since the Linux reliability issues have been resolved, as presented in Sect. 3.4, the OBCS system itself obtains ultimate reliability due to the Linux/software-based operations. Figure 5 schematically depicts an example of network operations.

Under normal operation, the data from each CS can be sent to the landing stations with load balancing. When one landing station is due for maintenance, the data from all CS can be sent to the other landing station. This operation can be set by researchers via IP/Ethernet access from the control station or a landing station. Once a fiber cable is broken,
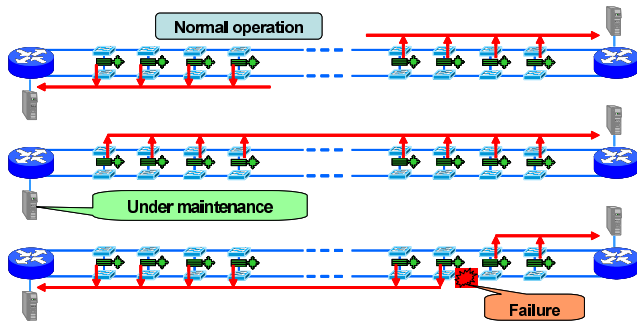
Fig. 5 High reliability and maintenancebility of the new OBCS.
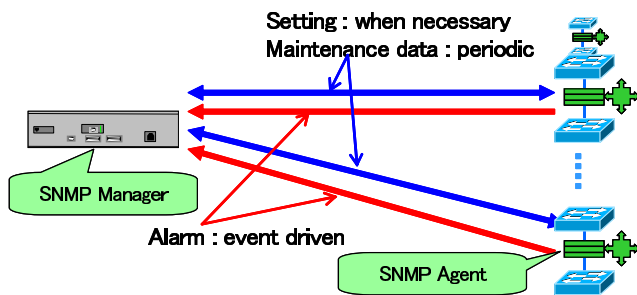

Fig. 6 Performance monitoring for preventive maintenance.

which is likely to happen within a lifetime of 20 years, data from the CSs can be sent to an individual landing station through an accessible path.

Further ideas have been introduced to realize ultimate reliability, and these are depicted in Fig. 6. By utilizing Linux and IP technologies, OBCS can now be maintained by performance monitoring. The Linux OS continuously monitors the status of parts and circuits, e.g. laser transmitting power of E/O, the temperature within a pressure vessel, voltages of power units, and so on. The Simple Network Management Protocol (SNMP) is a de-facto protocol in IP, and is used in the OBCS system for this purpose.

When performance degradation is detected, researchers are able to re-configure the network. This makes it possible to configure the network if it is still workable, hence avoiding serious problems such as an isolated CS due to multiple failures. The network can be configured as ring > dual line > single line, depending on failures and trouble. Data from each CS can be sent (retrieved) at least when a path to that CS can be configured.

4. Developed System and Evaluation

4.1 Linux and Clock Board

Based on studies of the architecture and system mentioned in Sect. 3, the new OBCS system was developed. Figure 7 shows the configuration of a CS. The Linux OS is able to access two Ethernet lines (upper and lower), as indicated in Fig. 7, depending on the engineered network configuration. The clock module derives a GPS clock signal from the landing stations, as well as control signals such as Linux restart.
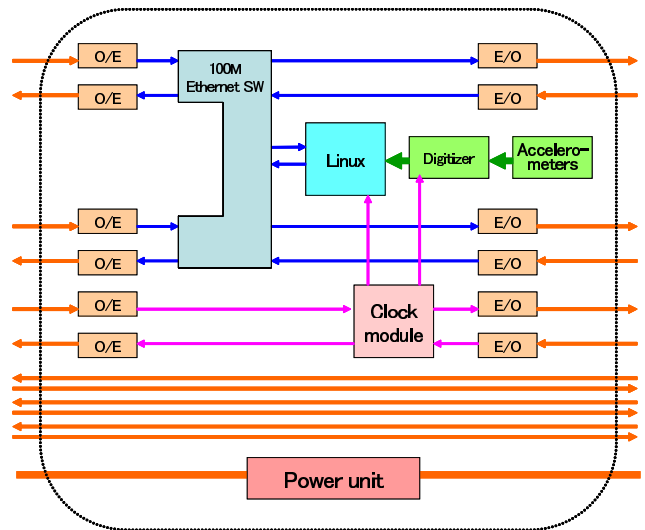

Fig. 7 Configuration of a cabled seismometer (CS).

Table 2 Specifications for the developed Linux board.

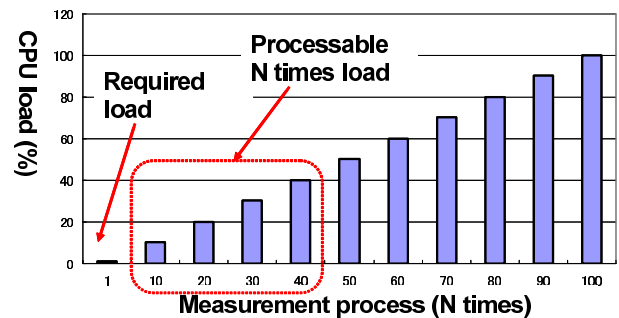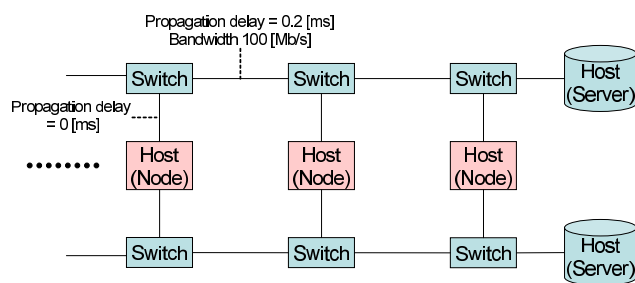| Items	Specifications
CPU	SH-4
Flash ROM	32 MB × 2
SDRAM	64 MB × 2
OS	Linux (kernel 2.6.9)
IP	version 4
FPGA	about 150 k gates
Digitizer interface	data transferred every 30 ms (1 ms data stored within FPGA)

Fig. 8 Performance evaluation of CPU and Linux OS.

Table 2 shows the specifications for the developed Linux board. SH-4 is a widely used industrial microprocessor over which Linux version 2.6.9 is installed. The field-programmable gate array (FPGA) on the board handles the interface to a digitizer, and stores 30 ms of data. Linux retrieves data every 30 ms and then sends it to the landing stations.

The performance of the Linux OS has been evaluated, and the results are presented in Fig. 8. As expected, processing of the required measurement operations is done by a few CPU load. The result also indicates that the combination of the SH-4 CPU and the Linux OS is capable of handling approximately 40 times of the required measurement

Table 3 Specifications of the developed digitizer board.

Items	Specifications
Seismometer	force balance accelerometer
Axis	three (X, Y, Z)
Range	±2.5G
Resolution	1 μG
Amplitude bandwidth	DC-300 Hz
Digitizer	24 bits sigma-delta A/D converters
Sampling rate	1 kHz (1 ms)
Time stamp	0.1 ms

Fig. 9 Network model for performance evaluation.

Fig. 10 Simulation results — Latency vs. number of CS.

Fig. 11 Simulation results — Occupancy vs. number of CS.

operations. This means that researchers are able to add more functions and operations to the board as necessary.
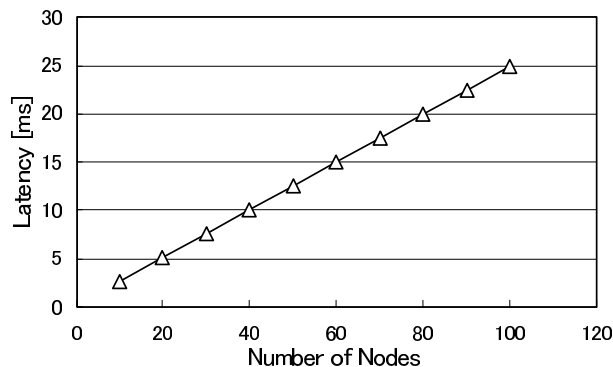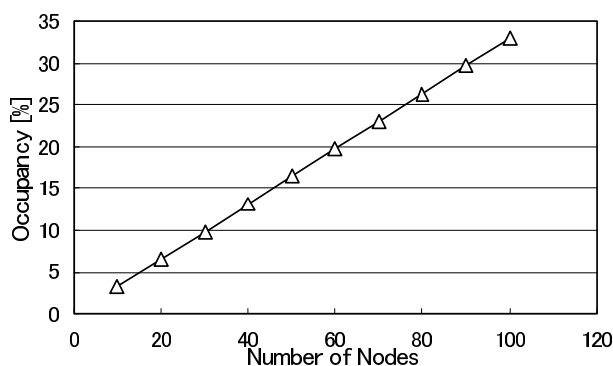
4.2 Seismometers, Digitizer and Clock

Specifications for the developed digitizer and seismometer are given in Table 3. The seismometer is a conventional force balance accelerometer (JA-5, Japan Aviation Electronics Industry, Ltd.), which is a single axial type. The JA-5 accelerometer has been used for the ocean bottom cable systems of ERI, JAMSTEC, and NIED (National Research Institute for Earth Science and Disaster Prevention). Each output of three accelerometers (X, Y, Z components) is synchronously digitized by 24 bit sigma-delta A/D converters with a sampling rate of 1 kHz.

A GPS clock signal from the landing stations is input to the digitizer, i.e., not through Linux, so that accurate 0.1 ms time stamping is performed using 100% hardware.

4.3 Data Transfer Methods and Evaluation of Network Performance

Digitized data is input to CPU every 1 ms, then redundant part is deleted, and it comes to 41 bytes per 1 ms. In order to simplify data transfer, 30 ms data is packed into 1 IP packet, i.e., $41 \times 30 + 28$ (UDP/IP header) = 1,258 bytes within 1 packet. Here, we do expect very low packet loss since transmission paths are provided by optical fibers, and realtime transmission is necessary for emergency operations, such as earthquake detection etc. So, UDP is chosen as transport protocol. Note that 30 ms is considered as satisfactory small for emergency operations.

We have conducted evaluation of network performance of new OBCS system. Figure 9 depicts a network model for NS2 simulation. Propagation delay between two adjacent

CSs is set as 0.2 ms, and a delay within an L2 switch is assumed negligible. Figure 10 shows simulation results about latency which expresses a transfer delay from the most remote CS to a host server. When the number of CS is 20, as indicated in Table 1 and Fig. 3, the latency is less than 5 ms. Figure 11 shows simulation results about occupancy of 100 Mbps Ethernet at an ingress port of a server. When the number of CS is 20, the occupancy becomes only 5%.

The reason why both latency and occupancy comes to a linear characteristics is that data generated by CS is regularly and periodically transferred to a server. We may consider fluctuation of this interval due to CPU's possessing time, but such fluctuation is expected to be small and 5 ms latency and 5% occupancy are considered as safe enough for reliable transfer of CS data.

Figures 10 and 11 also indicate that this system can support up to about 100 CSs on 1 ring, i.e., 200 CSs in total, with a reasonable latency and occupancy from network performance viewpoints. The maximum number of CS is, therefore, subject to a power consumption of CS, since there's a limit of a DC voltage supplied at a landing station. We'll have to continue to study for further reducing a power consumption of CS.

4.4 Packing of New OBCS

Consolidated studies for packing of the CS have also been performed, because the size of the CS is a critical issue for
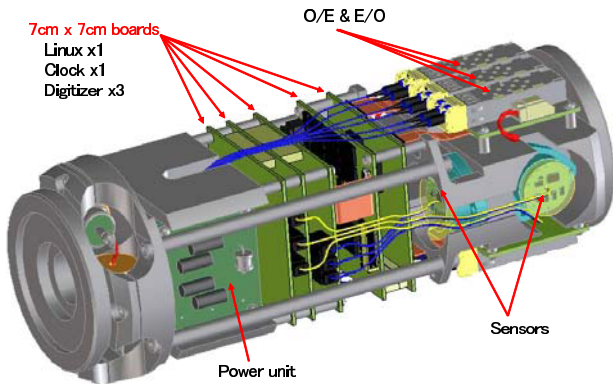
Fig. 12 Packing of the new CS.

Fig. 13 Comparison of the existing and new CS.

Fig. 14 The first installation of new OBCS — Japan sea on Sept. 2010.
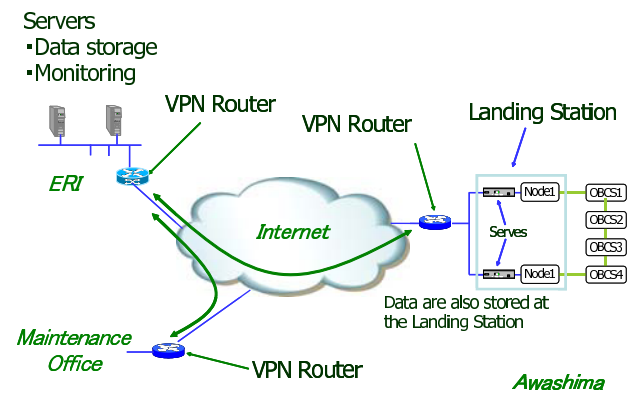
Fig. 15 VPN between landing station and ERI.

minimization of the costs, as discussed in Sect. 2. Figure 12 shows an approximate 3D image of the new packing method for the OBCS. There are only 5 boards; Linux, clock and 3 digitizers, for the CS, and the board is approximately $7 \times 7\,\mathrm{cm}^2$.

The size of the CS is 13 cm in diameter and 50 cm long, which is almost equal to that of a 2 litter plastic drink bottle. Compared to the existing OBCS, which has a 22 cm diameter and is 150 cm long, this is a remarkable reduction in size (See Fig. 13). Like communication cable system, OBCS should be buried in adjacent sea of Japan taking account of influence to inshore fishing industries. So, this small size of CS will make a burying method and construction easy, quick and less expensive.

5. First Installation of New OBCS at Japan Sea

Because the development of the OBCS system has been completed, we decided to product a practical system and deploy the new OBCS system in the field. Global Positioning System (GPS) observations with a dense station distribution revealed that the central coastal area of the Japan Sea has large strain rate, which is named the Niigata-Kobe Tectonic Zone (NKTZ) [8] (See Fig. 1). Recently, there were three large earthquakes (the 2004 Chuetsu Earthquake, the 2007
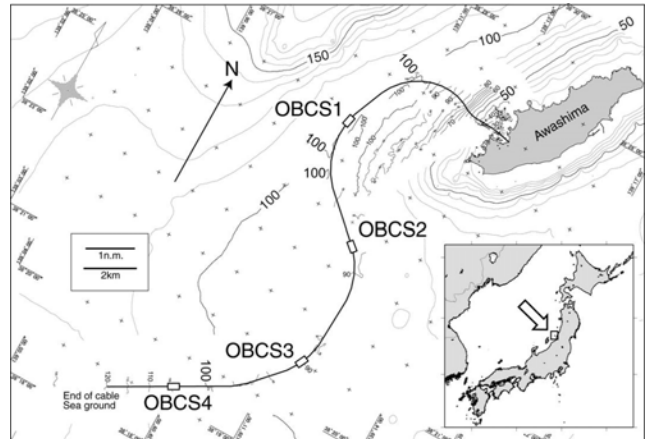
Noto-Hanto Earthquake, and the 2007 Chuetsu-oki Earthquake) in and around the NKTZ. From these reasons, we decided to install the first practical OBCS system in the marine area of the NKTZ.

Due to a limitation of the budget, the OBCS system for the first field installation has a total length of 25 km and 4 CSs with 5 km interval (See Fig. 14). Although the total length of the system and intervals of CSs are short compared to the conceptual design, this small size system is effective for earthquake observation since the target area is small and earthquakes occur at shallow depths. It is, of cause, aimed at proving and evaluating the new OBCS system with a small size system.

The data transmission channel using the Ethernet is duplicated and one of the Ethernet channels is turned in the furthest CS for ring configuration. So, the network itself is a ring configuration as the same as the conceptual architecture in Fig. 2, though it looks like an existing line configuration. We'll be able to prove and evaluate various features of the new OBCS such as changing network operations, performance monitoring for preventive maintenance, etc. as described in Sects. 3 and 4.

At the landing station, the data are stored in a large disk array system. In the case that the Internet has enough

capacity from the landing station to the data center, all the data from the CSs are transmitted to the data and control center at the ERI. In the case that the capacity of the Internet is limited, the system status of the OBCS and a part of the data are sent to the ERI. If a remarkable event occurs, all the data of the event will be retrieved via the Internet. The system control commands will be sent from the ERI. A VPN (Virtual Private Network) is configured between a landing station and ERI as shown in Fig. 15.

Since the installation of new OBCS on September 2010, seismic data has been sent to ERI and been contributed to earthquake researches.

6. Conclusions

A new OBCS system has been presented in detail, particularly how the application of IP technologies makes it possible to realize new features. IP technologies have enabled the new OBCS system to become more compact and less expensive and enabled IP access and the upgrade of OBCSs for measurement flexibility and expandability of measurements. The IP-based OBCS system has the following remarkable advantages:

1) The new compact OBCS can be made very compact since software processes various measurements, while a large amount of complex hardware is used in the existing OBCS.
2) Both the production and the installation of the compact OBCS is not expensive. Since a specific cable ship with high operation cost is no longer necessary, the compact OBCS can be used portably and timely to monitor the aftershocks that occur after huge earthquakes.
3) Reliability of the system is kept by using a redundant system that is easily constructed using IP network technologies.
4) The OBCSs installed on the sea floor can be accessed through IP protocol on UNIX systems on land. This will enable the efficient and quick study of seismogenic characteristics.
5) Because of the software-based OBCSs, it will be possible to change the measurement parameters of seismometers after installation, thus enabling detailed and investigative measurement.

The size of the new OBCS is 13 cm in diameter and 50 cm long, which is a remarkable reduction in size. We have evaluated particularly 1) CPU processing performance and 2) latency and occupancy of a network, by which it has been proven that the developed system satisfactorily meets design requirements.

The first OBCS system has a total length of 25 km and 4 CSs at 5-km intervals and has been deployed in the coastal area of the central Japan Sea, where large earthquakes occurred recently. Since the installation of this first OBCS system on September 2010, seismic data has been sent to ERI and has contributed to earthquake research.

The performance evaluation has revealed that the max-imum number of CS may become 200 in total with a reasonable latency. There is, however, a limit of a DC power supplied at a landing station. Therefore, we'll continue to study for further reducing a power consumption of CS by e.g., integrating three digitizer boards into one FPGA and so on. This will contribute to reduce the size of CS. Network management system will also be developed in the next version, since it'll be difficult to manage manually 200 CSs and layer 2 switching functions. If these objectives will be met, then we'll see, e.g., the maximum of 200 CSs with 5,000 km, long-haul observation system, which is effective enough for seismic observation in the oceans around Japan.

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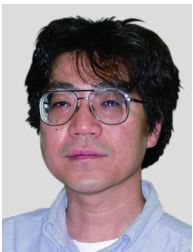
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