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A small ocean bottom electromagnetometer and ocean bottom electrometer system with an arm-folding mechanism (Technical Report)

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Abstract. Natural magnetic fields are attenuated by electrically conductive water. For that reason, marine magnetotelluric surveys have collected data at long periods (1000–100 000 s). The mantle structure has been the main target of seafloor magnetotelluric measurements. To ascertain crustal structure, however, electromagnetic data at shorter periods are important, e.g. in investigations of megathrust earthquake zones, or in natural resource surveys. To investigate of the former, for example, electromagnetic data for periods of less than 1000 s are necessary. Because no suitable ocean bottom electromagnetometer (OBEM) has been available, we have developed a small OBEM and ocean bottom electrometer (OBE) system with a high sample rate, which has an arm-folding mechanism to facilitate assembly and recovering operations. For magnetic observation, we used a fluxgate sensor.

Field observations were undertaken to evaluate the field performance of our instruments. All instruments were recovered and their electromagnetic data were obtained. Results of the first experiment show that our system functioned well throughout operations and observations. Results of other field experiments off Tottori support the claim that the electromagnetic data obtained using the new OBEM and OBE system are of sufficient quality for the survey target. These results suggest that this device removes all instrumental obstacles to measurement of electromagnetic fields on the seafloor.

Key words: arm-folding mechanism, fluxgate magnetometer, ocean bottom electromagnetometer.

Introduction

Natural magnetic fields are attenuated by electrically conductive water. For that reason, marine magnetotelluric surveys have collected data at long periods (1000–100 000 s). The mantle structure has been the main target of such seafloor magnetotelluric measurements. To ascertain crustal structure, however, electromagnetic data at shorter periods are crucial, e.g. in investigations of megathrust earthquake zones, or in natural resource surveys. Constable et al. (1998) developed a broadband ocean bottom electromagnetometer (OBEM) with induction coil sensors. Their type of OBEM has been used to examine the crustal structure (Key and Constable, 2002; Kasaya et al., 2005). Moreover, Weitemeyer et al. (2006) used such as system as a receiver in a controlled-source electromagnetic survey in a methane-hydrate area. They used a horizontal electric dipole source transmitted using a deep-tow system and obtained 1-D inversion results.

The Japanese electromagnetometer community began development of an ocean bottom magnetometer (OBM) system in the late 1970s (Segawa et al., 1982*a*; Segawa et al., 1982*b*), and an ocean bottom electrometer (OBE) system was also developed in the early 1980s (Hamano et al., 1984). A practical OBEM contained within three glass spheres was completed in the 1990s. In 2001, a next-generation instrument, with a geomagnetic field measurement resolution of 0.01 nT, could be contained within two glass spheres. These Japanese OBEMs were used for the Mantle Electromagnetic and Tomography (MELT) experiments at the southern East Pacific Rise (Baba et al., 2006) and for array observations in the Philippine Sea conducted by the Ocean Hemisphere Project (Seama et al., 2007). Another type of OBEM was also developed at Kobe University: it had a three-component electric field measurement system in addition to a three-component magnetic field measurement system (Seama et al., 2003). Tada et al. (2005) estimated a 1-D structure around a hydrothermal area in the central Mariana Trough, using a Magnetometric Resistivity dataset obtained with those OBEMs.

Another type of instrument, called a seafloor electromagnetic station (SFEMS), has been developed for long-term observation of electromagnetic fields. This instrument is equipped with an Overhauser absolute magnetometer with accuracy of 0.1 nT and a fibre-optical gyro, in addition to seven components of a magnetotellurics variograph (three-component fluxgate magnetometer, two-component horizontal electric dipole, and two-component tiltmeter). The SFEMS has already been deployed and recovered, yielding long-term datasets in several operations (Toh et al., 1998; Toh et al., 2006).

However, no suitable OBEM has been made available for our survey targets, which have a water depth of over 1000 m, for example to examine the fluid distribution in the crust and upper mantle around megathrust earthquake zones. Therefore, we decided to develop an OBEM and OBE system with a high sampling rate. The key concepts of the OBEM and OBE systems that we have developed are (1) miniaturization,

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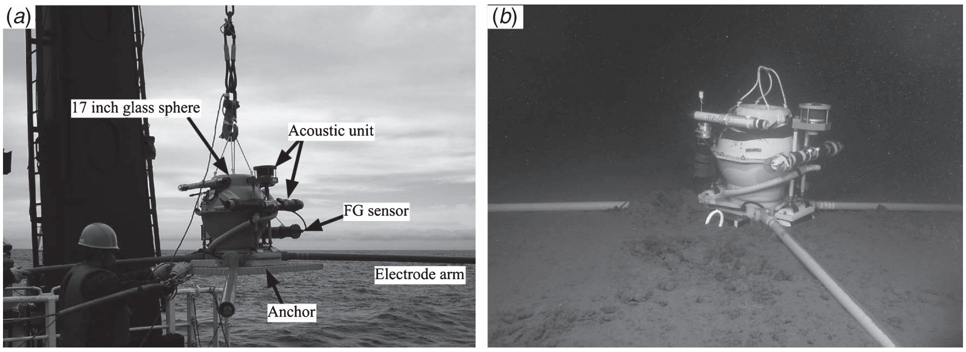


Fig. 1. (*a*) Deployment of the ocean bottom electromagnetic instrument. (*b*) Photograph of the ocean bottom electrometer system on the seafloor taken using the digital still camera of the ROV *Hyper Dolphin*.

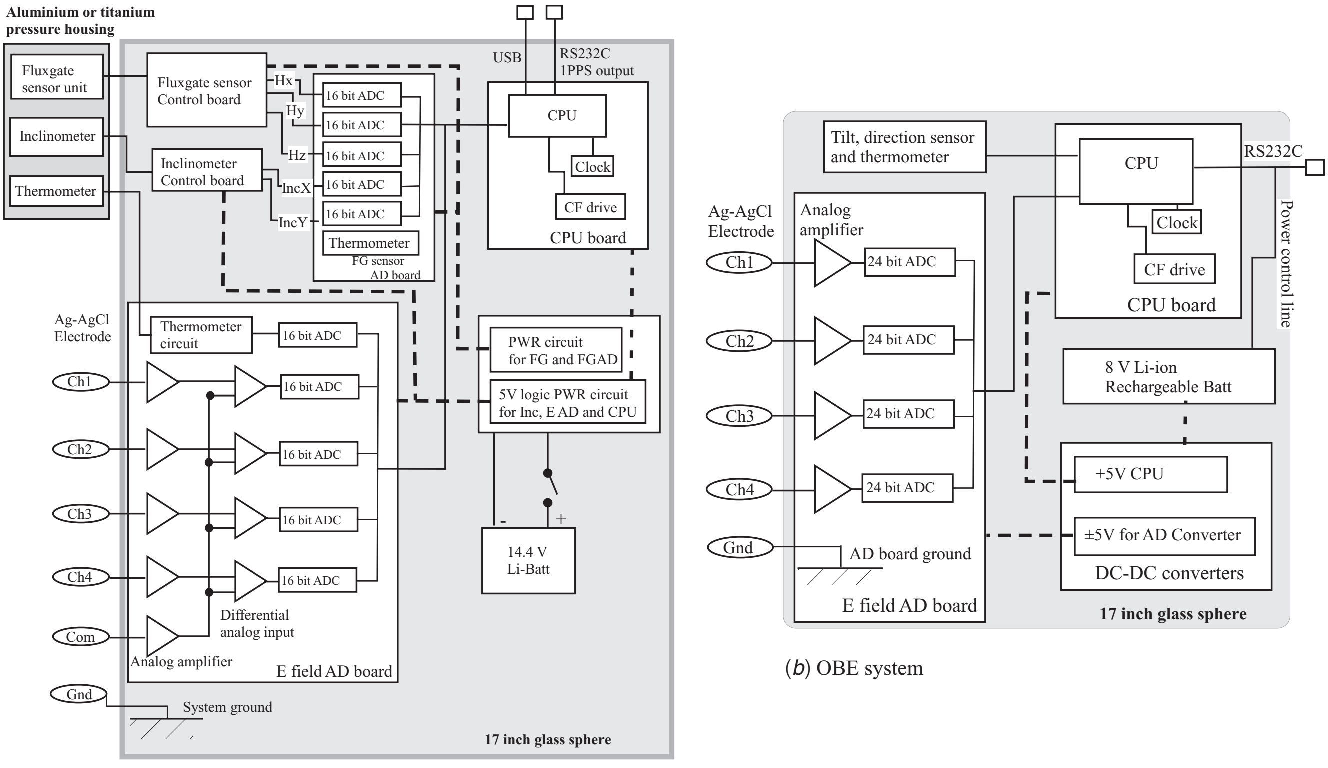
(2) a high sampling rate (greater than 1 Hz), (3) ease of assembly and recovery, and (4) low cost of construction and operation. Kasaya et al. (2006) showed an outline of the new instruments, and preliminary field data. We present here details of the mechanism of our system, and explain some field test results.

Outline of the developed OBEM and OBE instrument

The target depth for surveys with our newly-developed instrument is the crust and upper mantle, to a depth of a few hundred kilometers. To study such structures, it is necessary to obtain EM data in the period range from a few to 100 000 s. Constable et al. (1998) used an induction coil sensor for the instrument that they developed. However, we decided to adopt a high-accuracy fluxgate magnetometer for the OBEM system, because the fluxgate sensor has high sensitivity, and a response that is almost flat in the frequency range for our target depth. Moreover, the fluxgate sensor is more robust than an induction coil sensor for the sea bottom current. The fluxgate sensor is mounted outside the main glass sphere (Figure 1*a*). The OBE system can function as a complementary instrument of the OBEM, and as a receiver for controlled-source electromagnetic surveys in the future. Table 1 presents the specifications for each

Table 1. Specifications of the ocean bottom electromagnetometer (OBEM) and ocean bottom electrometer (OBE) systems.

	OBEM	OBE
Sampling rate	8 Hz	1 Hz
AD converter	16 bit	24 bit
Resolution	0.000305176 mV/LSB 0.01 nT/LSB	0.0000019 mV/LSB
Maximum battery lifetime	About 40 days (8 Hz sampling)	About 30 days (1 Hz sampling)
Power supply	Lithium battery	Li-ion rechargeable battery
Memory	Compact flash memory (Max 2 GB)	Compact flash memory (Max 1 GB)
Communication port	USB1.1/RS-232C	RS-232C



(*b*) OBE system

(*a*) OBEM system

Fig. 2. Block diagram of electronic circuits and sensors of the (*a*) ocean bottom electromagnetometer (OBEM) and (*b*) ocean bottom electrometer (OBE) system.

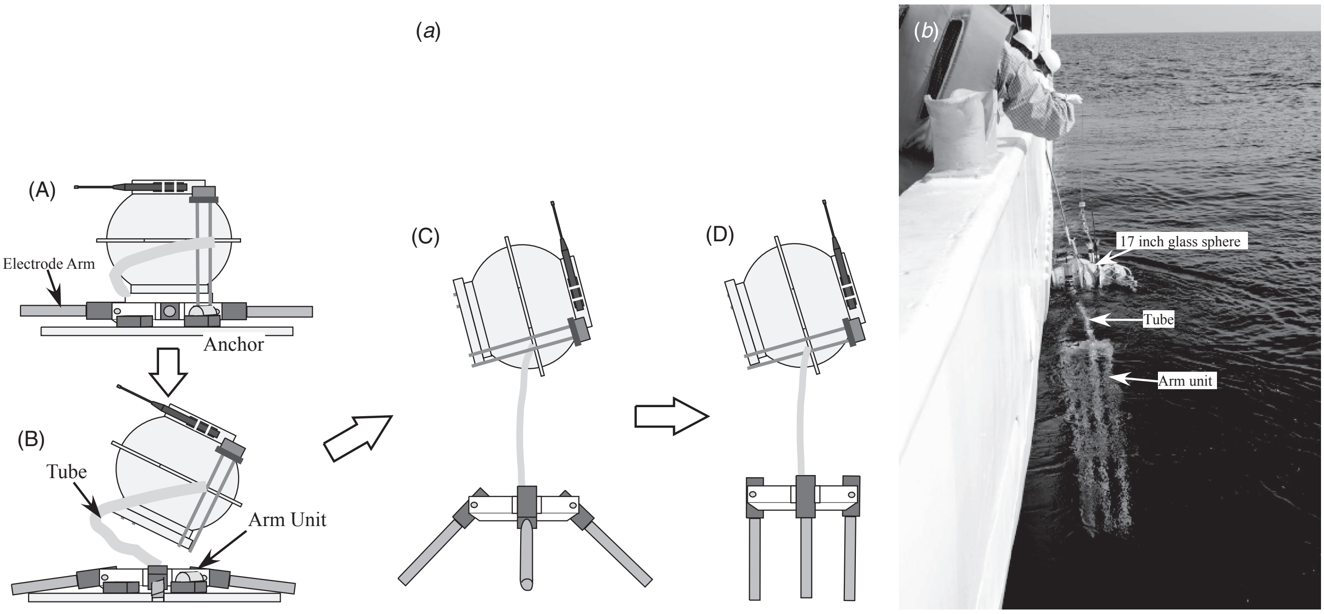


Fig. 3. (*a*) Diagram of the instrument sphere and arm-folding mechanism: (A) Setting on the seafloor. (B) The anchor is released by an acoustic unit on receipt of an acoustic release command code from an acoustic unit on board. The glass sphere then starts to pop up. (C) The arm unit is picked up as the sphere ascends; the electrode arms fold automatically. (D) Floating posture. (*b*) Photograph of the recovery operation using a 500-ton class vessel (*Tansei-maru*). The arm-folding mechanism worked well; all electrode arms folded perfectly.

system. Both systems can resist water pressure to depths of 6500 m; they are able to use common exterior equipment and an acoustic recovery system.

Figure 2 depicts block diagrams of the OBEM and OBE system. All of the OBEM electronics are installed inside a 17-inch (432 mm) glass sphere except the fluxgate sensor, inclinometer, and thermometer, which are within a metallic pressure housing (Figure 2*a*). All 16-bit analogue-digital converters, for each sensor component, are equipped individually for noise reduction. Differential analogue amplifiers were installed in the electric field measurement circuits, so that we can obtain four electrical components. Electric power is supplied by a lithium battery; the low power consumption system of this system enables measurements with a maximum sample rate of 8 Hz for more than 40 days. A 1 GB compact flash memory is used for data storage. An internal crystal clock is powered by another lithium battery so that it will continue to run even if the main battery fails.

Figure 2*b* is a schematic of an OBE system. This system has a 24-bit analogue-digital converter for each of the four electric field components. Electrical power is supplied from a lithium-ion rechargeable battery. The OBE can perform measurements at a maximum sample rate of 1 Hz for ~30 days. The internal clock of this system has a similar backup battery to that of the OBEM system. The clock drift rate of each system is typically less than 2 ppm.

Clock synchronisation before deployment and calibration after recovery are important for remote reference processing or controlled source sounding, because it is difficult to synchronise seafloor instruments using a GPS clock. The accuracy of clock synchronisation required for the target frequency range is less than or equal to 10 ms. A portable GPS clock unit was developed; it achieved sufficient accuracy for synchronisation and calibration. The OBE system is designed to connect directly to the clock unit. Therefore, it achieves accuracy of ~1 ms.

Natural electromagnetic signals are attenuated by conductive seawater. To check whether our system could detect a signal at the seafloor, we evaluated the amplitude of magnetic and electric fields on the seafloor, using a simple two-layered earth model. The predicted amplitudes at a water depth of 1000 m are 5.7 nT and 8.6 μV at a period of 100 s (refer to the Appendix for details of the prediction). Next, we estimate the Ag-AgCl electrode, instrumental, and environmental noise using parallel electric-field component measurements made by the after-mentioned OBE system, in a field test off Tottori Prefecture discussed below. Because our system measures four electric field components relative to the ground (common) electrode

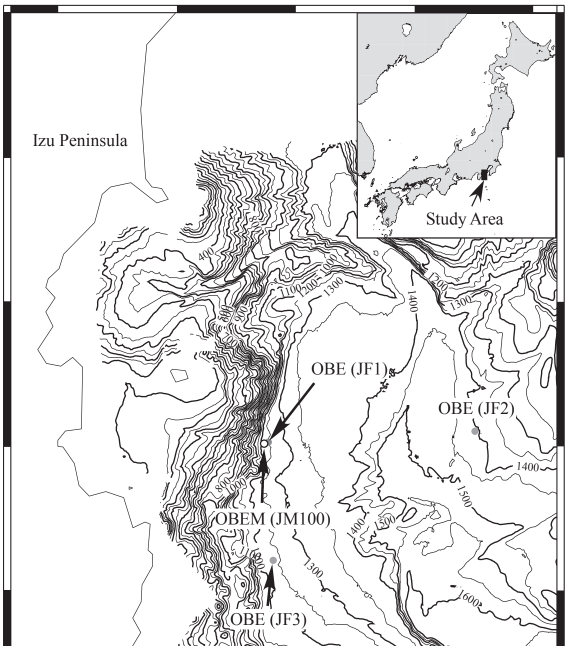


Fig. 4. Site location map for the first ocean bottom electromagnetometer (OBEM) and ocean bottom electrometer (OBE) experiment at Sagami Bay.

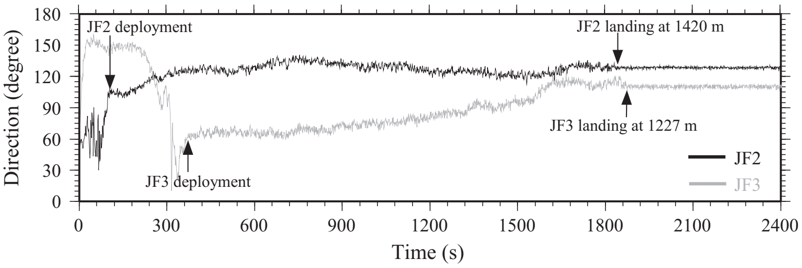


Fig. 5. Direction data obtained using the magnetic compass in the ocean bottom electrometer system. Zero degrees signifies magnetic north; clockwise rotation is defined as positive.

(+Ex, –Ex, +Ey, and –Ey), we can calculate the noise time series without the effect of geomagnetic induction by adding the positive and negative signals from the two sensors for each electric field component. The fluctuation of the calculated time series is below 0.3 µV. The skin depth in a sub-seafloor layer that has a resistivity of 1 Ω.m is calculated to be 5.0 km at a period of 100 s. As a result, our instruments offer a seafloor ability to acquire data for surveys of the crustal and upper mantle structure in a megathrust earthquake zone.

Arm-folding mechanism and acoustec release system

Long electric dipole arms are generally necessary to measure the electric field. In many cases, these solid electric dipole arms complicate shipboard operations. Existing OBEMs used by the Japanese research community have rigid electrode arms fixed on a metallic frame. These arms work well from the perspective of stability on the seafloor for long-term observations. However, shipboard operations using instruments with these arms are sometimes very difficult, especially during more difficult recovery operations. To resolve this problem, we designed a mechanism that folds each 2 m electric arm after ascent from the sea floor is initiated. Figure 3 is a diagram of that arm-folding mechanism (Japanese patent applied for, in 2005). An acoustic release system supplies thin stainless steel plates in the release units with electric current from the release system battery; a chemical reaction in the stainless plate system starts when the release signal is received. The stainless steel plates are cut within 10–15 min, after which the main glass sphere starts to pop up (B in Figure 3*a*). The glass sphere picks up the polypropylene arm unit; then the polyvinyl chloride (PVC) arms also start to fold as ascent commences (C in Figure 3*a*). Finally, all arms are folded completely and the OBEM reaches the sea surface in the same configuration (D in Figure 3*a*). The arm unit is separate from the glass sphere; it connects via the PVC tube, which has the electrical cables inside. Further, the arm unit remains submerged after reaching the surface, because its total buoyancy is negative (Figure 3*b*). We tested this folding mechanism in a diving training pool before the first deployment (Kasaya et al., 2006). The mechanism facilitates and simplifies our shipboard operations, so that we can carry out recovery operations using a small fishing boat.

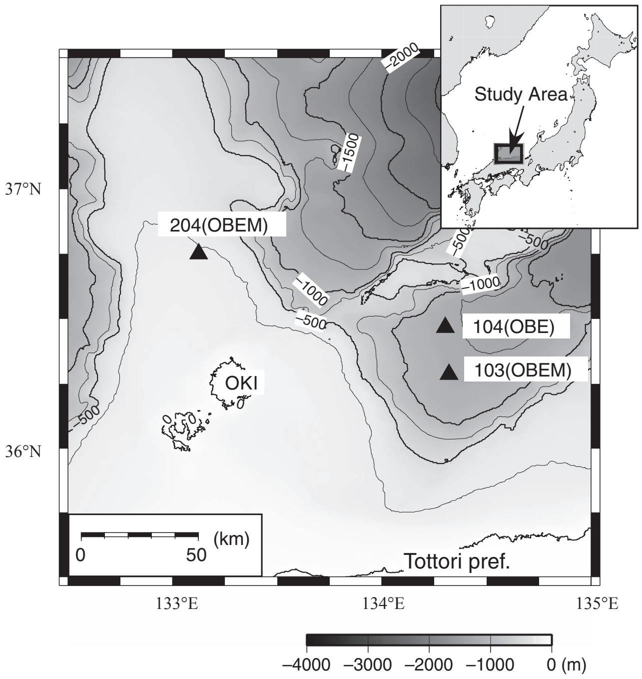


Fig. 6. Map showing locations of seafloor sites off the Tottori region.

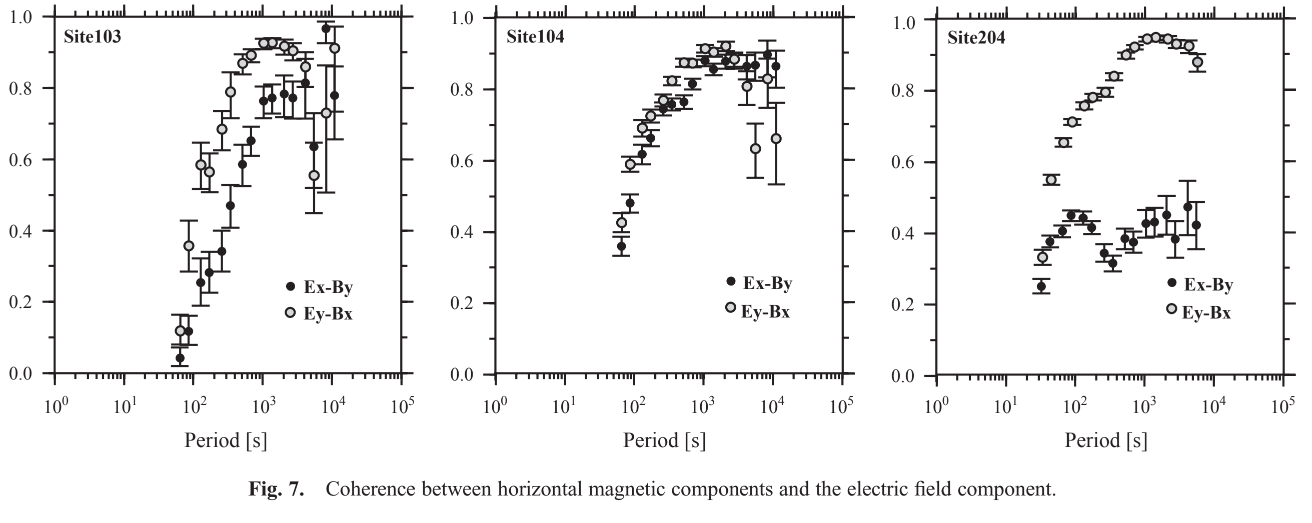


Fig. 7. Coherence between horizontal magnetic components and the electric field component.

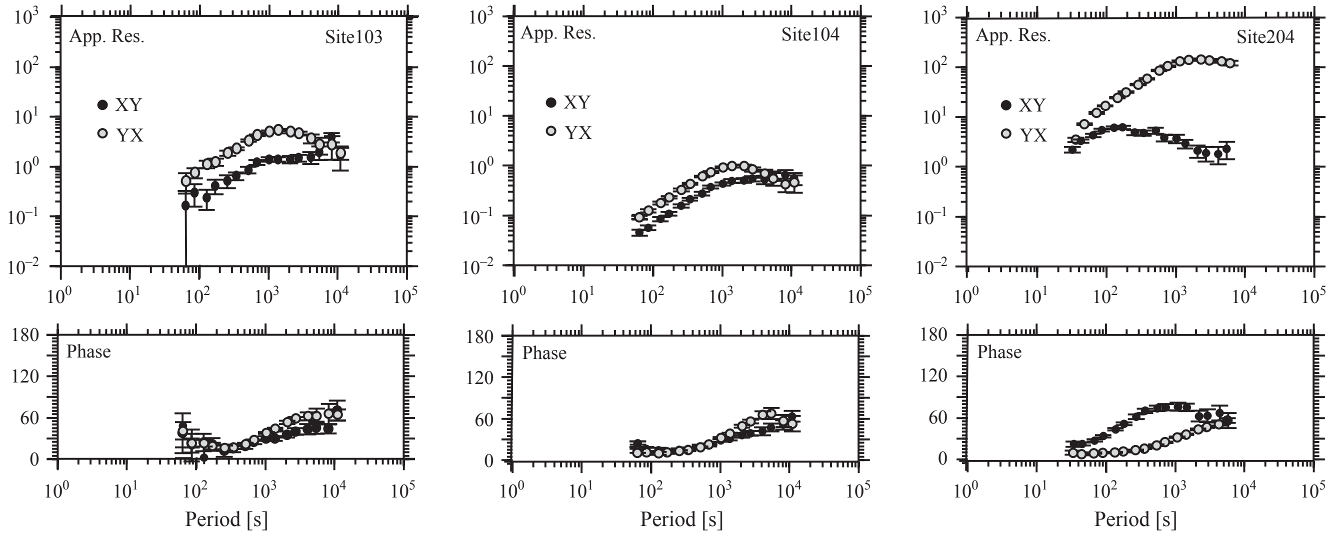


Fig. 8. Apparent resistivity and impedance phase calculated using the robust remote reference method program. Measurement angle rotated to true north and *x*-axis signifies it. Closed circles show *XY* components, and open circles show *YX* components.

We used an acoustic release system that is already used for the Ocean Bottom Seismograph by the Japan Agency for Marine Science-Technology (JAMSTEC). Vessels of JAMSTEC are equipped with an acoustic transducer system that is suitable for use with a Super Short Base Line (SSBL) system. Our acoustic system also accommodates the frequency of this SSBL system. For that reason, it is easy for us to detect its position in the sea or on the seafloor. The transducer continues operating under water after reaching the sea surface, so that it is easy to detect the position of the instrument after it has reached the surface.

Field data

We carried out field test observations in two different places to evaluate the field performance of our instruments. The first field operation was carried out in Sagami Bay with the R/V *Natsushima* with the ROV *Hyper Dolphin* in 2005 (Figure 4). The main purpose of this examination was to confirm the operation of the new arm-folding mechanism. An OBEM and three OBE systems were deployed: about 1 week of EM data was obtained during this cruise. Figure 5 shows the time variation of the OBE system orientation during deployment and landing on the sea floor. This shows clearly that the OBE system retained a very stable posture; it rotated only slightly during sinking. The set-up depths and duration times during the respective descents of the instruments were 1420 m and 29 min, and 1227 m and 25 min. Further, we confirmed the landing posture on the sea floor using photographs obtained with a digital still camera on the ROV *Hyper Dolphin* (Figure 1*b*). These results demonstrate that our instrument retained high stability during deployment. After ~7–10 days of observation, all equipment was recovered. The rate of ascent was ~45 m/min. The ascent rate of existing long-term type OBEMs with rigid electric field arms is ~35 m/min. Therefore, it is clear that our new system provides an ascent rate that is improved by ~30%. This improvement is expected to shorten operation time spent on station.

After the first field test, several experiments were conducted. We recovered all equipment each time. Next, we will show the marine magnetotellurics (MT) results obtained off Tottori prefecture, at depths of 1200 and 230 m (Figure 6). In this experiment, the OBEMs and the OBE system recorded EM data with 8 Hz and 1 Hz sampling rates, respectively. We obtained natural EM data for ~40 days. Deployment and recovery operations were carried out using 500-ton class vessels (*Wakatori-maru*, *Tansei-maru*, and *Seifu-maru*).

The time series of OBEM data was re-sampled at 1 Hz to match the OBE system sampling rate of 1 Hz. Visual confirmation leads us to believe that the time series sampled at 1 Hz were almost free of noise. We estimated MT responses (apparent resistivity and phase difference) using the robust remote reference method developed by Chave et al. (1987). To calculate the MT response at the OBE site, the OBEM magnetic field of site 103 was used as magnetic data for the OBE site. Measurement angle was rotated to true north. Figure 7 presents coherencies between magnetic and electric fields calculated at three sites. Coherencies at both sites were high in the calculated period range. Figure 8 presents the respective computed MT responses for the OBEM and OBE sites. Over the whole period range, the data quality is excellent and response curves are very smooth. Figure 8 also shows that response curves at the two eastern sites are similar, despite the fact that the sites were separated by ~25 km. The shortest period of these results is ~60 s. Short-period responses show apparent resistivities less than 1 Ω.m. However, the western site (Site 204) data shows higher resistivity than the other two sites, and each curve is split in the period range above 100 s. Sounding curves are relatively smooth in the period range of 30 s to 6000 s, although coherency of the *XY* component at this site is worse than for other data.

Summary

To survey crustal and upper mantle structure in detail, we have developed a small OBEM and OBE system with a high sample rate. We used fluxgate sensors for magnetic observations over a period range of a few to 100 000 s. The instrument has an arm-folding mechanism that facilitates assembly and recovery operations. Field observations were carried out to evaluate our instruments' field performance. All instruments were recovered with their acquired EM data. Results of the first experiment show that our system functioned well through all operations and observations. Moreover, the results of other field experiments off Tottori show that the electromagnetic data obtained by the OBEM and OBE systems are of sufficient quality. OBEM data at western sites, at shallow water depth, show enough quality even in the short-period range. This result indicates that the sea-bottom current effect is very small, and that the OBEM can detect natural signals. In fact, the predicted amplitude of magnetic and electric fields with water depth of 100 m is 0.42 nT and 0.41 μV at the period of 10 s, using simple two layered earth model, and these values are larger than system noise. Taken together, these results demonstrate that no instrumental obstacle remains to impede measurements of electromagnetic fields on the seafloor.

Marine magnetotelluric methods using natural signals can only be undertaken to limited survey depths because of attenuation by conductive seawater as mentioned above. From now on, DC resistivity surveys or controlled-source electromagnetic surveys will necessarily be directed at shallower survey targets. For that reason, we have developed a DC resistivity survey system (Goto et al., 2008). This system has an electrically controlled source, which has other capabilities. Therefore, we will propose upgrading the OBEM system with a 24-bit analogue-digital converter and a rapid-sampling OBE system, to develop into a controlled-source electromagnetic survey system. Furthermore, we plan to adapt our OBEM/OBE system for use in long-term surveys by developing small long-term acoustic units. These efforts will make our system flexible for use at different depths for various survey targets and survey terms.

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Appendix: Predicted amplitude of electromagnetic field on the seafloor

We demonstrate here how we predict the amplitude of the magnetic and electric field on the seafloor, to be recorded by an OBEM system. Two-layered earth models are considered: a 1 Ω.m earth covered by seawater layer with 0.3 Ω.m, with water depths of 100 m and 1000 m, respectively. The relationship between magnetic field (B_0, in nT) and electric field (E_0, in μV/m) on the sea surface is described as follows:

$$E_0 = \left(\frac{5}{T}\right) B_0^2 \rho_{a0}.$$

Here, T (s) is the period and ρ_{a0} (Ω.m) is the apparent resistivity on the sea surface, derived by the 1D MT forward calculation. Then, we can estimate the magnetic field (B_{sf}, in nT) and the voltage difference between two electrodes (V_{sf}, in μV) on the seafloor as follows:

$$B_{sf} = A_b B_0.$$

$$V_{sf} = A_e E_0 L = A_e \left(\frac{5}{T}\right) B_0^2 \rho_{a0} L.$$

Here, A_b and A_e are attenuation factors for magnetic and electric field on the seafloor, derived by Constable et al. (1998: see Figure 2). L (m) is the length of the dipole for measuring the electric field, 4.4 m in this study. Although B_0 varies from day to day, the representative amplitude during geomagnetic storms is reported by Matsushita and Campbell (1967) as ~0.1, 0.5, 10, and 20 nT at periods of 1, 10, 100, and 1000 s, respectively. If we use these values as B_0, we can estimate B_{sf} and V_{sf} at various periods and water depths (Table A1).

Table A1. Predicted amplitude of B_{sf} and V_{sf} on the seafloor with water depth of 100 m and 1000 m, respectively. The skin depth with resistivity of sub-seafloor layer (1 Ohm-m) is added.

	Period (s)	1	10	100	1000
W.D. = 100 m	B_{sf} (nT)	0.059	0.42	9.5	20
	V_{sf} (μV)	0.085	0.41	20	8.6
W.D. = 1000 m	B_{sf} (nT)	0.0026	0.13	5.7	16
	V_{sf} (μV)	0.0030	0.071	8.6	6.6
Skin depth for seafloor MT (km)		0.50	1.6	5.0	16

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アーム折りたたみ機構を備えた小型海底電位磁力計および海底電位計の開発

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要　旨：　電気伝導度の高い海水による自然の磁場信号の減衰は短周期ほど顕著であるので、これまでの海域での MT 法探査では主に長周期データを用いたマントル構造探査が主であった。しかしながら、プレート沈み込みと密接な関係のある巨大地震発生帯や資源調査などを探査ターゲットとする場合、1000 秒より短周期のデータが非常に重要となる。1970 年代後半から国内でも海底電磁場観測のための機器開発が進められていたが、地殻や上部マントルを調査するのに適切な機器が存在しなかったため、高いサンプリングレートで観測が可能な小型海底電位磁力計および海底電位計の開発を行った。本装置は電位測定アームを浮上時に折りたたむ機構を備えているのが特徴で、相模湾で実施された試験観測において仕様通りの動作をすることが確認された。また、鳥取沖での観測では水深約 1200m 前後の観測のみならず、水深約 230m の浅海でも良好な MT レスポンスを得ることができた。このことは、開発した装置が深海のみならず浅海でも十分な性能を発揮することを示している。

キーワード：海底電位磁力計，電位測定アーム折りたたみ機構，フラックスゲート磁力計

팔–접힘 구조를 가지는 소규모 OBEM 과 OBE 시스템 (기술보고서)

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요 약： 자연적인 자기장은 전기 전도도가 높은 물에서는 감쇠한다. 이러한 이유로, 해양 지전류 탐사법에서 장주기 (1000 – 100000 초) 자료를 측정하였다. 맨틀 구조가 해저 지전류측정의 주된 적용 대상이었다. 반면에 지각구조를 밝히기 위해서, 예를 들어, 메카트러스트 지진지역이나 천연자원조사와 같은 분야에서는 보다 짧은 주기의 전자기장에 대한 자료가 중요하다. 예를 들어 전자의 조사를 위해서는 1000초 보다 짧은 주기를 가지는 전자기장 자료가 필요하다. 그러나, 이러한 용도를 위한 적절한 해저 전자력계 (OBEM)가 없기 때문에 높은 샘플링 속도와 조립과 회수 과정을 용이하게 하기 위한 팔-접힘 구조를 가지는 소규모 OBEM과 해저 전위계 (OBE)를 개발하였다. 자기장 측정을 위하여 플럭스게이트 센서를 이용하였다.

개발된 장비의 현장 성능을 평가하기 위한 현장측정이 이루어졌다. 모든 장비는 전자기 측정자료를 획득한 채로 회수되었다. 첫번째 실험의 결과, 개발된 시스템은 동작과 측정 모두 그 기능이 정상적으로 잘 이루어지고 있음을 확인하였다. 돗토리 근해에서의 또 다른 현장실험 결과는 새로운 OBEM과 OBE 시스템으로 획득된 전자기 자료가 탐사 목적에 충분한 양질의 자료라는 주장을 뒷받침해 주었다. 이러한 결과들은 개발된 장비들이 해저면 전자기장 측정에 대한 장비적인 장애를 모두 해결하고 있음을 확증하고 있다.

주요어：해저 전자력계, 팔–접힘 구조, 플럭스게이트 자력계