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A new seafloor electromagnetic station with an Overhauser magnetometer, a magnetotelluric variograph and an acoustic telemetry modem

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A new type of SeaFloor ElectroMagnetic Station (SFEMS) has been newly developed by adding a magnetotelluric (MT) variograph to its prototype built previously (Toh and Hamano, 1997). New SFEMS is able to conduct long-term electromagnetic (EM) observations at the seafloor, which is one of the principal goals of the Ocean Hemisphere Project (OHP). Long-term seafloor EM observations enable us to probe into the deep Earth (both the mantle and the core) by improving the spatial coverage of the existing EM observation network. The SFEMS has been tested in three sea experiments to yield 3 components of the geomagnetic field, 2 horizontal components of the geoelectric field and 2 components of tilts in addition to the absolute geomagnetic total force. The SFEMS is designed for measuring these EM signals at the seafloor continuously for as long as 2 yrs.

The SFEMS mainly consists of the following three parts: (1) An Overhauser proton precession magnetometer for the absolute measurements of the geomagnetic total force with a possible bias of less than 10 nT. (2) An MT variograph that measures the rest of the EM components and tilt. (3) An Acoustic Telemetry Modem (ATM) that allows us to control/monitor the seafloor instrument as well as data transmission at the maximum rate of 1200 baud.

Construction of seafloor EM observatories in regions where significant EM data have never been collected is now quite feasible by development of the SFEMS.

1. Introduction

Recently, the necessity for long-term seafloor EM observations has been recognized (Chave *et al.*, 1995), and is now being established as a new area of marine geophysical research in various international projects (Kasahara *et al.*, 1995; De Santis *et al.*, 1997). Two kinds of observation are now available: realtime monitoring of seafloor EM fields utilizing semi-permanent infrastructure and off-line measurements by long-life pop-up type instruments. Monitoring of Earth's geoelectric field using trans-ocean submarine cables (Lanzerotti *et al.*, 1985) is a typical example of the former while the latter is realized by a few large international co-operative projects such as the Mantle ELectromagnetic and Tomography (MELT) experiment (Forsyth and Chave, 1994). In Japan, OHP has been operating since 1996, which is also a seismic-EM joint project like MELT to probe into the deep Earth through the ocean window.

We have succeeded in the development of an SFEMS in conjunction with OHP. The objectives of SFEMS are two fold:

1) To probe the electrical conductivity structure of the deep Earth via long-term seafloor magnetotellurics.
2) To detect geomagnetic secular variation at the deep seafloor.

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Since Earth's electrical conductivity is known to be a strong function of Earth's temperature as well as volatile fraction, the former will lead to determination of a geotherm of the Earth provided that both the effect of volatiles and lateral inhomogeneities of Earth's electrical conductivity near the surface are correctly removed. It should be noted, however, that the seafloor electric field is dominated by the oceanic dynamo effect at periods longer than a few days and hence the MT method cannot be utilized at very long periods in the ocean. This limitation should be taken into account in achieving the first objective.

Schultz *et al.* (1993) showed that even the discontinuities corresponding to those in seismic velocity are detectable by long-term MT measurements on a shield. Although Lizarralde *et al.* (1995) failed to detect the corresponding conductivity contrasts beneath the seafloor, long-term seafloor magnetotellurics in the stable temperature environment may provide a clear view of the Earth's deeper conductivities. Recent seismic studies (Flanagan and Shearer, 1998) showed the undulation of the 410 km discontinuity is at most 40 km, which is too faint to be resolved by the MT method. However, topography of the 410 km discontinuity is even within the scope of long-term MT especially in regions of active mantle upwelling as Nolasco *et al.* (1998) have imaged the mantle plume in the Tahiti hot spot region.

Although it is rather difficult to estimate the electrical conductivity of the lower mantle by seafloor magnetotellurics alone, it is possible to derive its upper bound by detection of the geomagnetic secular variations with time scales of

Table 1. Specifications of SFEMS.

Resolutions	0.1 nT, 0.3 μV (5.1 m span $\rightarrow$ $\sim$60 nV/m) and $\sim$30 μradian
Sampling interval	Every minute (Selectable; $\geq$10 sec)
Baud rate	max. 1200 baud $\sim$6 min/month/component
ATM frequency band	15 to 20 kHz
ATM acoustic source level	+190 dB (re 1 μPa @ 1 meter)
Life time	384 days (OBEM)
	1 yr (ATM) $\sim$ Capable of 15 h continuous transmission
	2 yrs (Overhauser and acoustic release)
Submersible depth	6000 m
Power supply	Lithium batteries
Data storage	SRAM and flash memory
Recording modes	I. Full recording: Every 360 samples
	II. Differential recording: Other samples

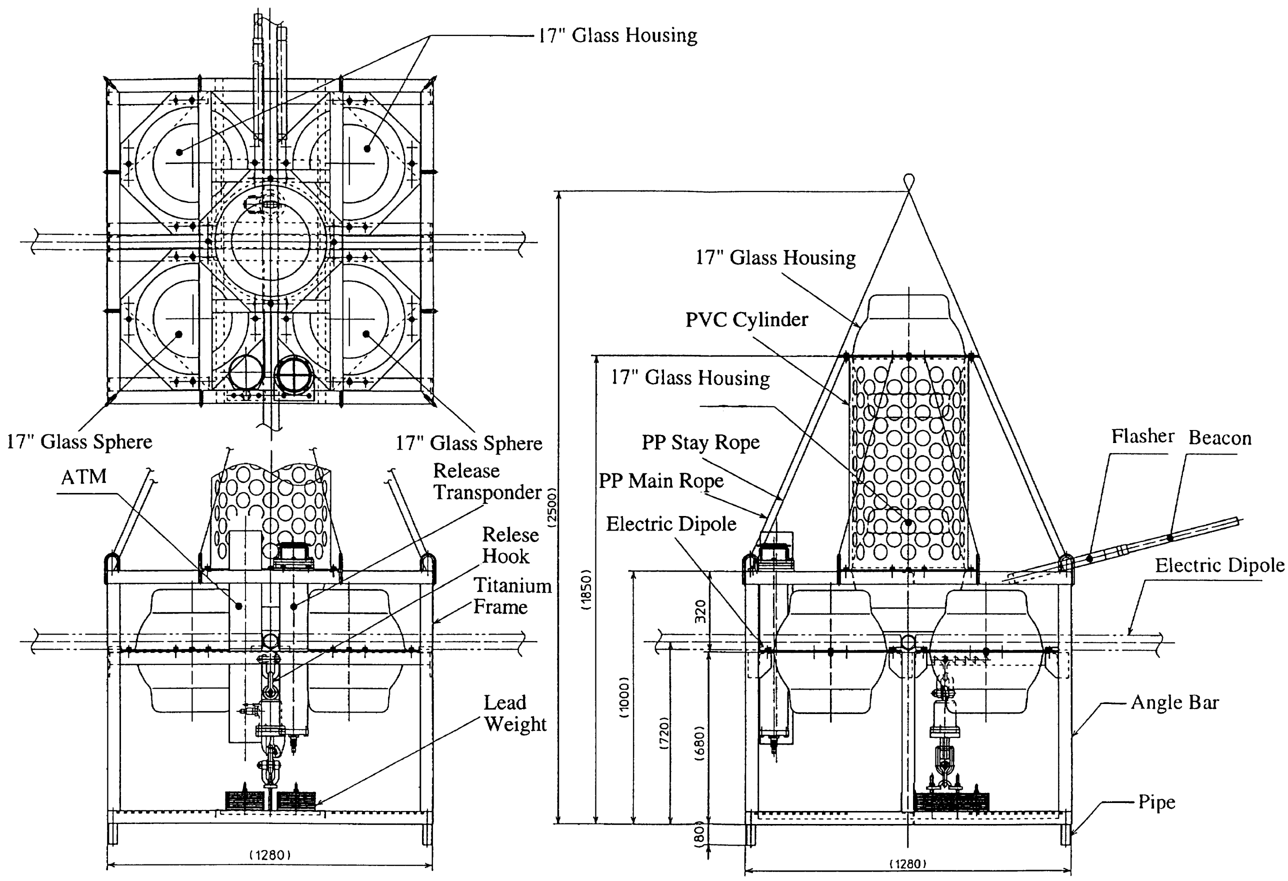


Fig. 1. Outer view of SFEMS.

several tens of years (Yokoyama, 1993) provided that better knowledge of the dynamics in the Earth's outer core is available. The biased distribution of existing geomagnetic observatories will be greatly alleviated by the installation of the SFEMSs in regions, e.g., in the northwest Pacific, where continuous EM observations have never been carried out.

The intent of this paper is to report briefly to what extent SFEMS is capable of probing into the deep Earth. In the following two sections, instrumentation and experiments at sea using the SFEMS will be described. Some results and

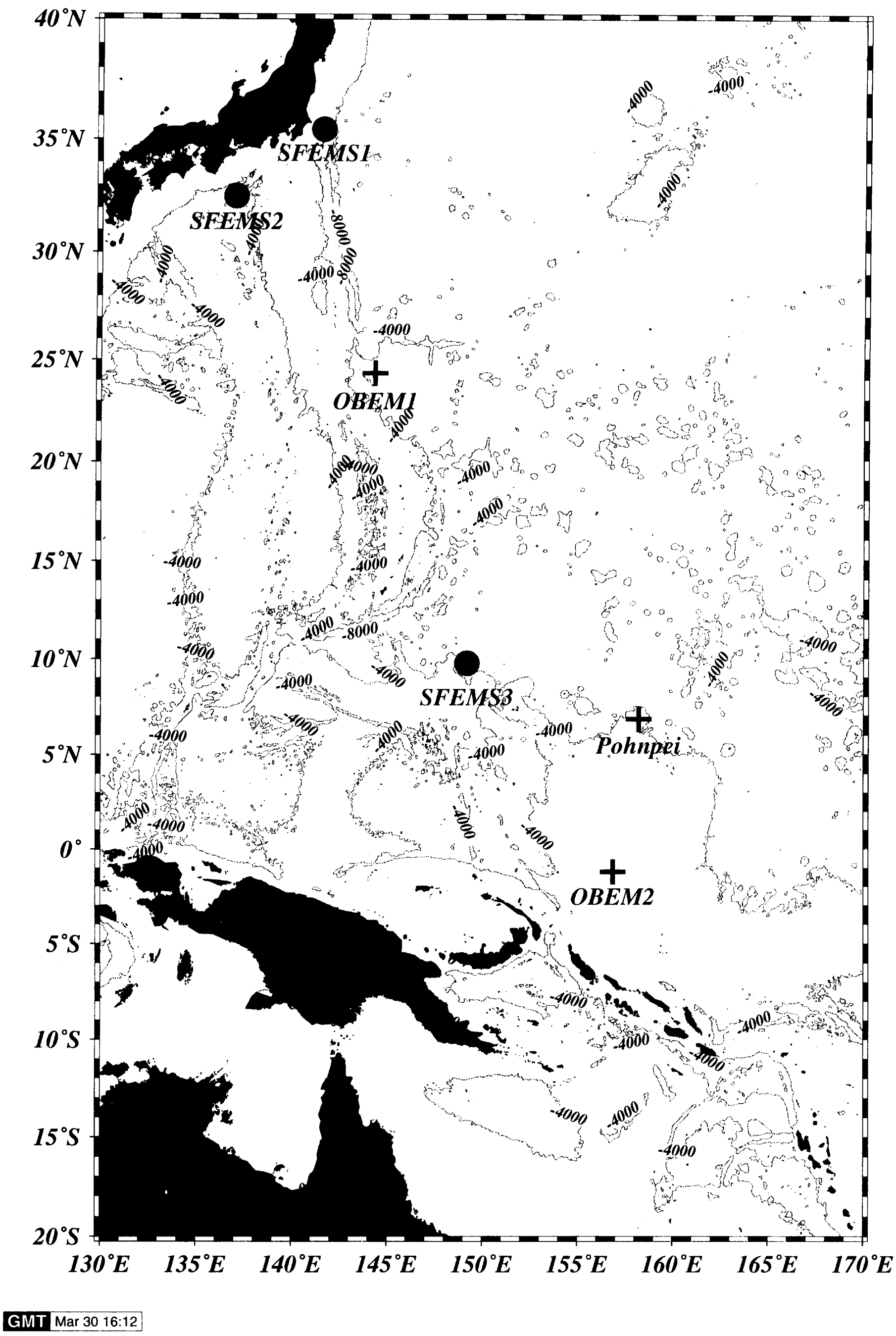


Fig. 2. Site map of the three sea experiments conducted so far (circles). Crosses are the seafloor/island reference sites where simultaneous magnetic data are available for SFEMS3. 4000 and 8000 m depth contours are also shown.

future problems will be summarized in the last section.

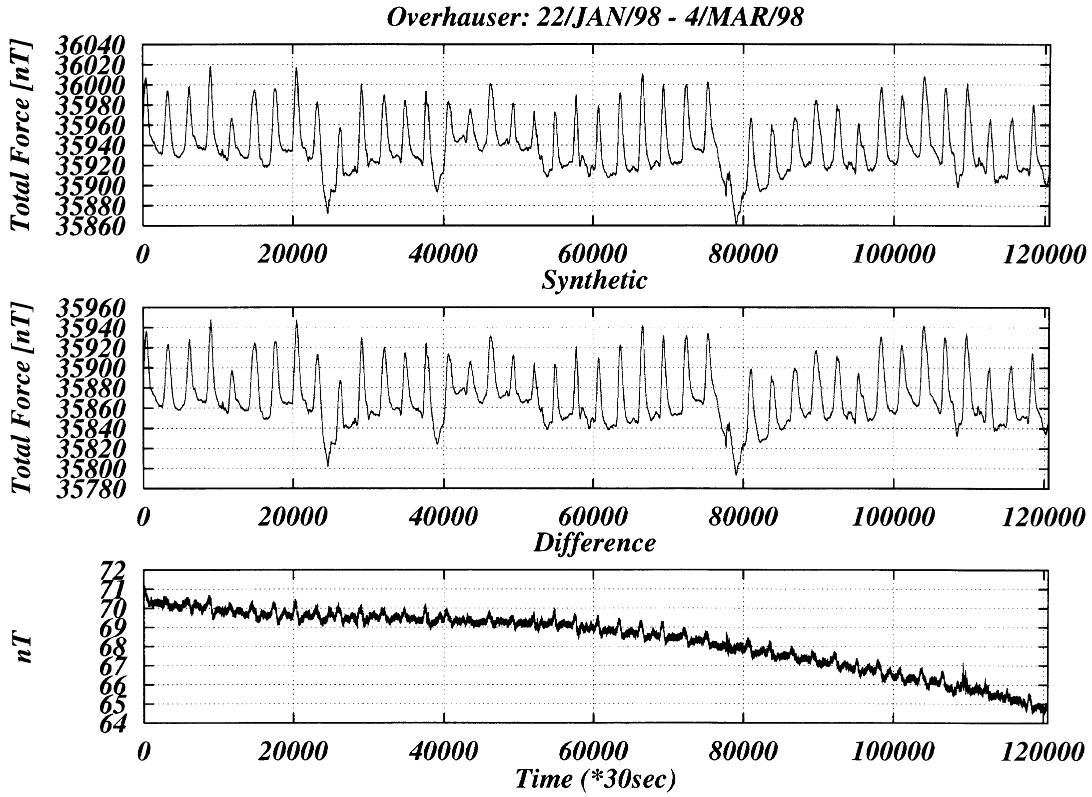
2. Instruments

The SFEMS consists mainly of an Overhauser absolute scalar magnetometer, an MT variograph and an ATM, which allows acoustic communication with the seafloor unit from the sea surface. These three main parts of SFEMS will be itemized in the following subsections together with their general features.

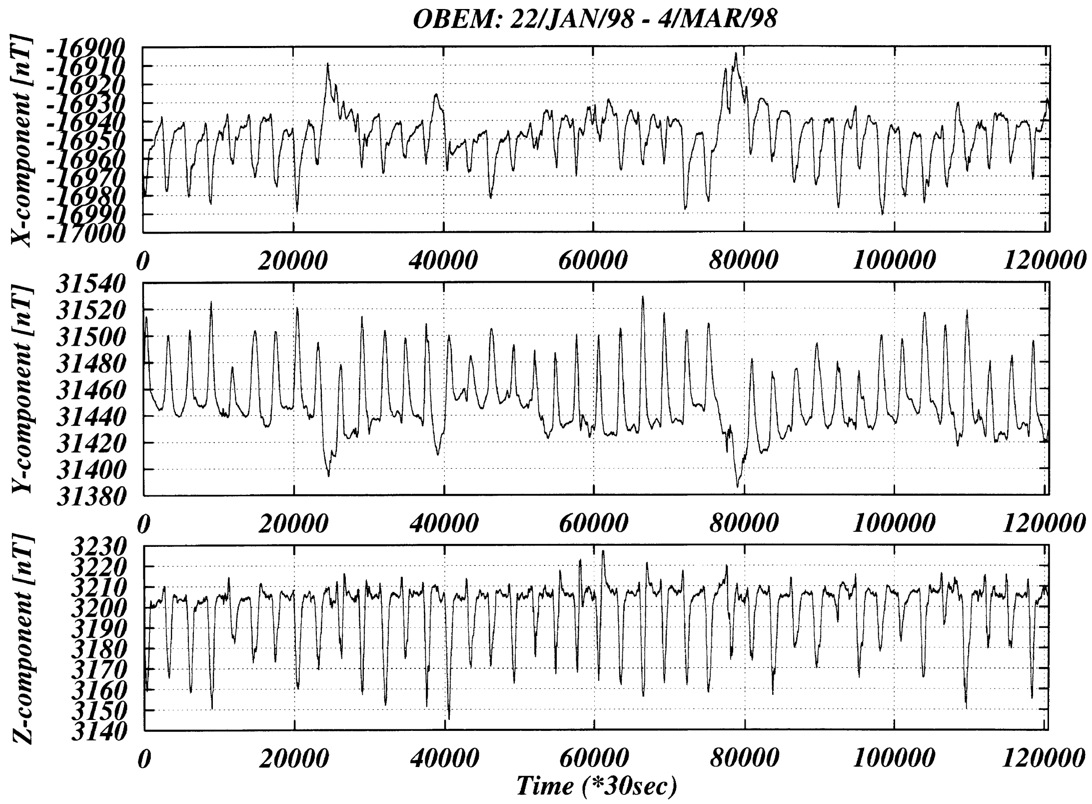
2.1 General

Table 1 summarizes the specifications of the SFEMS. What was intended for the SFEMS is data acquisition without recovery of the whole system, including control over the seafloor instrument from the sea surface and realtime data transmission whenever desired. These three functions were successfully made available by use of the attached ATM.

Figure 1 shows the physical dimensions of the SFEMS. The Overhauser magnetometer is housed in a 17” pressure-tight glass sphere and is mounted at the top of a PVC cylinder on a non-magnetic titanium frame. It is located as high as approximately 1.85 m from the seafloor. Two of the 6 glass spheres used are for buoyancy alone, which give SFEMS +40 kg buoyancy, while the remaining four contain lithium batteries, an interface board connecting the EM sensors to the

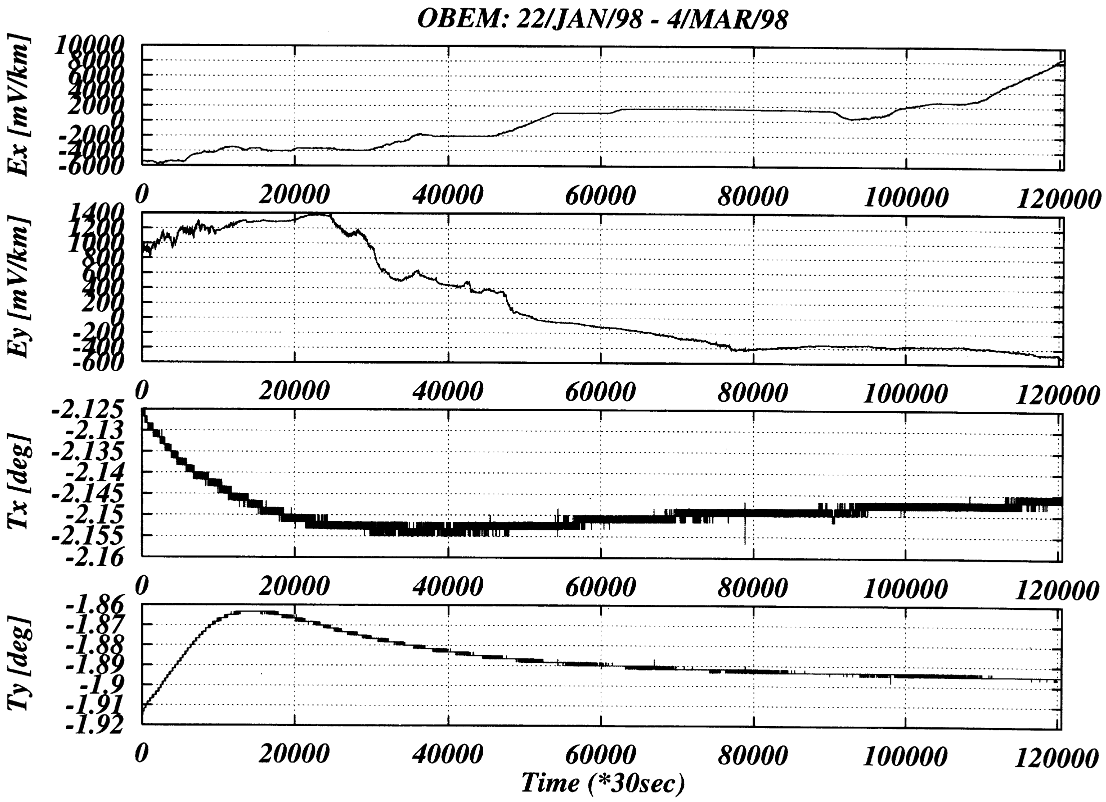


(a)



(b)

Fig. 3. The 8 components observed by the new SFEMS. (a) The absolute geomagnetic total force by the Overhauser magnetometer (top), the synthetic total force calculated from the three geomagnetic components by the MT variograph (middle) and the difference in between (bottom). (b) Unrotated 3-component geomagnetic field. (c) Unrotated horizontal geoelectric field (upper two) and tilt (lower two), respectively.



(c)

Fig. 3. (continued).

ATM, the MT variograph and the Overhauser magnetometer, respectively. All of the timing of the SFEMS is controled by a quartz clock on the interface board that has an accuracy of ±0.2 ppm. The SFEMS assembly is completed by adding an ATM, a transponder for acoustic release, a release hook, 100 kg lead weights and a pair of radio transmitter and flasher in addition to the glass spheres. Acoustic release of the lead weights is enabled by the explosion of a gas generator in the release hook. The transponder controlling the acoustic release is also made of non-magnetic titanium and has a lifetime of as long as 2 yrs. If fully equipped, the SFEMS weighs 385 kg in air and 60 kg in water, respectively. In order to guarantee a stable "Overhauser Effect", all metallic equipment including the transmitter and the flasher is kept away from the Overhauser sensor. Hence, the SFEMS will lie on its side at the sea surface to let the transmitter and the flasher extend out of water to facilitate.

2.2 Overhauser proton precession magnetometer

The most outstanding feature of the SFEMS is the first application of the Overhauser magnetometer to the deep seafloor. Overhauser magnetometers are known to be the only sensors for practical use for long-term absolute magnetic measurements by unmanned systems because of their low power consumption. In the following, the principle of the Overhauser proton precession magnetometer will be reviewed to reveal why it works with the minimum power.

It is well-known that any charged particles begin to precess in an ambient magnetic field, B. The Larmor Frequency of the precession, ω, is given by;

$$\omega = -qB/2m, \tag{1}$$

where q and m are the charge and the mass of the particle. Typically, $\omega_e \sim 1.4$ MHz for electrons and $\omega_p \sim 2$ kHz for protons in the geomagnetic field of, say, 50000 nT. However, ω_e can be as large as a few tens of MHz for certain chemicals that contain free radicals, e.g., unpaired electrons.

Ordinary proton precession magnetometers can acquire sufficient sensor magnetization M;

$$M = N\gamma_p \hbar I, \tag{2}$$

by applying a very large polarization magnetic field to a proton-rich fluid in the sensor. In Eq. (2), N, γ_p, $\hbar$ and I ($= \pm 1/2$) are the number of efficient protons in the liquid, the gyromagnetic constant of the proton, Planck's constant and the quantum number of the proton spin, respectively. This type of magnetization method requires a huge amount of energy due to the large polarization field required and a long excitation time. However, once sufficient sensor magnetization is achieved, determination of the absolute strength of the ambient magnetic field, B, is straightforward and obtained by $B = \omega_p/\gamma_p$. We need only to measure ω_p generated by the precession of M as precisely as possible since γ_p is very accurately known.

The difference between an Overhauser proton magnetometer and an ordinary proton magnetometer consists in the mag-

Table 2. Summary of deployments.

Site name	Latitude	Longitude	Depth	Start time	Duration
SFEMS1	35°24.85′N	141°34.96′E	1593 m	3/AUG/96 18:40 UT	12 hrs
SFEMS2	32°30.06′N	137°00.08′E	4192 m	11/FEB/97 01:20 UT	19 days
SFEMS3	9°44.98′N	149°10.01′E	5378 m	22/JAN/98 00:00 UT	42 days

netization methods of the sensors, viz., the Overhauser proton precession magnetometer takes advantage of the "Overhauser Effect" (Overhauser, 1953) or "Dynamic Polarization" to acquire sufficient magnetization M. Unpaired electrons of free radicals in the proton-rich liquid tend to couple with nuclear spins. Since the nuclear spin-electron spin coupling obeys Maxwell-Boltzmann Statistics, the steady state condition for the spin-spin coupling is given by (Abragam, 1961);

$$N_+ n_- W_{(+-)\to(-+)} = N_- n_+ W_{(-+)\to(+-)}, \qquad (3)$$

where N, n and W are the number of proton spins, that of electron spins and the transition probability between two different energy levels, respectively. The subscripts $+$, $-$, and $(+-) \to (-+)$ denote the "spin-up" and "spin-down" states and the transition from an "up-down" pair to a "down-up" pair, for example. According to Maxwell-Boltzmann Statistics, the ratio between the two transition probabilities is given by:

$$\begin{aligned} W_{(+-)\to(-+)}/W_{(-+)\to(+-)} &= \exp\{(E_{+-} - E_{-+})/kT\} \\ &= \exp\{\hbar(\omega_e - \omega_p)/kT\}. \qquad (4) \end{aligned}$$

If we apply an external RF field of angular frequency ω_e to saturate the electron spin spectrum (i.e., to let $n_+ = n_-$), it follows from Eqs. (3) and (4):

$$N_+/N_- = \exp\{\hbar(\omega_e - \omega_p)/kT\}. \qquad (5)$$

The "proton spin-up" to "proton spin-down" ratio is greatly enhanced as large as several hundreds to several thousands since $\omega_e \gg \omega_p$ whereas, in the absence of the spin-spin coupling, this ratio should remain $\exp(-\hbar\omega_p/kT)$ which is nearly equal to unity. As a result, an Overhauser magnetometer enables energy saving and faster sampling because the saturation of electron spin flip (to make $n_+ = n_-$) can be achieved by very small energy and requires almost no time.

Specifically, the Overhauser proton precession magnetometer attached to SFEMS can measure one-minute values of the absolute geomagnetic total force with an accuracy of 0.1 nT for as long as 2 yrs by a 18V-120Ah lithium cell package, which is impossible by ordinary proton precession magnetometers. Faster sampling is also possible at the cost of lifetime. However, it can not be faster than 5 sec since the present Overhauser sensor is not a so-called "Proton Oscillator" that creates continuous proton precessions. It takes at least a few seconds (the relaxation time of the proton precession) per measurement.

2.3 MT variograph

The most significant difference of new SFEMS from the older version is the addition of a 7-component MT variograph. It is able to measure the 3-component geomagnetic field, 2-component horizontal geoelectric field and two components of tilt for as long as 384 days at 1 min intervals. The geomagnetic field is measured by ring-core fluxgate sensors while the geoelectric field is sensed by two orthogonal electric dipoles with a span length of 5.1 m. The TOK silver-silver chloride electrodes (Perrier *et al.*, 1997) were used since the electrodes were proved to have the most reliable long-term stability for use at the seafloor. The electrode chopper that removes the baseline errors of the geoelectric measurements (Filloux, 1987) is not adopted to avoid magnetic noises generated by the chopping system. The variograph was originally developed for use in the MELT experiment (Toh *et al.*, 1996). However, its adaptability enables integration into the SFEMS.

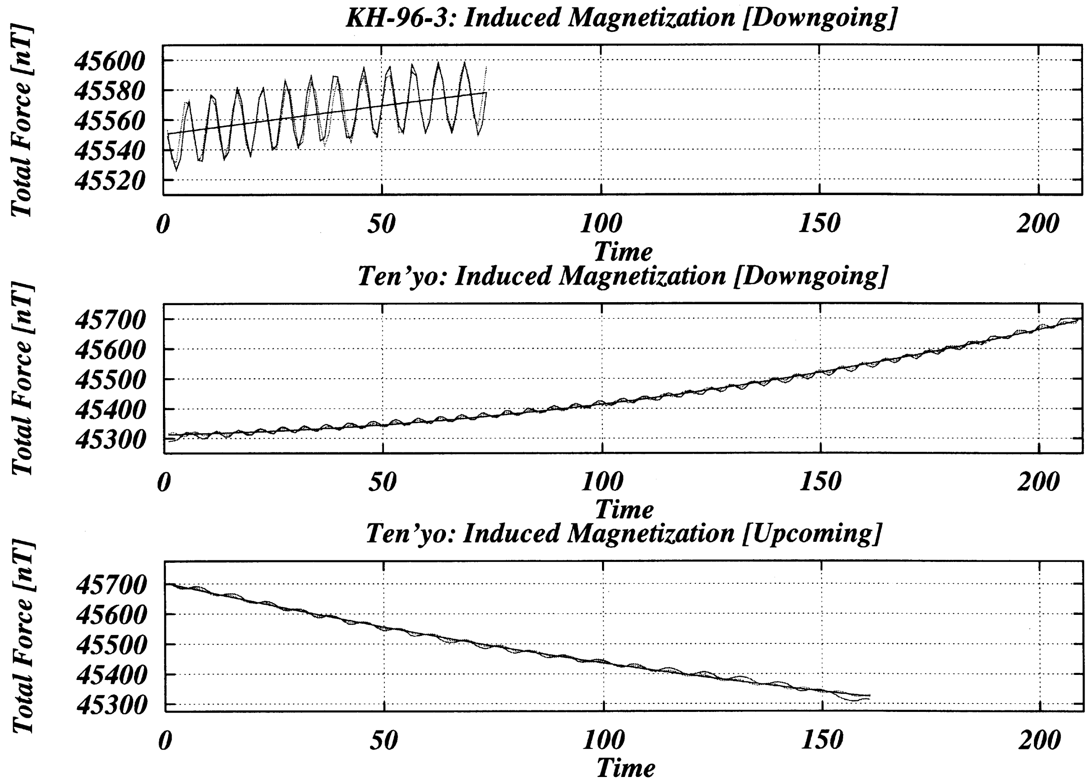
2.4 Acoustic telemetry modem

The ATM allows control or monitoring the SFEMS at the seafloor as well as providing (realtime if desired) data transmission. The present ATM is capable of continuous 15 h transmission at the maximum rate of 1200 baud using Multiple Frequency Shift Key (MFSK). The baud rate is acoustically changeable. Since 10 bits are required to send a byte, it requires 6 min to transmit a month of one-minute-sampled data per component. It follows that it takes about 9.6 hrs to retrieve 8-component 1-year data, which can easily be covered by the present ATM. The transmitted data from the seafloor will be encoded and stored into a PC connected to an on-board deck unit of the ATM. Tuning of the Overhauser magnetometer, which is sometimes most critical to collect good readings of the geomagnetic total force, is also possible by choosing a suitable measuring range through the ATM.

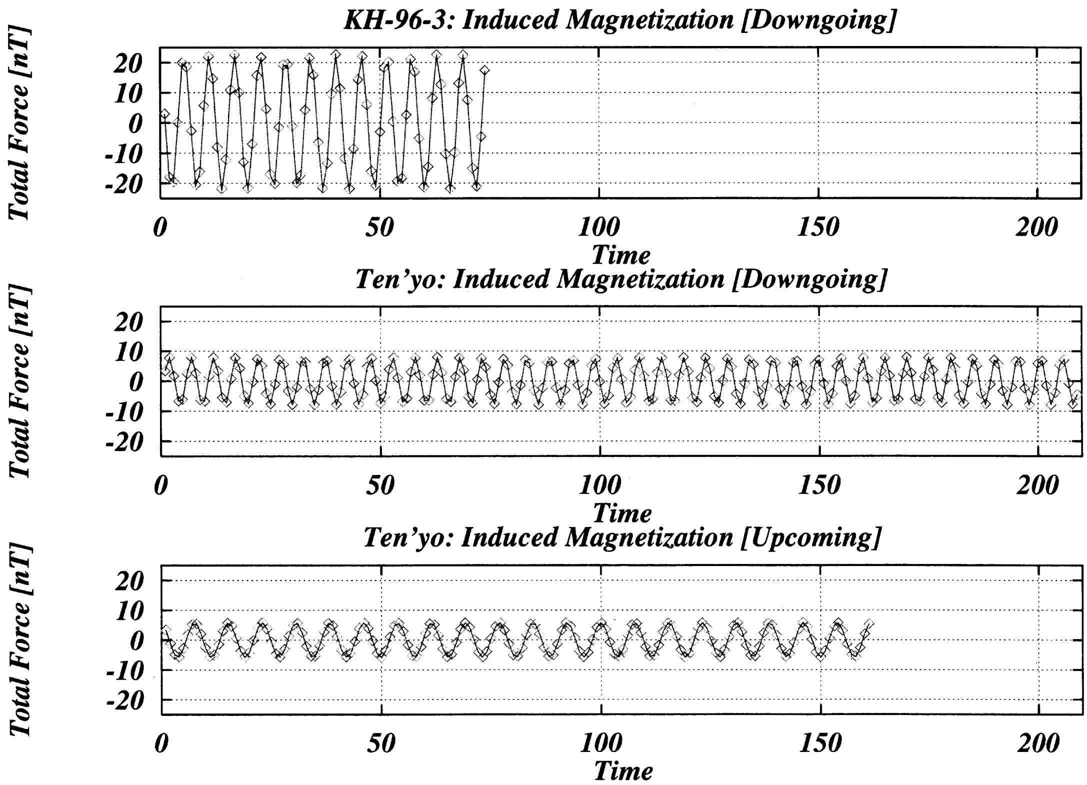
3. Sea Experiments

The SFEMS thus developed was tested three times at sea. Table 2 summarizes the three deployments conducted so far. The sampling rate was fixed at 30 sec in all experiments. Figure 2 shows a map of the installation sites. A wire-suspended test was tried at the first deployment to confirm the functions of the older version of SFEMS and acoustic communication. The realtime data telemetry of the seafloor geomagnetic total force was also carried out then (Toh and Hamano, 1997).

The SFEMS was suspended at the tip of the ship's wire with an additional weight of 100 kg and lowered as deep as 500 m at a speed of 0.2 m/sec. Successful realtime mon-



(a)



(b)

Fig. 4. (a) The sinusoidal changes of the absolute geomagnetic total force observed on the way to/from the seafloor. (b) Interpretation of the observed sinusoidal changes (diamonds) by the induced magnetization models (solid lines).

itoring implied the stability of the measurement of the geomagnetic total force and acoustic communication even at a relatively high noise level. After the wire-suspended test, the realtime data telemetry from the seafloor was tried for about 30 min. It yielded an averaged value of the seafloor geomagnetic total force at the Choshi spur of 45582.0 nT. The standard deviation of the measurements was also calculated by a polynominal fit of the data to give 0.10 nT. The deviations are almost within ± 0.2 nT, which is equal to the absolute accuracy of the Overhauser magnetometer utilized here.

Long-term reliability of the SFEMS was examined in the remaining two experiments. Figure 3 shows time series of the EM components and tilt collected in the third experiment. It is evident from the figure that continuous measurements of the seafloor EM fields was successful. The drift rate of the 3-component fluxgate magnetic sensor of the variograph can be estimated from the long-term trend shown in the bottom diagram of Fig. 3(a) as well. The high frequency residuals in the figure are due to incorrect scale factors of the fluxgate sensor, which can be minimized by calibration of the sensors.

An interesting topic of SFEMS is its magnetic bias determination using the geomagnetic total force data during its travels to/from the seafloor. Since the instrument rotates with a period of 3 to 4 min in seawater, the geomagnetic total force shows sinusoidal variations as shown in Fig. 4 superimposed on gradual trends due to either the dipole gradient of the Earth's main field (top of Fig. 4(a)) or local magnetic anomalies (bottom two of Fig. 4(a)). The extracted sine curves can then be interpreted in terms of either induced or remanent magnetization of the instrument. In Fig. 4(b), they were explained by least squares fits to non-linear induced magnetization models. It turned out that the sine curves can be accounted for by induced magnetizations placed 0.50 to 0.70 m below the Overhauser sensor. It is noteworthy that the intensity of the magnetization is time-dependent. The initial amplitude of the sine curve obtained at the first sea experiment was as large as 25 nT. However, the amplitude rapidly decreased to 9 or 7 nT in the second experiment conducted 6 and 7 months after the first experiment, respectively, while the sinusoidal change was not recognizable any more in the third experiment. It, therefore, can be concluded that the SFEMS has been so demagnetized as to measure the absolute geomagnetic total force at the seafloor with a possible bias of less than 10 nT now.

Acoustic ranging of SFEMS was also conducted whenever possible. Acoustic slant ranges and respective ship's GPS positions were measured simultaneously. These positioning data were combined to give a least squares solution of the precise instrument's positions based on the geodetic datum of WGS84 at the seafloor. As a result, the instrument's positions at the seafloor were determined within ± 50 m.

4. Summary

The new SFEMS capable of measuring 8 components has been successfully developed and tested in the sea experiments. It enabled the long-term absolute measurements of the seafloor geomagnetic total force by the Overahuser magnetometer with a possible bias of less than 10 nT.

In the future, 9600 baud transmission using a Phase Shift Key (PSK) ATM is desirable instead of MFSK ATM though it is still feasible to handle the 1-year dataset in 10 hrs by the presently fastest 1200 baud transmission. Stable acoustic communication at much longer distances is also preferable since the error rate of the present ATM is proved to abruptly rise up at distances longer than two nautical miles. Orientation of the SFEMS at the seafloor can now only be determined with respect to the geomagnetic north, which can be calculated from the 3-component magnetic data by the MT variograph. Addition of a gyrocompass is another necessary future improvement since knowledge of the geographical orientation is crucial to distinguish the true geomagnetic secular variation from the drift of the magnetic sensors.

SFEMS has been originally developed for long-term seafloor EM observations in search for detecting deeper structures via long-term seafloor magnetotellurics and/or geomagnetic secular variational signals. Possible installation sites of SFEMS's will be found in regions such as the northwest Pacific where continuous EM observations have never been carried out. SFEMS, however, turned out applicable to tectonomagnetism as well since ATM enables repetitive absolute geomagnetic measurements at the seafloor which have been logistically very difficult so far.

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