Physics of the Earth and Planetary Interiors, 7 (1973) 323–338

TECHNIQUES AND INSTRUMENTATION FOR STUDY OF NATURAL ELECTROMAGNETIC INDUCTION AT SEA

JEAN H. FILLOUX
Scripps Institution of Oceanography, La Jolla, Calif. (U.S.A.)

Accepted for publication February 2, 1973

Electromagnetic fluctuations in the ocean have external sources above (ionospheric) and below (secular variation of the earth's magnetic field), and internal, purely oceanic sources associated with interaction between water velocity fields and the earth's field. Energy diagrams indicative of the electromagnetic activity in the sea are presented. From the latter, estimates of the resolution required in electromagnetic research at sea can be made. Absolute minima of 1 γ and 0.05 μV/m are necessary for magnetic and electric fields, respectively. Because the ocean shields overhead sources at frequencies above a few hundred c/h and because motional fields have weak signatures, a resolution at least 10 times higher would considerably enhance the scope of such research.

The response of electric field instruments to motionally induced fields depends upon whether they are fixed or drifting, but both types respond similarly to fields of external origin.

The most stringent limitation to electric field sampling in the sea is the difficulty in achieving low-noise electrical continuity between measuring circuits and sea water. Even the best matched silver–silver chloride electrodes introduce variable electrochemical signals hard to maintain below a millivolt. These mask very low frequency signals unless sophisticated techniques such as electrode switching are used.

1. Introduction

Excepting the ancient discovery of the earth's magnetic field, the earliest identification of terrestial electromagnetism was the discovery by Gellibrand in 1635 of the secular variation of the earth's field. Almost a century later Graham discovered the existence of quasi-continual rapid magnetic fluctuations that Andreas Celsius and Hiorta related to aurorae. Another century later when telegraph lines began to flourish Barlow demonstrated the existence of spontaneous earth electric currents and the electric vs. magnetic storm correlation was recognized. Fundamental to these findings were the compass, of uncertain origin, perhaps used in China thousands of years ago and known in Europa during the Middle Ages, the galvanometer and telegraph lines. It is noteworthy that all these discoveries originated on land and also that the earliest induction process observed in the ocean was reported less than a century ago (Adams, 1881). One should, however, remember Faraday's speculations (1832), about a motionally induced electric field in water streams and his attempts to detect it across the Thames, failing by lack of adequate instrumentation. This field was observed in 1851 by Wollaston while studying telluric currents across the English Channel using a telegraphic cable. The presence of lunar periodicities puzzled Wollaston who postponed his report. Hence, in the mid 1800's the mixed nature of telluric currents at sea, those induced by magnetic pulsations, and those induced by water motion caused hesitations in interpretation.

Early this century, Young et al. (1920) demonstrated that the oceanic electric field could be recorded aboard a steaming ship by electrodes towed astern and that such signals are related to water motion. This introduced an alternate electric field instrument concept, the "drifting" type, in opposition to the "fixed electrodes" type used on land. The properties of the two, however, differ considerably.

The late beginning of electromagnetic induction discoveries at sea was followed by slow initiation of oceanic research in this field and our present efforts to exploit electromagnetic induction at sea continue

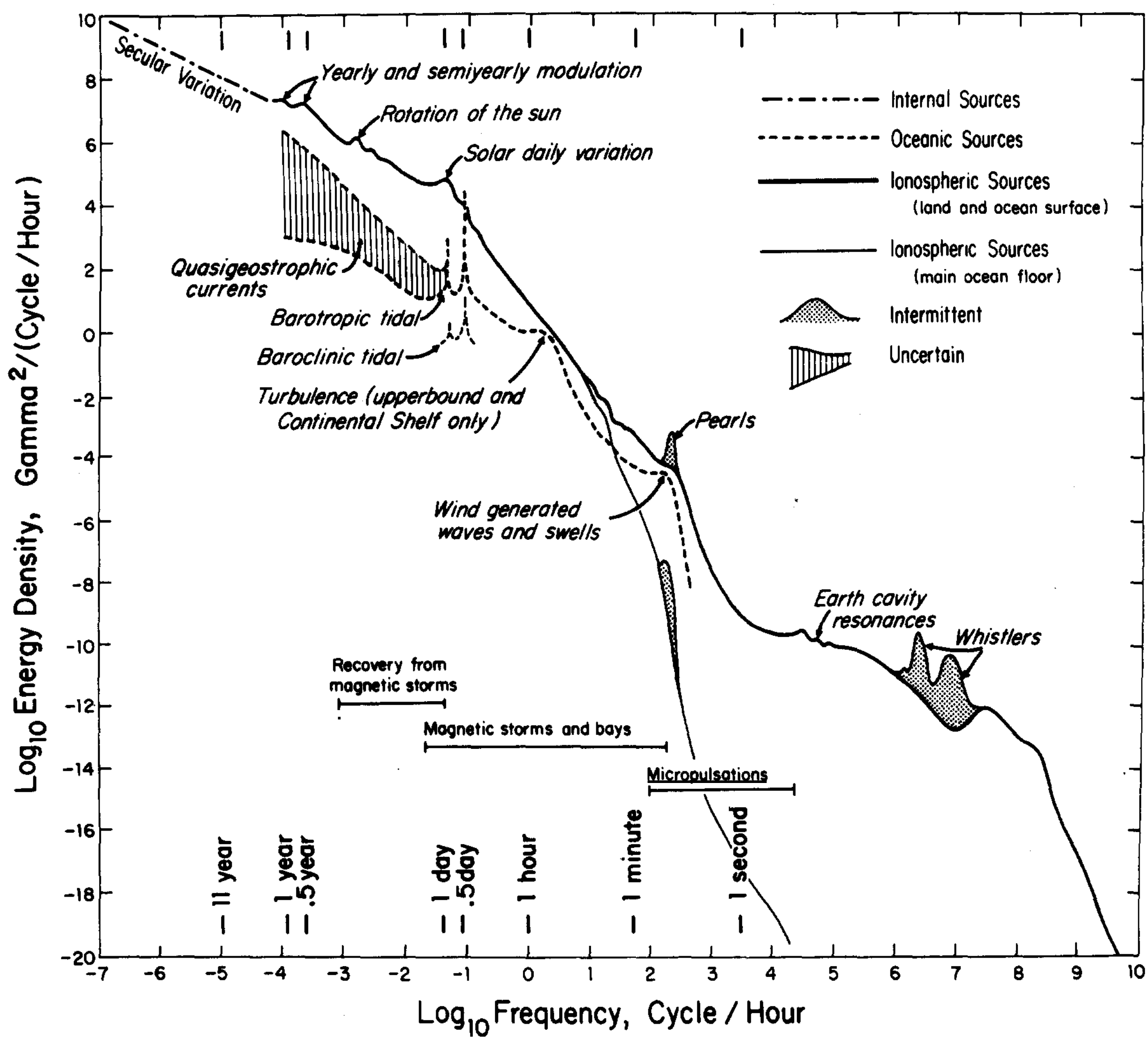

Fig. 1. Energy level of magnetic pulsations in the ocean.

to lag their counterpart on land. This situation is undoubtedly due to the hostile and discouraging nature of the oceanic environment with its intense and destructive motions, the strong chemical activity of its water, its abyssal pressure and the remoteness of the only stable place, the sea floor. Such factors make the simplest observations very difficult and render useless almost all land-type instrumentation.

Another problem inherent in the ocean is the existence there of two induction processes with broad frequency overlap, one having for sources external pulsations (ionospheric), the other involving local interaction of velocity fields with the earth's field. Fortunately, in return for this complexity two subjects can be enlightened by electromagnetic observations at sea; (1) induction by magnetic pulsations which bears on the earth's structure; and (2) oceanic water motions. Both are interrelated and must be considered together. This contributes to extend the coverage and variety of observations necessary to achieve adequate interpretation. The instrumentation to fulfill this goal is in its infancy.

2. Energy levels of the natural fields

In the following we use the rationalized M.K.S.-system of units. We refer to magnetic field the vector

TABLE I
Seawater skin depth as a function of frequency (assumed conductivity = 4 $\Omega^{-1} m^{-1}$)

Frequency		D (meters)
Cycles per hour	hertz	
$3.6 \cdot 10^3$	1	252
10^3	$2.8 \cdot 10^{-1}$	478
$3.6 \cdot 10^2$	10^{-1}	780
10^2	$2.8 \cdot 10^{-2}$	1480
$3.6 \cdot 10^1$	10^{-2}	2520
10	$2.8 \cdot 10^{-3}$	4780
3.6	10^{-3}	7800

B classically defined by $B = \mu H$, where, for our present purposes the permeability μ does not differ anywhere from that in a vacuum ($4 \cdot 10^{-7}$ henry/meter). B is then in weber/m^2. Since this unit is inconveniently large, a sub-unit has been selected, the gamma (γ) equal to one nanoweber/m^2. For the electric field the microvolt/m has been substituted for the M.K.S.-units or volt/m.

2.1. Magnetic signals

In Fig. 1 we summarize the magnetic activity level observed at the earth's surface..The heavy line indicates roughly the average magnetic energy from atmospheric and ionospheric origin at mid-latitudes. Several important features are identified. These are cherished by investigators because of their high energy density and their simpler field geometry. From the pearls micropulsations around 300 c/h and toward lower frequencies the magnetic storms cover a wide frequency range, followed by the solar daily variation and its harmonics, the recurrence of solar storms at sun rotation periodicities and finally the 11-year cycle of solar activity. At this point the heavy line merges into the dash-dot line that characterizes the secular variations of the earth's main field.

At frequencies lower than a few cycles per hour the level of magnetic activity is essentially the same in the ocean as it is at the earth's surface. However, at higher frequencies the currents induced in the sea reflect away the incident electromagnetic waves, preventing their downward penetration. The effect becomes appreciable when the water depth becomes larger than the seawater skin depth D. (The skin depth is the distance over which the amplitude of an electromagnetic wave diffusing into a conducting medium falls to e^{-1} its initial value. $D = (\pi f \mu \sigma)^{-\frac{1}{2}}$ where f is the frequency in hertz and σ the electrical conductivity.) The skin depth of sea water is tabulated for various frequencies in Table I. A skin depth of 4.5 km, the average oceanic depth, corresponds to 10 c/h. Beyond this frequency the heavy line that, in Fig. 1, represents the level of magnetic activity from overhead sources, branches down and falls rapidly. Except for shallow seas, the ocean is shielded from ionospheric activity at frequencies greater than a few hundred cycles per hour.

The energy density originated by motional processes within the ocean is outlined in Fig. 1 by dotted lines. Few data are available to compile these estimates which must be regarded as guide lines. Except at the semidiurnal lunar frequency where oceanic tides create a sharp and narrow spectral peak, motionally induced fluctuations remain below ionospheric signals.

Although magnetic signals from oceanic sources have been used to investigate ocean tides (Larsen and Cox, 1966; Larsen, 1968) the prospect of extracting extensive information from such observations appears uncertain.

2.2. Electric signals

The estimated level of oceanic electric fluctuations is illustrated in Fig. 2.

The most prominent ionospheric signals are those due to magnetic storms and bays which cover the range 0.02–50 c/h – typical spectra, Filloux (1967b) – and the daily solar variation Cox et al. (1971). Again no appreciable energy remains at frequencies above a few hundred cycles per hour.

Due to the great variety of velocity fields in the ocean, motionally induced fields there are widespread, active and complex (see Fig. 2). Quantitative descriptions of these fields have to be consistent with the frame of reference in use, namely stationary with respect to the sea floor or moving with the water. Interpretative guidance in that respect is provided by Fig. 2.

Of all motional electric fields in the ocean the most conspicuous are those associated with: (1) wind driven surface drift; and (2) turbulent eddies of major ocean currents. Large signals are also generated on the continental shelf, (Cox et al., 1971), by turbu-

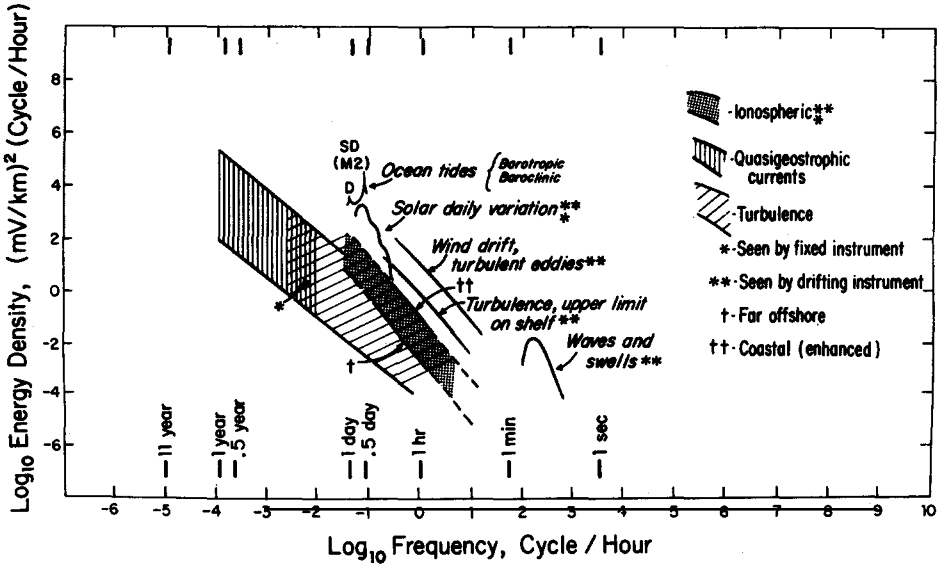

Fig. 2. Energy level of electric pulsations in the ocean.

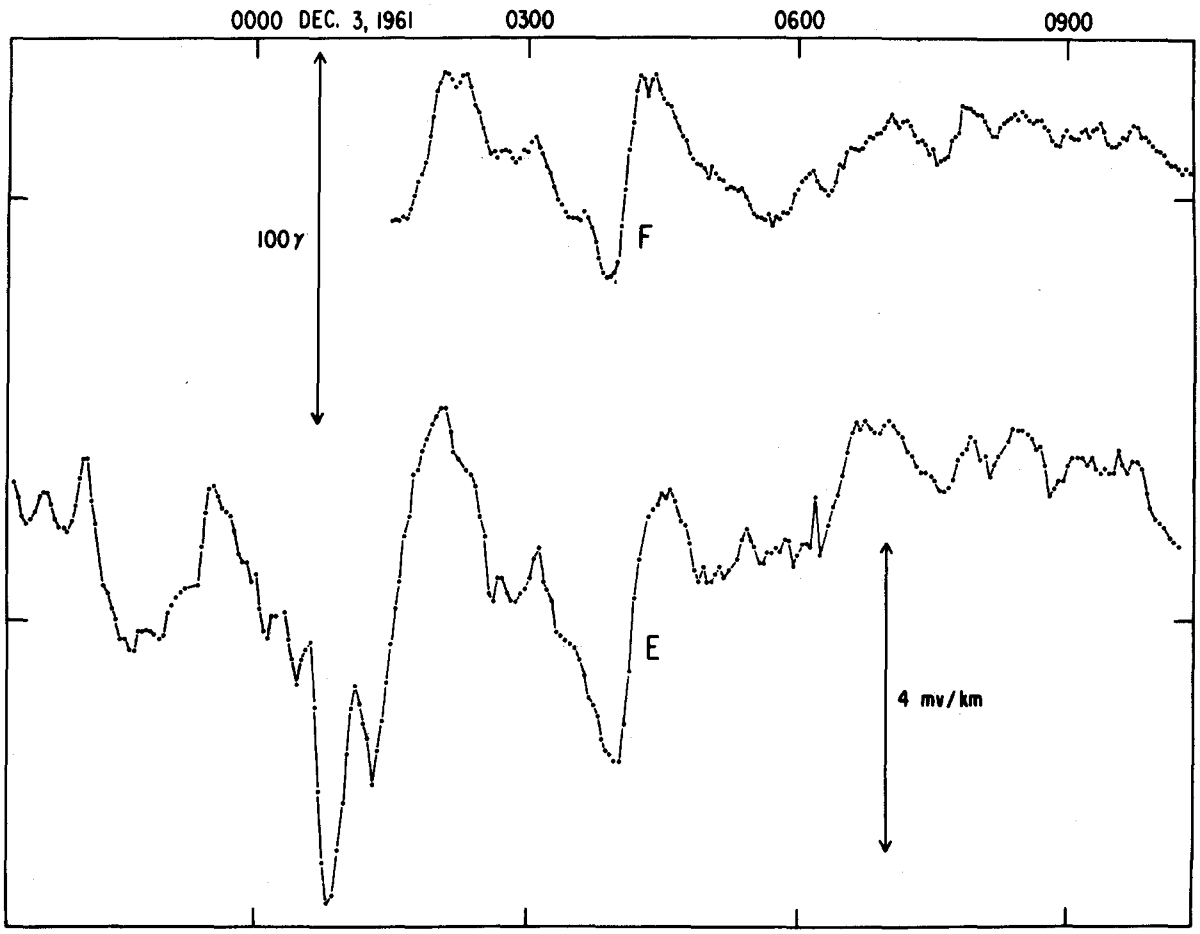

Fig. 3. Total magnetic variations, F, after correction, a few miles off California's continental slope, and electric field parallel to the coast on the sea floor below, E.

lent tidal energy dissipation and at higher frequencies, a prominent bump corresponds to swell and wind waves (Weaver, 1965). Emerging from the solar cluster, a narrow peak at lunar semidiurnal frequency represents the effects of tidal currents, Cox et al. (1971).

Large-scale quasi-geostrophic velocity fields are as yet very poorly understood. Tentative estimates of their associated fields have been made by Cox (unpublished). The background energy of gravitational and ionospheric tides during magnetically quiet days also provides an upper limit to the signature of these little known velocity fields.

2.3. Resolution and stability

For observations to be useful: (1) the instrumental resolution must provide a faithful description of the signals; and (2) the noise must be small enough not to distort these signals appreciably. Minimum least count and maximum allowable drift for various studies are shown in Table II. The assumption have been that: (1) sampling around f requires a least count of 10^{-1} of the peak to peak amplitude in the band $0.5f$ to $1.5f$; and (2) the drift during the time interval f^{-1} should not exceed the least count.

Table II stresses the stringent long-term stability required, and shows that meaningful research begins with a resolution of the order of 1 γ for the magnetic field and 0.05 μV/m for the electric field. Tenfold improvement could be taken advantage of readily.

Magnetic observations suffer another limitation. The measurements must be carried out in the presence of the main field (average intensity of $4 \cdot 10^4 \gamma$). If not rigidly supported, rotation of the sensors may cause errors as high as $4 \cdot 10^4 \gamma$/rad. Attempts were made, Alldredge and Fitz (1964), to use oceanic stable platforms. Tilts as large as 10^{-2} rad have been recorded, discouraging hope of sufficient improvement of this technique with realistic budgets.

More successful were experiments carried out near the north pole by Russian researchers, Zhigalov (1960), Trofimov et al. (in preparation), who supported their magnetometers on icebergs.

3. Instrumentation and techniques

3.1. Magnetic field measurements

The earliest observation of magnetic variations bearing on the ocean were made last century at island or coastal observatories. These used suspended magnet variographs with theodolite reading. Representative models are those of Schmidt and LaCour (Chapman and Bartel, 1940). Remarks on the coastal effect originated mainly from interpretation of their records (Parkinson, 1959). Improved variographs of the same principle, reduced in size and weight and recording on film have reached portable capabilities. Arrays of such stations, using Askania models, were used for studies of the coastal effect in Peru and California by Schmucker (1964). More recently Gough and Reitzel (1967) have developed a model more readily constructed by experimentalists.

The first magnetometer without a moving magnet used at sea was the fluxgate or saturable reactor magnetometer. Improvements of this instrument by Vacquier (Dobrin, 1952), brought its resolution to the neighborhood of 1 γ opening the possibility of airborne magnetic surveying (in this configuration the fluxgate was used during the Second World War as a submarine detecting service).

The fluxgate principle allows miniaturization, low power, and direct digital translation. These are valuable advantages in oceanography and several sea floor fluxgate magnetometers have been built (Pepper, 1968; Owen and Sik, 1972). Measurements off California are reported by Greenhouse (1972).

Of various types of magnetic resonance magnetometers, only the proton magnetometer appears to have been used at sea. Invented in 1953 (Packard and Varian, 1954), the instrument is based on the natural precession of protons seeking equilibrium in the magnetic field to be measured, after having been temporarily polarized in a different direction. The precession frequency is given by $f = (\Gamma/2\pi)B$ where Γ is the gyromagnetic ratio of the proton. With B in gammas (γ) and f in hertz then $B = 23{,}487 f$. Proton magnetometers therefore, measure the total field and will detect changes of the main field only. Sensitivity to variations in directions at right angles can be obtained by adding fields which result in the wanted total field orientation. The stability of such biasing fields, however, must match the resolution wanted. The challenge is great and even if met the power requirement would remain overwhelming.

Even when used as total field instruments, proton magnetometers require considerable electric power

TABLE II
Resolution and drift compatible with various type investigations

Type of measurement	Magnetic		Electric	
	resolution required (γ)	maximum drift (γ/h)	resolution required (μV/m)	maximum drift (μV/m/h)
a Ionospheric effects during moderate magnetic storm, 0.1–1 c/h	1.5	5.0	0.05	0.05
b Same as (a) but for average ionospheric activity	0.3	1.0	0.01	0.01
c Same as (a) but 1–10 c/h	1.0	1.5	0.005	0.05
d Same as (c) but for average ionospheric activity	0.2	0.3	0.001	0.01
e Wind drift, eddies measured with GEK, (frequencies around 1 c/h)	–	–	0.3	0.3
f Quasi-geostrophic velocity fields around 10^{-3} c/h	0.2	0.0002	–	–
with fixed electrodes system	–	–	0.1	0.0001

to activate the polarization coils. Since they are insensitive to positional stability they are ideally suited to survey the static anomalies of the sea floor (Warren and Vacquier, 1961). With adequate precautions they can also be used to record temporal total field variations (Filloux, 1967b). An example of a total field record made off California by means of a towed proton magnetometer is given in Fig. 3. Successful removal of the noise due to bottom anomalies, necessitated: (1) a local survey of the magnetic anomalies (see Fig. 4); and (2) continuous tracking of the ship's position (see Fig. 5).

The fragility of suspended magnet variographs can be reduced by using sensitive angular detectors that relax the compliance requirements on the suspension fibers. A single component magnetometer of this kind has been successfully operated on the sea floor (Filloux, 1967a, b). Although the stiff tungsten suspension reduces the angular sensitivity of the device, a grid-type optical lever inspired by Jones (1961) allows a resolution of one γ. A section of such a record is shown in Fig. 6. A peculiarity of the instrument is a simple orientation control that insures proper orientation on the sea floor (see Fig. 7).

Although the fragility of suspensions should not be overlooked the simplicity and low drain of suspended magnet variographs are attractive.

Because high-frequency magnetic signals in the sea are cut off, air and iron-core induction magnetometers cannot be effective at sea, except, perhaps on the shelf.

Other sensitive devices such as Hall effect sensors and magnetic resistors have been investigated but not used probably because of long-term stability limitations.

3.2. *Electric field measurements*

The significance of motional electric fields in the ocean and their relation to measuring methods has been examined formally by Longuet-Higgins et al. (1954). The case where magnetically induced fields are also present is treated in Cox et al. (1971).

Two types of electric field devices (Fig. 8) are used in the ocean. In the first one, Fig. 8a, two electrodes in contact with sea water at A and B are connected to the measuring meter by an insulated cable c. In the second case, Fig. 8b, the electrodes are laid near the meter, within nonconducting tubes t, opened at A and B (such electrolytic conductors are called salt bridges).

It can be shown that the signal u registered by the infinite resistance meter M is in either case:

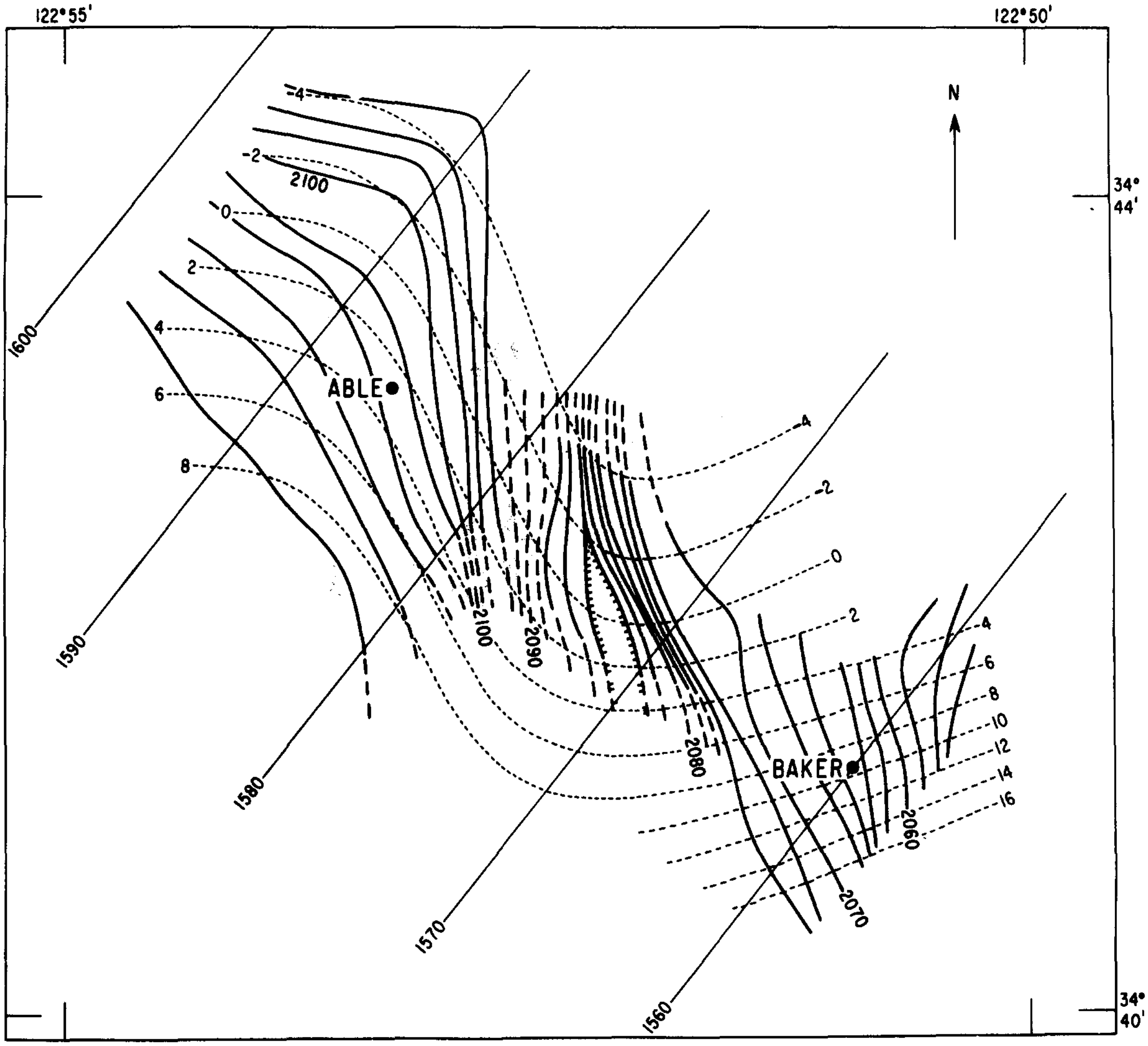

Fig. 4. Contours of total anomaly (γ) dashed lines, depth contours (fathoms) dark continuous lines.

$$u = \int_{c(\text{or } t)} \left(\frac{i}{\sigma} - (V - V_c) \times B \right) \cdot \mathrm{d}s \qquad (1)$$

where V is the water velocity, V_c the cable (or tube) velocity, i the current density and ds an element of the circuit. The validity of eq. 1 is general and covers the case where magnetically induced pulsations are present. An instrument fixed on the sea floor ($V_c = 0$) records the field:

$$E = \frac{i}{\sigma} - V \times B \qquad (2)$$

while an instrument drifting with the water ($V_c = V$) records the field:

$$E_\text{d} = \frac{i}{\sigma} \qquad (3)$$

(the subscript d refers to drifting). Hence the signals measured by the fixed or drifting instruments differ by the motional field $V \times B$. If one of the two senses

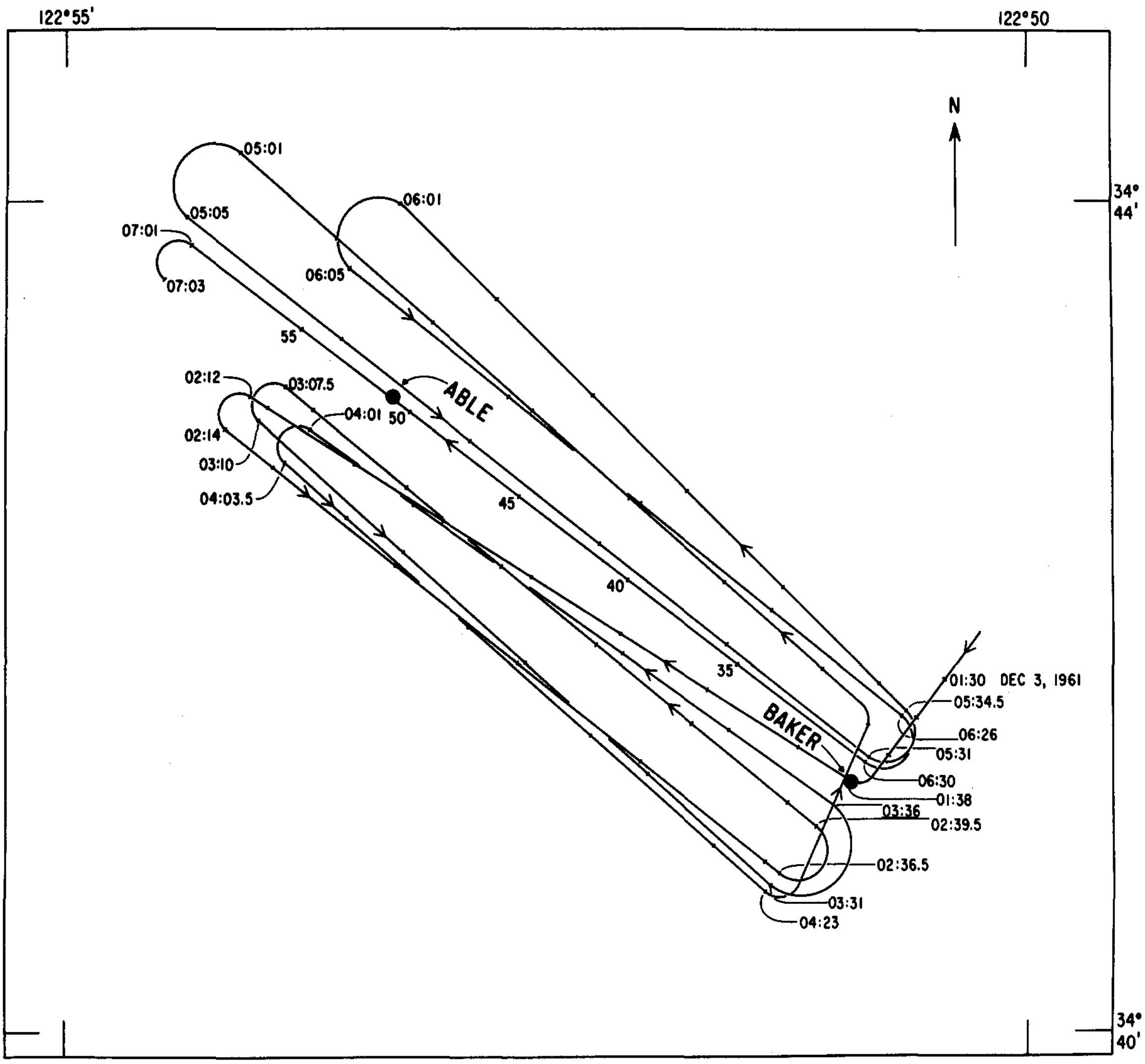

Fig. 5. Track of ship, position and time, for removal of spurious signals due to magnetic bottom anomaly.

fully the motional field, the other must register no signal at all. In practice the situation is not clear cut and both fixed or drifting instruments register complementary fractions of the motional field. The relative value of these contributions depends on the geometry of the velocity field and on the shape and conductivity of the boundaries. This dual behavior is illustrated in Fig. 9 where the response of the GEK (geomagnetic electrokinectograph) is compared with that of fixed electrodes in the case of a two-layer system. Shallow surface drift is best recorded by the GEK while barotropic motion is sensed best by stationary installations.

Quick statement of exactly what signal is registered by drifting and by fixed instruments is possible only in simple cases. However, the following guideline is useful: velocity fields of small size with respect to adjacent stationary water produce only small signals in fixed instruments while instruments drifting within the motion cell register the major part of the motional signal. The reverse is true for large-scale motions within low conductivity boundaries. For

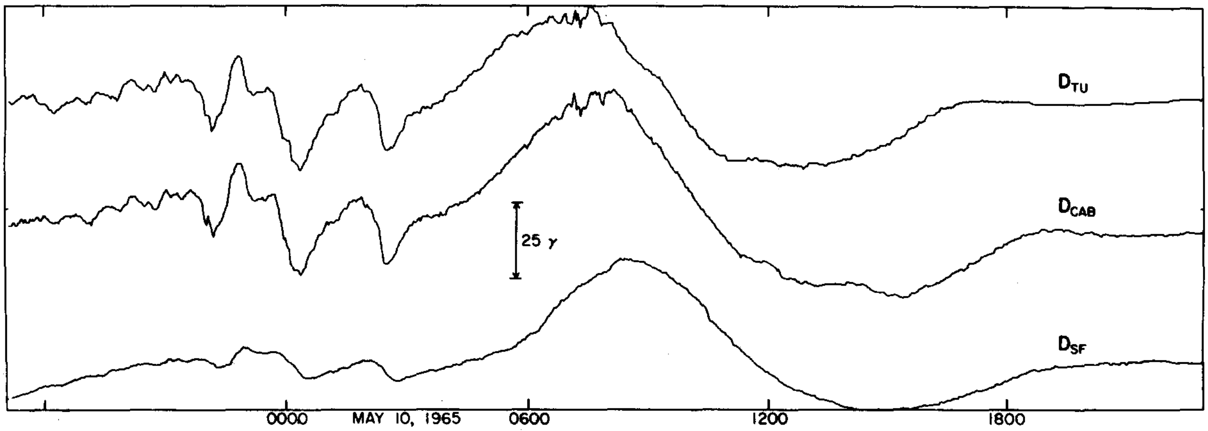

Fig. 6. Magnetic fluctuations eastward, D_{SF}, on the sea floor and 600 km off California. Magnetic variation D_{CAB} along the coast (Cambria) and D_{TU} at Tucson.

instance, in the two-layer case of Fig. 9: (1) when $h_a/h \to 0$ the drifting GEK registers $V_a \times B$ and the fixed electrode system registers nothing; and (2) when $h_a/h \to 1$, the GEK registers no signal and the fixed installation registers $-V_a \times B$.

All the statements made earlier for the cable type of electrical field recorders, Fig. 8a, hold for the salt

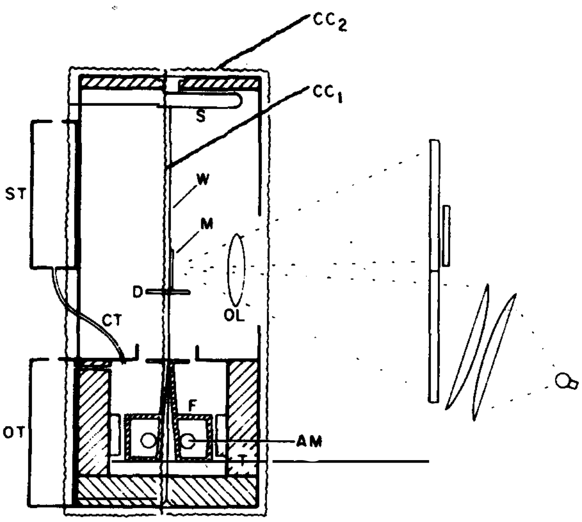

Fig. 7. Automatic orientation of magnetic suspension in sea-floor magnetometer. At launching magnets *AM* in float *F* rest in tank *T*. Oil dripping through capillary tube *CT* from storage tank *ST* fills tank *T*. Float *F* rises and connects with discs *D* and mirror *M*. Subsequent mirror rotations are picked up by grid-type optical lever. CC_1 and CC_2 = calibration coils; *OL* = objective lens; *OT* = oil overflow tank.

bridges type, Fig. 8b. However, due to the low conductivity of sea water with respect to copper, salt bridge instruments do not permit large electrode separations. Their advantage is that the electrodes can be located near the recording system, a requirement for drift removal by electrode switching (see later).

With long cables an average field:

$$\bar{E} = \mu/l \tag{4}$$

is obtained where l is the electrode separation. When the separation is derived from the cable length proper stretching is highly critical. If the electrode's position is known by other means, a non-straight

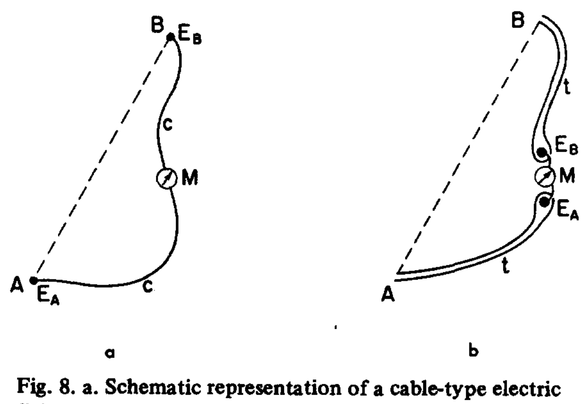

Fig. 8. a. Schematic representation of a cable-type electric field sensor and b. salt bridge version of the same instrument. E_A, E_B = electrodes, C = cables, t = salt bridge tubes, M = meter.

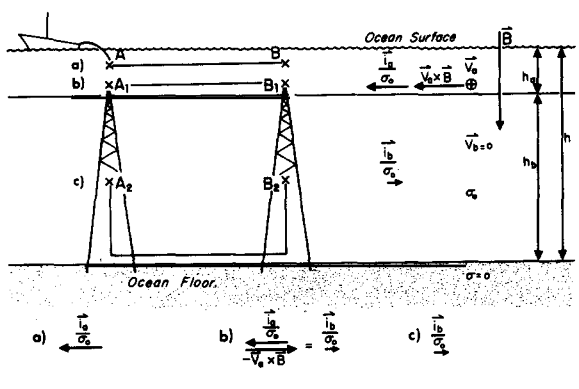

Fig. 9. Response of GEK and fixed electrodes in a simple two-layer flow. The surface layer of thickness h_a moves with velocity V_a, cutting vertical magnetic component B to produce motional field $V_a \times B$. Electric currents with density i_a set in surface layer return in stationary lower layer (density i_b). Layer thickness h_a (above) and h_b (below). a. Response of GEK; b and c. Response of fixed electrodes in moving and stationary layers, respectively.

path may result in errors due to signals induced in the loop made by the cable and the straight line between the electrodes. This error remains small for electrode separations under a few tens of km, Cox et al. (1971). Signals from transoceanic telegraph cables may therefore require correction.

Among instruments used to record electric fields in the ocean we have already referred to oceanic telegraph cables. We have also mentioned the GEK used in tow behind a steaming ship to estimate the surface drift. A description of this instrument, its uses and problems, is given by Von Arx (1950). Typically, electrode separation is 100 m. Hence a surface velocity of 1 cm/sec, at mid-latitudes where the vertical component of B is around $4 \cdot 10^4\ \gamma$ generates a signal of 40 μV, often below electrode voltage. The time-independent part of the latter can be removed by reversal of the steaming direction. Since components at right angles are needed, steaming

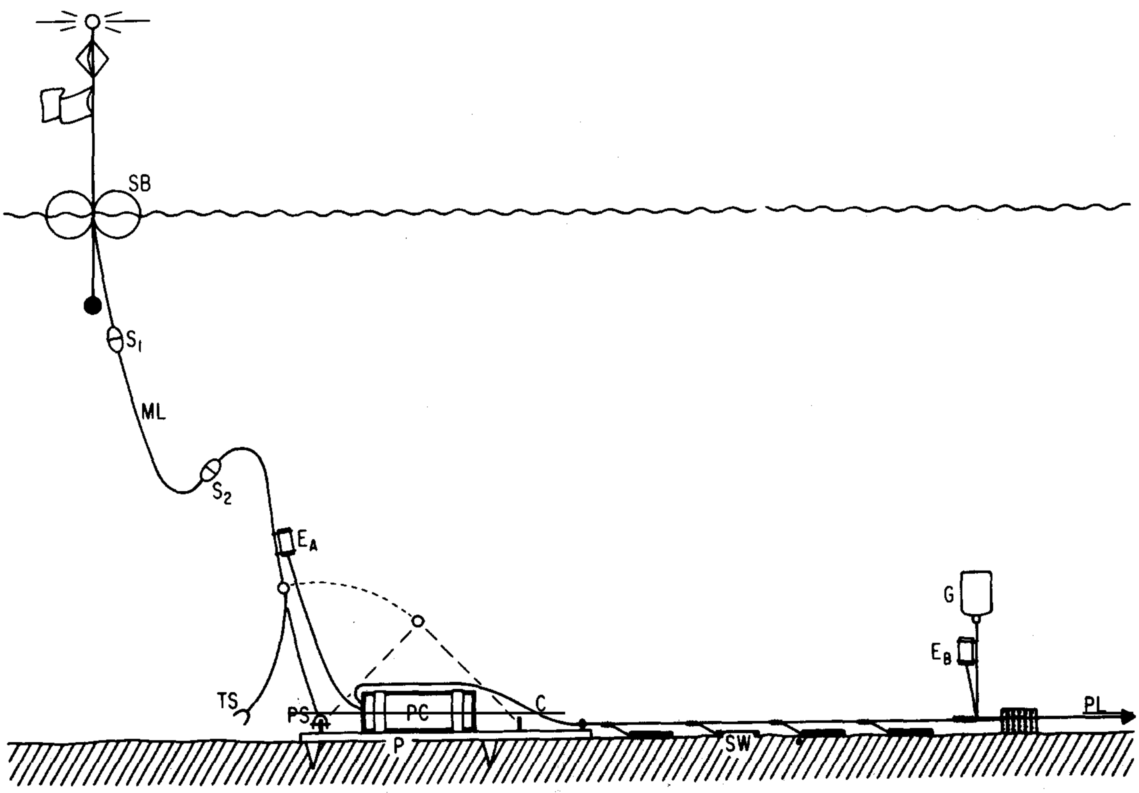

Fig. 10. Fixed electric field recorder on the sea floor. *PC* = recording voltmeter in pressure case; *C* = cable; E_A and E_B = electrodes; *G* = gasoline float; *ML* = mooring line; S_1, S_2 = swivels; *SB* = surface buoy; *PL* = pulling wire; *SW* = sash weights; *P* = platform; *PS* = permanent shackle; *TS* = temporary shackle.

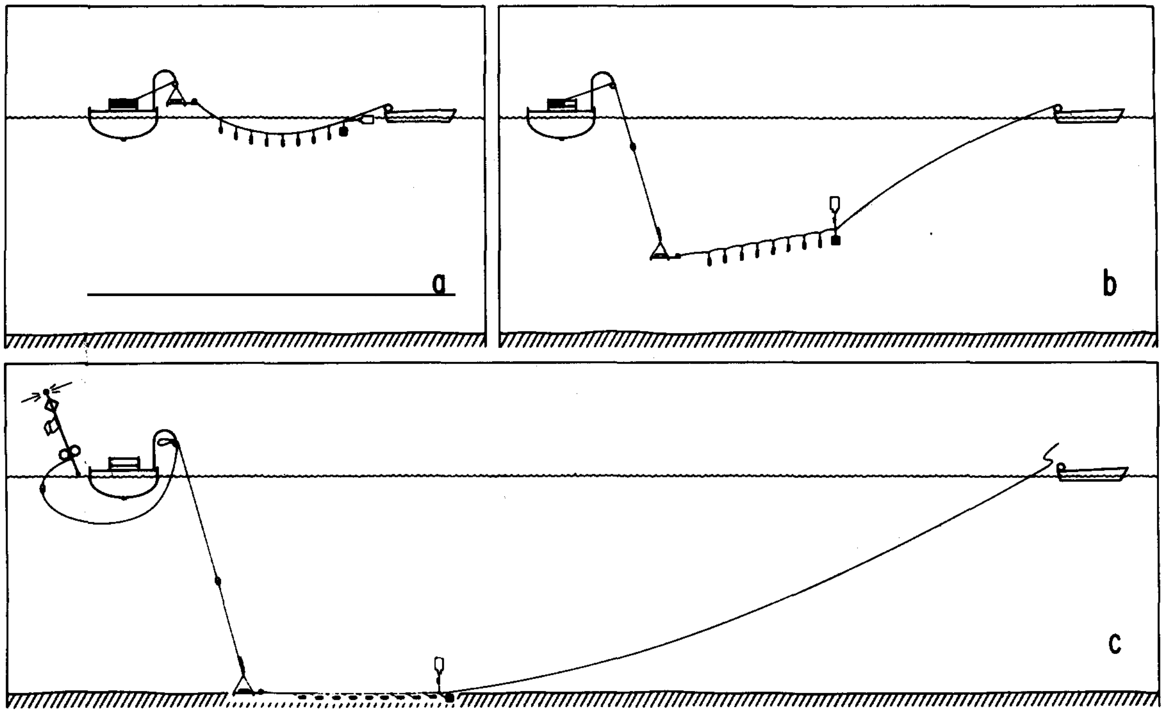

Fig. 11. Installation of long cable electric field recorder on the sea floor. a. The cable is stretched at the surface and ballasted to create a 0.5 m/sec natural sinking speed. b. Lowering from ship at 0.5 m/sec and stretching from small boat by means of long pulling wire. c. Release of pulling wire and launching of float.

in a square pattern is common practice when GEK measurements are in progress.

The replacement of cables by salt bridges has been pioneered by Mangelsdorf (1968) with a view to electrode voltage suppression by electrode switching. If the recorded voltages before and after switching are U_b and U_a then the electrode noise and the electric field signals are respectively:

$$U_E = \frac{1}{2}(U_b + U_a) \qquad U_s = \frac{1}{2}(U_b - U_c) \tag{5}$$

With salt bridge GEK's the electrodes are kept aboard, protected against leakage and temperature variations. Switching is made by means of insulated valves.

A recent development (Sanford, 1967; Dreyer and Sanford, 1970), extends the scope of drifting instruments to sampling of the horizontal electric field from surface to bottom. The self-contained instrument is a short span, salt bridge freefall GEK that rotates on its way down (and up). Rotation around the vertical replaces the GEK square steaming pattern. Differentiation of the signals at opposed orientations is built in the electronics which also suppresses other unwanted signals associated with free-fall velocity and rotations. Reference to magnetic north uses a small pickup coil. The present resolution is ± 2 cm/sec, a significant result for a system using a salt bridge 0.3 m long, and the authors expect to improve it. The instrument is seven feet long and weighs about 70 kg. The free-fall speed is around 1 m/sec with rotation at 0.1 revolution/sec. The small silver–silver chloride electrodes are mounted back to back on a berylium oxide plate to minimize temperature differences. The horizontal velocity in this case is with respect to the mean or barotropic velocity. The latter can be estimated only with fixed systems.

Attempts to record potential differences in the deep ocean by laying cables from coastal stations have demonstrated that landing the cables through the surf zone is a major obstacle. Moored sea-floor

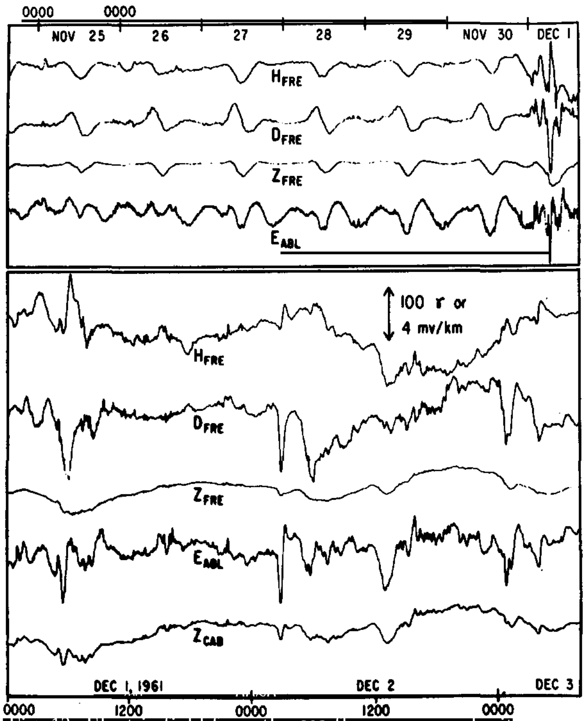

Fig. 12. Electric field from the sea floor compared with various magnetic signals E_{ABL} = electric field 100 km off California; Z_{FRE}, H_{FRE}, D_{FRE} = magnetic variations (vertical to magnetic north and to magnetic east) 100 km inland; Z_{CAB} = vertical magnetic variation along coast. Upper box: during magnetically quiet week. Lower box: during magnetic storm.

recorders have been more practical, Filloux (1967b), see installed configuration on Fig. 10. To lessen the electrode noise, the cable is as long as practical. With 1 km length, magnetic storm pulsations have been recorded with amplitudes as low as 0.2 μV/m. Full stretching of the electrode cable and control of the azimuth are primordial. Fig. 11 illustrates several steps of this difficult operation. Successful stretching as well as achieved azimuth can be verified by means of orientation compasses attached along the cable, Filloux (1967b).

An example of electric field recording in deep water (4 km) is given in Fig. 12.

Another electric field approach to estimate oceanic velocities is described by Harvey (1972). The electrodes, spread vertically, sense horizontal velocities in the magnetic east–west directions. Because no appreciable electric current can flow through the air–sea interface no interpretation difficulty arises from sea-floor conduction.

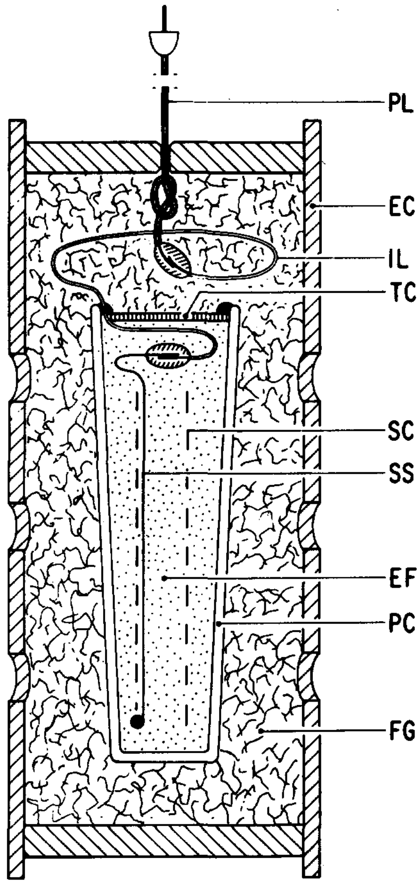

Fig. 13. Silver–silver chloride electrode cross-section. *PC* = porous container; *SC* = silver gauge cylinder; *SS* = silver stem; *EF* = electrode filler (silver chloride); *TC* = top cap; *EC* = electrode housing; *FG* = shock absorber (pyrex wool); *PL* = plug; *IL* = intermediate lead.

In spite of the operability of long cable systems, the availability of small, two-component instruments would improve oceanographic research considerably. One major obstacle in developing these is the gross mismatch between the signals to be sensed and the electrode noise.

3.3. Electrodes

At the points where metallic circuits make contact with sea water the metal–electrolyte junction generates an electrochemical e.m.f. variable from metal to metal but always near one volt. Even so the e.m.f. of perfectly matched junction pairs would cancel each other. The degree to which this can be approached is very unsatisfactory.

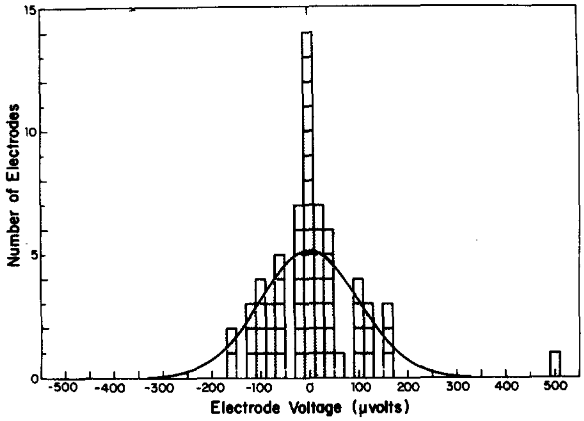

Fig. 14. Electrode voltage distribution of 66 Ag-Ag Cl. electrodes. Gaussian distribution with same area and same standard deviation also shown.

Of all the electrodes tried for junction with sea water, the silver–silver chloride type has enjoyed an unchallenged lead in spite of performances far below oceanographers' needs. Ives and Janz (1961) review the problem of reference electrodes and describe fabrication methods for three classic types of Ag-Ag Cl electrodes, namely electrolytic, thermal and hybrid (thermal-electrolytic). These are mainly used in laboratory research, chemistry and biosciences, where care and optimum utilization are the rule. These good practices cannot be respected in oceanographic work. Sturdier electrodes are described by Von Arx (1950) and Filloux (1967b). A cross section of the latter is shown in Fig. 13. Unfortunately, there does not seem to be a fabrication technique leading to sure success. Performances improve with: (1) general care, cleanliness in particular; (2) training; (3) large numbers; and (4) massive use of silver and silver chloride. In Fig. 14 the distribution of voltage deviation around their mean for 66 electrodes is seen to approach a Gaussian distribution. Properly matched, new electrode pairs have e.m.f. well below one millivolt. Noise spectra for electrode pairs of high and of marginal performance, in their oceanic environment, are given in Fig. 14.

Independently from their inherent noise, Ag-Ag Cl electrodes can produce spurious signals if the temperature or the salinity changes. The intrinsic electrode sensitivity to changes in temperature and salinity is hard to separate from further manifestations of the

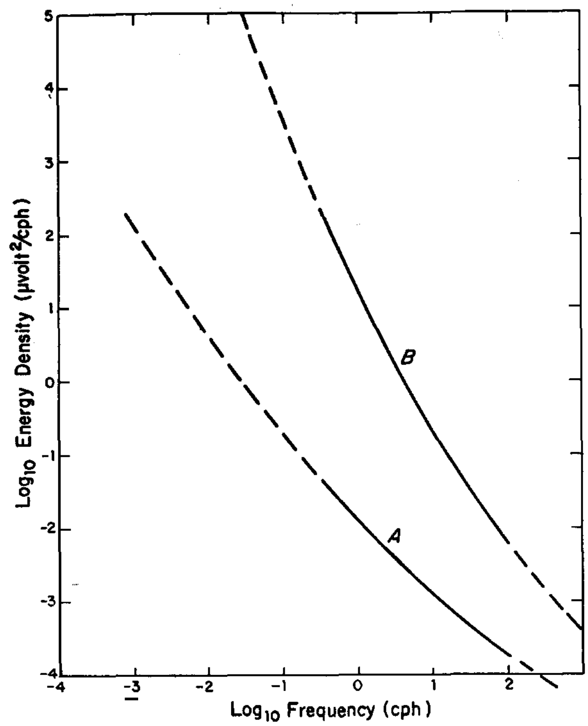

Fig. 15. Energy spectra of electrodes near the ocean floor. *A* for low noise electrodes, *B* for marginal electrodes.

Seebeck effect along the salt water path. Von Arx (1950) reviews this subject. Dreyer and Sanford (1970) give for sensitivity figures: 350 μV/°C and 500 μV/% of salinity change. Research capable of resulting in a clear separation of electrode and water path sensitivity to temperature and salinity gradients would be most valuable. If undertaken, this research should also evaluate the effect of diffusion slowing by gelatin as advocated by some researchers.

The unknown signal bias due to electrode voltage can be estimated by means of electrode reversal. Extension of this technique into regular and rapid electrode inversion is identical to the "chopping" technique used in drift removal of d.c.-amplifiers. We therefore gave to the double pole double throw valve that performs this operation the name of "water chopper". It is clear that the drift correction capabilities apply not only to the electrodes, but also to all circuits between the electrodes and the recorder, greatly enhancing the benefits of "water chopping".

Because of cut-off at frequencies beyond a few hundred c/h, the highest chopping frequency com-

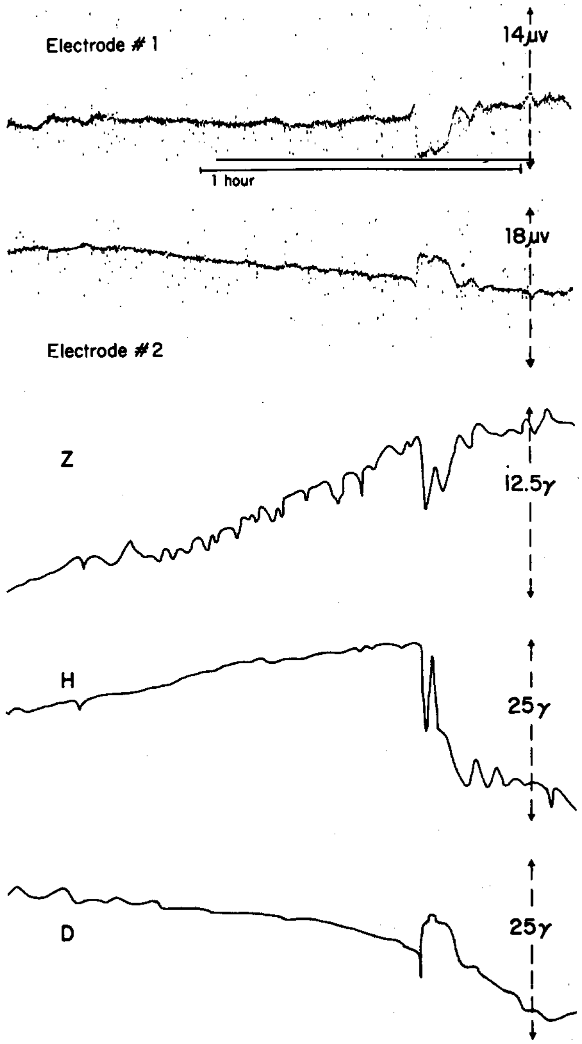

Fig. 16. Lower three traces: magnetic pulsations (Z, H, D = vertical, northward, eastward). Upper two traces: electric pulsations in opposite direction in 2.5 m salt bridge. Depth is 1000 m.

patible with resolving the existing signals is also of this order. The electrode noise energy at this frequency, see Fig. 15, is compatible with this chopping rate and electrode reversal does not need to be faster than every 10 seconds.

3.4. Feasibility of short span, free fall electric field recorder.

The tests that produced the electrode noise spectra in situ shown on Fig. 14 also indicate that the natural

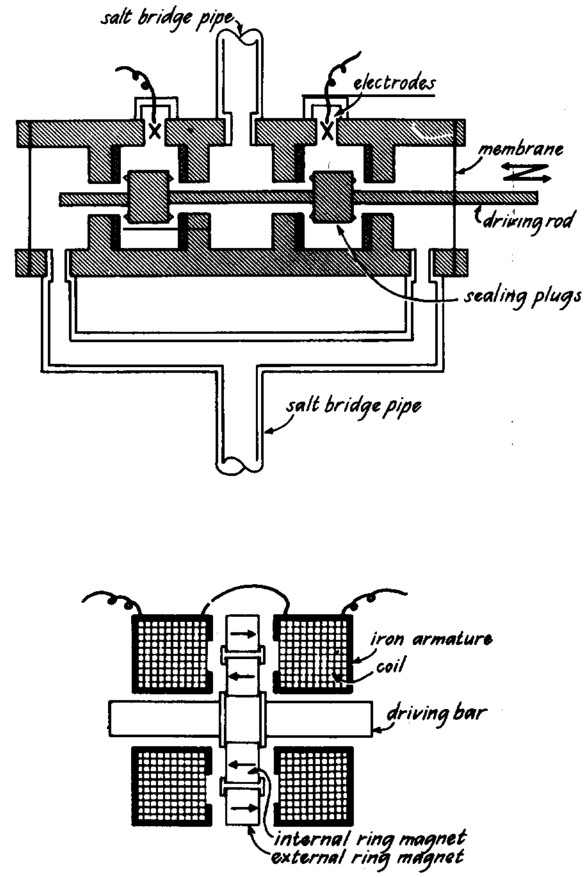

Fig. 17. Top: double pole double throw "water chopper". Bottom: low power driver for above

noise level at the sea-floor interface for a few meters separation is well below the electrode noise. More recent tests at 1 km depth with 2.5 m long salt bridges oriented in opposite directions further confirm the feasibility of short span bottom electric recorders, see Fig. 16. The lower three traces represent the magnetic forerunners of a magnetic storm. Perfect correlation and identity – except for sign – of two independent and simultaneous electric signatures, see upper two traces, indicate irrefutably the induced electric field nature of the signals. Quantitative considerations lead to resolution estimates of about 0.1 μV/m for 2.5 m electrode separations.

In practice, the two main problems are to insure: (1) high open to closed resistance of the valves; and (2) minimal power drain of the mechanical driver. An approach to switching and to low power driving is illustrated in Fig. 17. If present expectations are fulfilled, it will be possible in the near furture to construct two-component self-contained bottom electric field recorders with free fall and buoyant recovery capabilities.

4. Conclusion

The great variety of the electromagnetic activity in the ocean justifies extensive experimental research. However, this research requires extremely sensitive instrumentation, deployed in substantial arrays and capable of working unattended for long period of time. There is little to be gained in trying to operate by means of simple adaptations of land instrumentation to the oceanic rigors. Higher success and lower costs are in general derived from concepts that take the ocean into account right at the beginning. For those who value experimental sciences, research about or based upon electromagnetic induction in the ocean offers many challenges.

Acknowledgement

Preparation of this review and recent work by the author first reported here were supported in part by the National Science Foundation grant number GB-31342.

References and bibliography

Adams, A.J.S., 1881. *J. Soc. Tel. Eng.*, 10: 35.

Alldredge, L.R. and Fitz, J., 1964. Submerged stabilized platform. *Deep-Sea Res.*, 11: 935–942.

Chapman, S. and Bartels, J., 1940. *Geomagnetism*, 2 Vols. Clarendon Press, Oxford, 1049 pp.

Cox, C.S., Filloux, J.H. and Larsen, J.C., 1971. Electromagnetic studies of ocean currents and electrical conductivity below the ocean floor. In: A. Maxwell (Editor), *The Sea*. Vol. 4, Part I.

Dobrin, M.B., 1952. *Introduction to Geophysical Prospecting*. McGraw-Hill, New York, N.Y., 435 pp.

Dreyer, R.G. and Sanford, T.B., 1970. A free-fall electromagnetic current meter-instrumentation. In: *Proceedings of the I.E.R.E. Conference on Electronic Engineering in Ocean Technology*. I.E.R.E., London, p. 353–370

Faraday, M., 1832. Bakerian Lecture IV, Experimental research in electricity. *Philos. Trans. R. Soc.*, 175.

Filloux, J.H., 1967a. An ocean bottom, D component magnetometer. *Geophysics*, 32: 978–987.

Filloux, J.H., 1967b. *Oceanic Electric Currents, Geomagnetic Variations and the Deep Electrical Conductivity Structure of the Ocean-Continental Transition of Central California*, Thesis, Univ. of California, San Diego, Calif., 166 pp.

Gough, D.I. and Reitzel, J.S., 1967. A portable three-component magnetic variometer. *J. Geomagn. Geoelectr.*, 19 (3): 203–215.

Greenhouse, J., 1972. *Geomagnetic Time Variation on the Sea Floor off Southern California*. Thesis (S10 Reference 72–67). Univ. of California, San Diego, Calif.

Harvey, R.R., 1972. *Oceanic Water Motions Derived from the Measurement of the Vertical Electric Field*. Hawaii Institute of Geophysics, Univ. of Hawaii, Honolulu.

Ives, D.J.G. and Janz, G.J. (Editors), 1961. *Reference Electrodes, Theory and Practice*. Academic Press, New York, N.Y., 651 pp.

Jones, R.V., 1961. Some developments and applications of optical levers. *J. Sci. Instrum.*, 38.

Larsen, J.C., 1968. Magnetic and electric fields induced by deep sea tides. *Geophys. J.*, 16: 47–70.

Larsen, J.C. and Cox, C.S., 1966. Lunar and solar daily variation in the magnetotelluric field beneath the ocean. *J. Geophys. Res.*, 71: 4441–4445.

Longuet-Higgins, M.S., Stern, M.E. and Stommel, H., 1954. The electric field induced by ocean currents and waves, with applications to the method of towed electrodes. *Pap. Phys. Oceanogr. Meteor.*, 13 (1): 1–37.

Mangelsdorf, Jr., P.C., 1968. Gulf stream transport measurements using the salt bridge GEK and Loran C navigation. *Trans. Am. Geophys. Union*, 49: 198 (abstract).

Owen, T.R.E. and Sik, J.M., 1972. A three-component fluxgate magnetometer for sea bottom use. *Oceanogr. Int.*, 38.

Packard, M.E. and Varian, R., 1954. Free nuclear induction in the earth's magnetic field. *Phys. Rev.*, 93: 941.

Parkinson, W.D., 1959. Direction of rapid geomagnetic fluctuations. *Geophys. J.*, 2: 1–14.

Pepper, C.S., 1968. *Vehicle System Developed for a Sea Floor Recording Magnetometer*. Univ. of California, San Diego, Calif., MPL-U-21/168, 13 pp.

Sanford, T.B., 1967. *Measurement and Interpretation of Motional Electric Fields in the Sea*. Thesis, M.I.T., Cambridge, Mass. 148 pp.

Schmucker, U., 1964. Anomalies of geomagnetic variations in the southwestern United States. *J. Geomagn. Geoelectr.*, 15: 193–221.

Trofimov, I.V., Fonarev, G.A. and Shneyer, V.S., in preparation. Some results of magnetotelluric research in the Central Artic.

Von Arx, W.S., 1950. An electromagnetic method for measuring the velocities of ocean currents from a ship under way. *Pap. Phys. Oceanogr. Meteor.*, 11 (3): 1–62.

Warren, R.E. and Vacquier, V., 1961. *A Ship-towed Proton Magnetometer*. Univ. of California, San Diego, Calif. MPL-U-17/61, 16 pp.

Weaver, J.T., 1965. Magnetic variations associated with ocean waves and swell. *J. Geophys. Res.*, 70 (8): 1921–1929.

Young, F.B., Gerrard, H. and Jevons, W., 1920. On electrical disturbances due to tides and waves. *Philos. Mag., Ser. 6,* 40: 149–159.

Zhigalov, L.N., 1960. Some features of the variation of the geomagnetic vertical component in the Artic Ocean. Translated from *Geomagnetic Disturbances.* In: Collection of Articles No. 4 relating to Section 3 of I.G.Y. Program. Academy of Sciences Press, Moscow.