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SIGNALS AND NOISE IN MAGNETOTELLURICS

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September 1985

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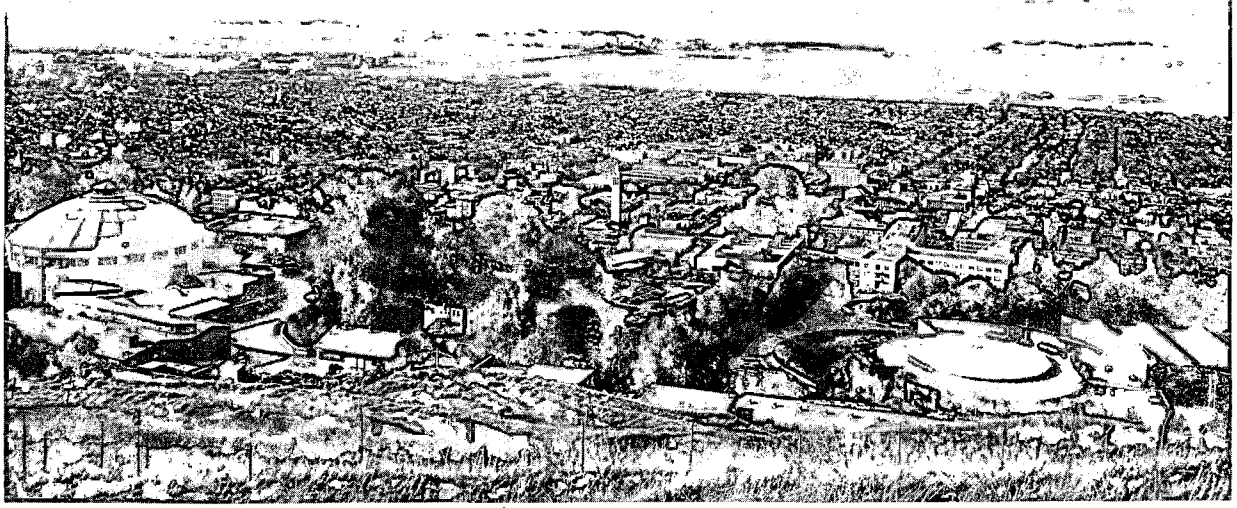

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SIGNALS AND NOISE IN MAGNETOTELLURICS

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Signals and Noise in Magnetotellurics

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University of California, Berkeley

Summary

We have determined magnetotelluric noise properties as a function of separation using an orthogonal array of stations. The simultaneous recording of high sensitivity biaxial tiltmeters along with the electric and magnetic fields allowed us to measure the magnetic noise caused by sensor movement within the Earth's static field. We used a point-by-point time domain linear least squares model allowing routine remote magnetic signal cancellation of typically 40 to 50 dB, with an optimum of over 60 dB. This method corrects for orientation and calibration errors of the magnetometers and removes tilt induced magnetic signals, thereby allowing accurate gradient magnetic field measurements on short baselines (< 3 km).

Microseismic activity in the low signal MT band, from 0.1 to 1 Hz, is demonstrated to bias the impedance estimate downward, even using the remote reference technique, due to correlated tilt motion. Tilt corrected expressions for both single site and remote reference MT impedance are formulated and compared to the standard remote reference expression.

Introduction

In two previous studies, (Goubau et al., 1984, Morrison et al., 1984) the apparent noise in magnetic sensors operated in the Earth's field was deduced from signals measured simultaneously at two spatially separated sensors. The noise power spectra so obtained for SQUID and coil magnetometers were remarkably similar (Figure 1) even though the two magnetometers have very

different intrinsic noise properties, suggesting that some external factor was creating the low frequency noise. The spectral density of this noise was characteristically $1/f^3$, where f is the frequency. Sensor motion, magnetic field gradients or source effects were postulated to cause this unexplained increase in noise and led to the design of this array experiment.

A SQUID magnetometer array was deployed to determine the lowest detectable magnetic field changes at a local site using measurements from remote sites to cancel natural field fluctuations. This technique was spectacularly successful at a recent hydraulic fracture experiment where cancellations of natural field signals at the 60 dB level allowed detection of level shifts of less than 0.03 nT in a background magnetic field variation of over 50 nT (Figure 2a and 2b). These high cancellations have allowed identification of the tilt motion as a significant noise source in high accuracy magnetic field determinations. One microradian of tilt movement introduces a 0.035 nT level change in the magnetic field.

Equipment

Four SQUID magnetometers, each having an internal high sensitivity biaxial tilt meter, three external biaxial bubble type tilt meters, six channels of optically isolated electric fields, three microbarographs and five temperature monitors comprised the sensors recorded for the array study. Figure 3 illustrates the station locations occupied in Grass Valley, Nevada during October 1984. Except for the base station, each station consisted of a 1.5 m deep fiberglass walled vault having a silica sand base supporting a 1 m diameter granite slab; the base vault had a 0.7 m by 1.3 m granite slab to support two magnetometers. All vaults had 0.15 m thick styrofoam and plywood tops and were allowed to stabilize for over 2 weeks before the equipment was set up.

Sixty-four channels of 19-bit data was recorded at each of six separations ranging from 1 m to 3 km. Each channel was sampled at 2 Hz with individual site recording times of 36 to 48 hours, yielding a 1.5 gigabyte data base for the Nevada array study. Data acquisition and preliminary processing was conducted in the field with an HP 9000 computer.

Instrument noise was determined by means of two sensors simultaneously recording the same signal, for example, two parallel E-field dipoles separated by 0.5 m, and two magnetometers mounted on the same slab. At the base station, two magnetometers separately recorded the tilt and magnetic fields.

Least Squares Approach

At any given site, we can consider the magnetic signal as being composed of natural signals, tilt induced signals and local site noise. Assuming no source field gradients and that tilt motion is small we obtain for each site:

$$\mathbf{H}_i(t) \approx \mathbf{H}_s(t) + \mathbf{R}_i \Theta(t) + \mathbf{N}_i(t),$$

where $\mathbf{H}_s(t)$ is the assumed uniform source field, $\mathbf{R}_i$ is a tensor relating tilt changes to magnetic field, $\Theta(t)$ is the tiltmeter output, and $\mathbf{N}_i(t)$ is the noise at site i .

However, in making real measurements there are different channel calibrations and orientation errors between any two sites, so that one needs a correction tensor, $\mathbf{C}_{ij}$, to predict the magnetic field at site i from site j :

$$\mathbf{H}_i^p(t) = \mathbf{C}_{ij}[\mathbf{H}_j(t) - \mathbf{R}_j \Theta_j(t)] + \mathbf{R}_i \Theta_i(t) + \alpha.$$

This equation allows one to apply least squares to minimize

$$\sum_t |\mathbf{H}_i(t) - \mathbf{H}_i^p(t)|^2$$

and to solve for $\mathbf{C}_{ij}$, $\mathbf{R}_j$, $\mathbf{R}_i$ and α .

This approach has successfully accounted for up to 60 dB of the background variation. Figure 4a demonstrates the residual magnetic signal $(\mathbf{H}_i(t) - \mathbf{H}_i^p(t))$

after correcting for orientation and calibration errors, $\mathbf{C}_{ij}$. Including the tilt correction (Figure 4b) provides an additional reduction of 15 dB to the residual standard deviation. This type of cancellation has allowed us to detect magnetic field gradients as small as $10^{-15} Tm^{-1}$. The use of this simple linear model for remote cancellation with controlled source methods would yield an immediate reduction of background telluric signals by at least 40 dB.

The assumption of a frequency independant model relating source magnetic fields at each site does not allow for the possibility that each site has a different impedance function. We have observed a time variation of the $\mathbf{C}_{ij}$ possibly implying a dependence on the source frequency and polarization.

Magnetotelluric Impedance Bias by Tilt Noise

We observed a significant peak in the tilt spectrum due to microseismic activity around 0.15 Hz which falls in the low signal MT band of 0.1 to 1 Hz. This tilt signal is coherent between stations separated by 3 km and can significantly bias the magnetic signal, effectively lowering the impedance estimate at this frequency. A straightforward subtraction in the time domain of the term $\mathbf{R}\Theta(t)$ will remove this bias signal.

We also observed that the tilt power spectrum varied approximately as $1/\mathbf{f}^2$. This coherent tilt noise would give rise to an increasing bias in the impedance as the frequency is lowered were it not for the fact that the power spectrum of the natural magnetic field fluctuations varies approximately as $1/f^3$ in this range.

Acknowledgment

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References

Goubau, W.M., Maxton, P.M., Koch, R.H., Clarke, J., 1984, Noise correlation lengths in remote reference magnetotellurics, Geophysics, **49**, 433-438.

Morrison, H.F., Conti, U., Labson, V.F., Nichols, E., Goldstein, N.E., 1984, Field tests of noise in SQUID and induction coil magnetometers, Lawrence Berkeley Laboratory, University of California, **LBL-901** .

Stanley, W.D. and Tinkler, R.D., 1982, A practical, low noise coil system for magnetotellurics: Open file report, U.S. Geological Survey, Denver, CO.

Figure Captions

Fig. 1 Comparison of apparent sensor noise for SQUID and coil magnetometers operated in the Earth's magnetic field. The measured results (dots) have similar low frequency response as compared to the predicted noise for each magnetometer system.

Fig. 2a H_y observed magnetic field.

Fig. 2b Residual H_y after cancellation by remote site 0.7 km away.

Fig. 3a Grass Valley magnetometer site locations occupied during September and October, 1984.

Fig. 3b Standard vault arrangement.

Fig. 4a Residual magnetic field after cancellation to correct for static calibration and orientation errors.

Fig. 4b Residual magnetic field of Figure 4a with the additional reduction obtained by including the tilt motion in the least squares model.

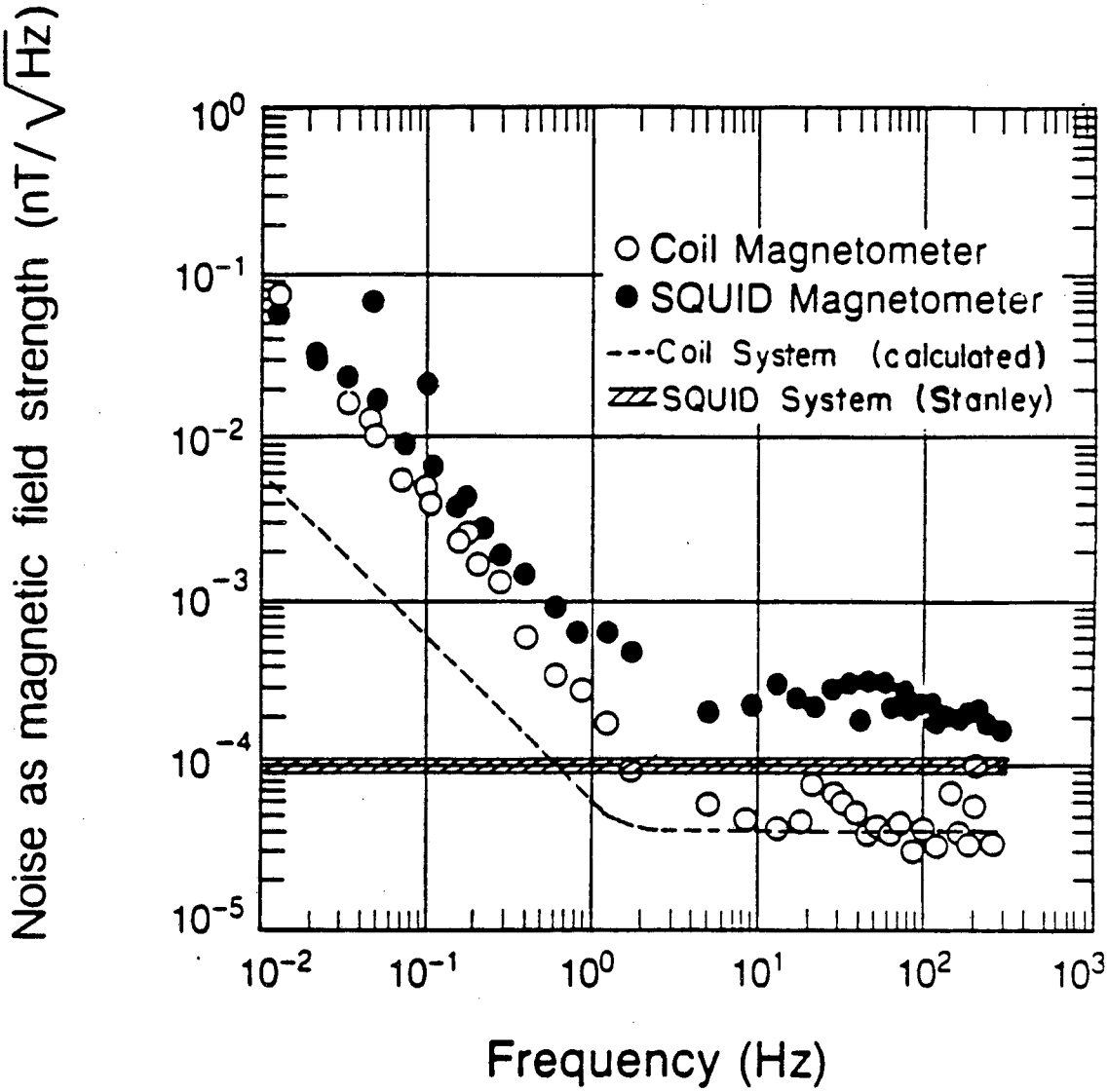
Noise as magnetic field strength (nT/√Hz)
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-2
10^-1
10^0
10^1
10^2
10^3
Frequency (Hz)
Coil Magnetometer
SQUID Magnetometer
Coil System (calculated)
SQUID System (Stanley)

Fig. 1

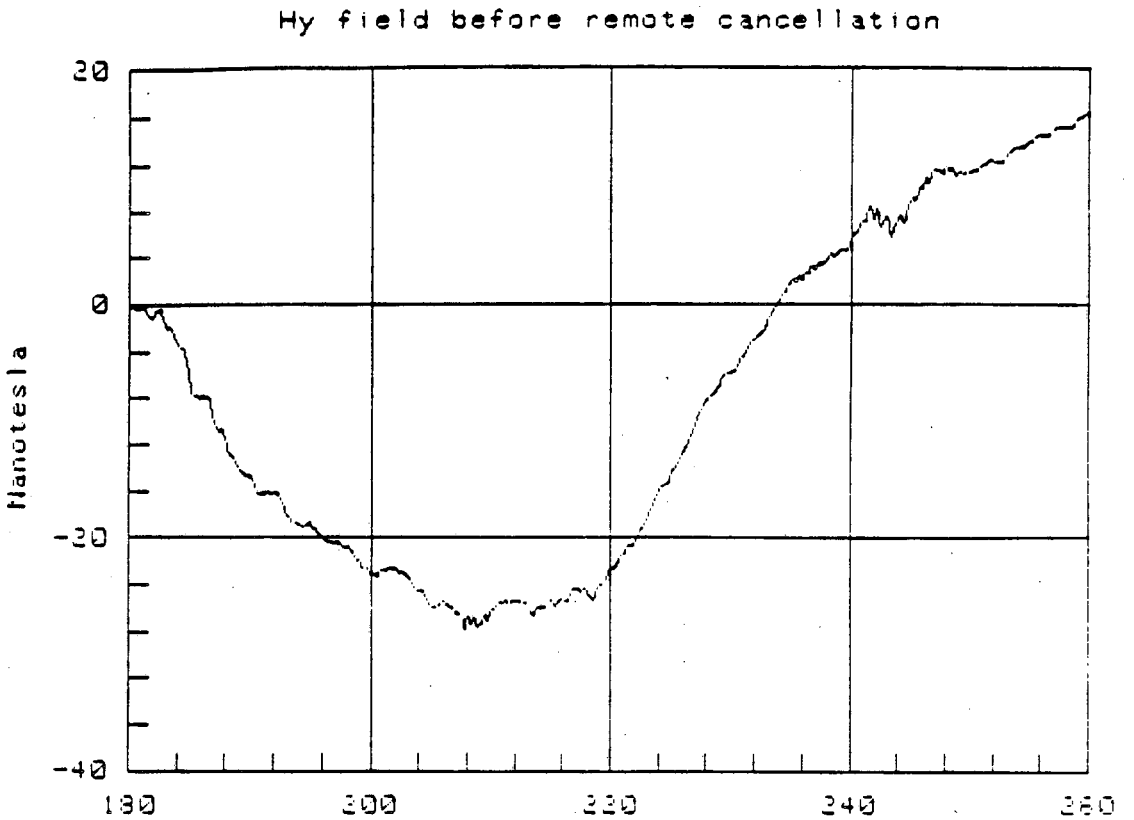

Figure 2a

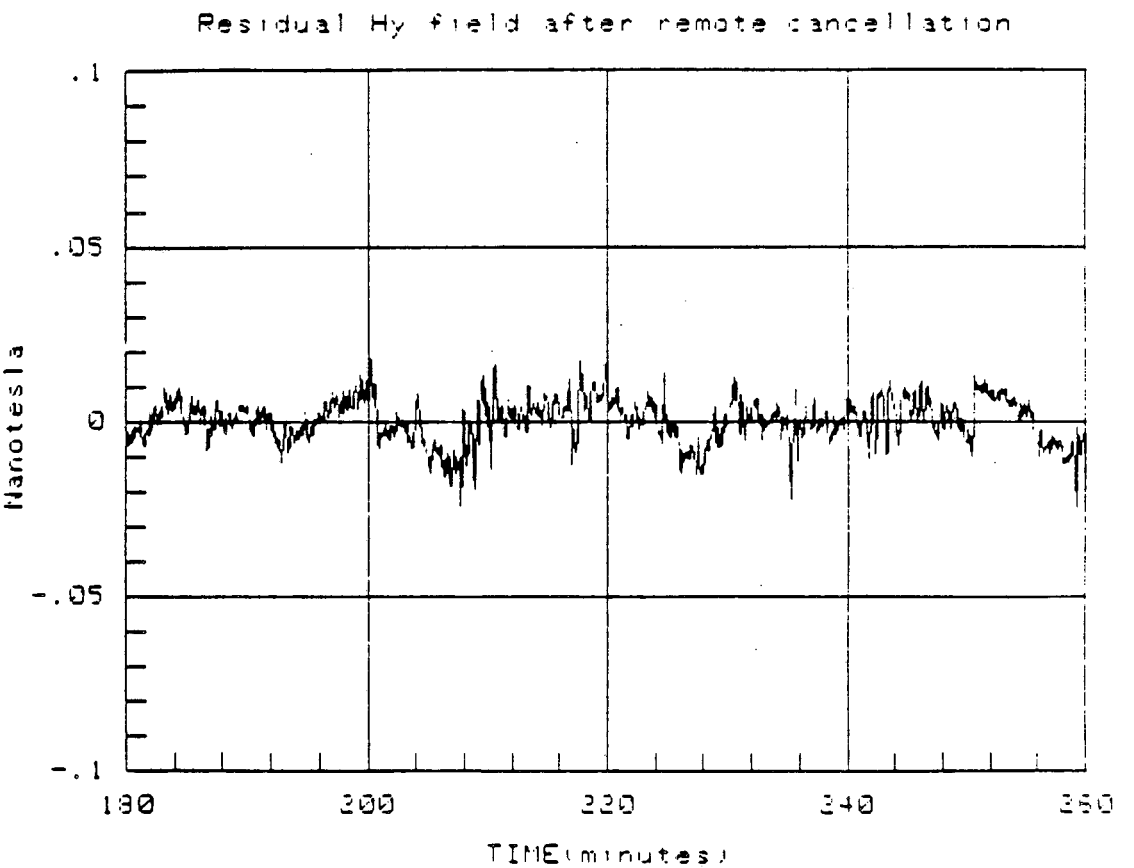

Figure 2b

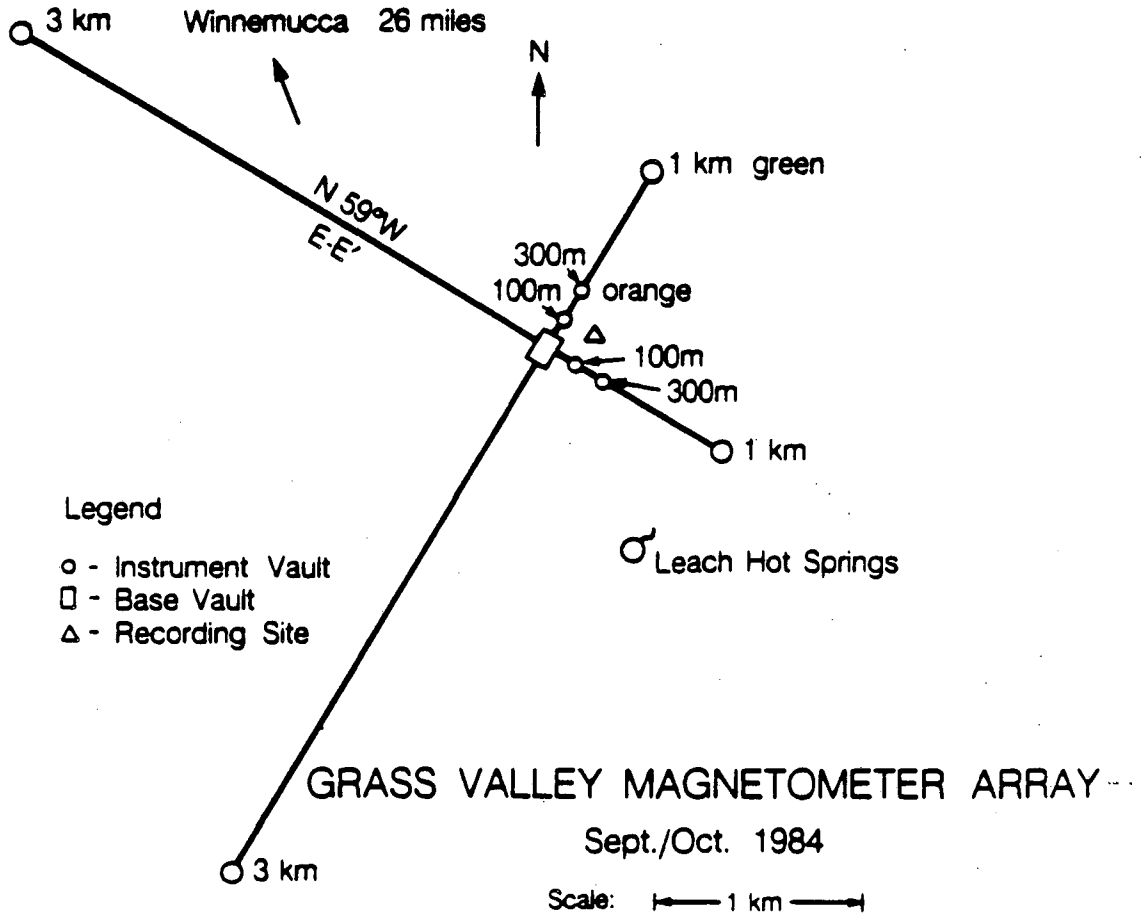
3 km
Winnemucca 26 miles
N
1 km green
N 59°W
E-E'
300m
100m
orange
100m
300m
1 km
Legend
o - Instrument Vault
□ - Base Vault
Δ - Recording Site
Leach Hot Springs
GRASS VALLEY MAGNETOMETER ARRAY
Sept./Oct. 1984
3 km
Scale: 1 km

Fig. 3a

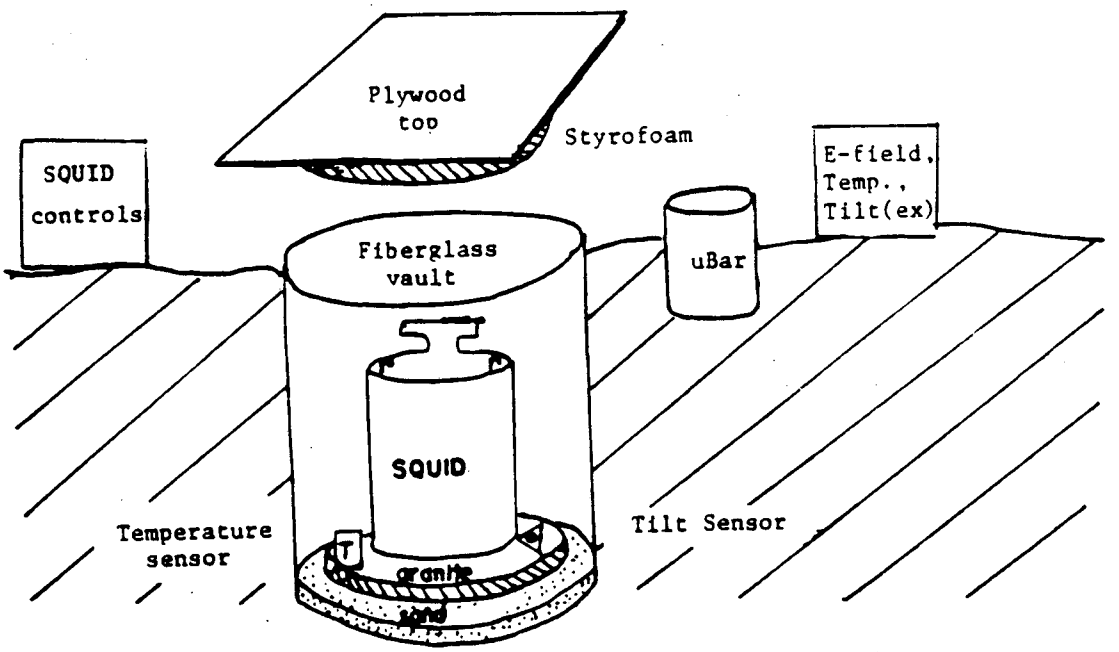
Plywood
top
Styrofoam
SQUID
controls
E-field,
Temp.,
Tilt(ex)
Fiberglass
vault
uBar
SQUID
Temperature
sensor
T
granite
sand
Tilt Sensor

Fig. 3b

Residual magnetic field between Orange and Green sites (Hx)

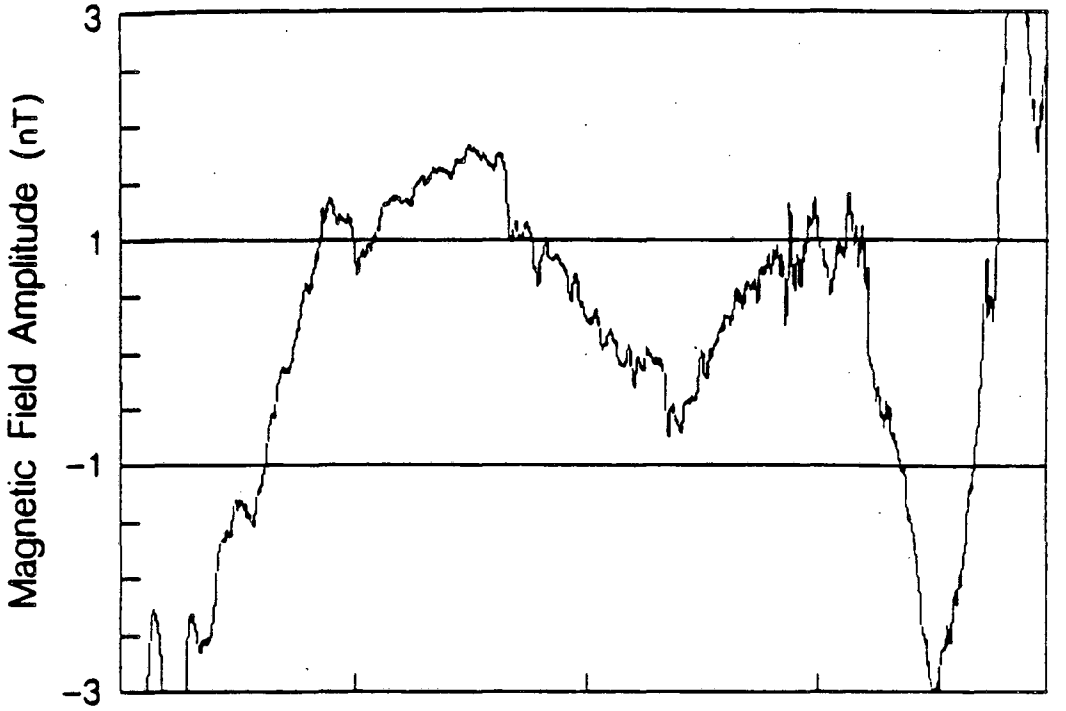

Fig. 4a

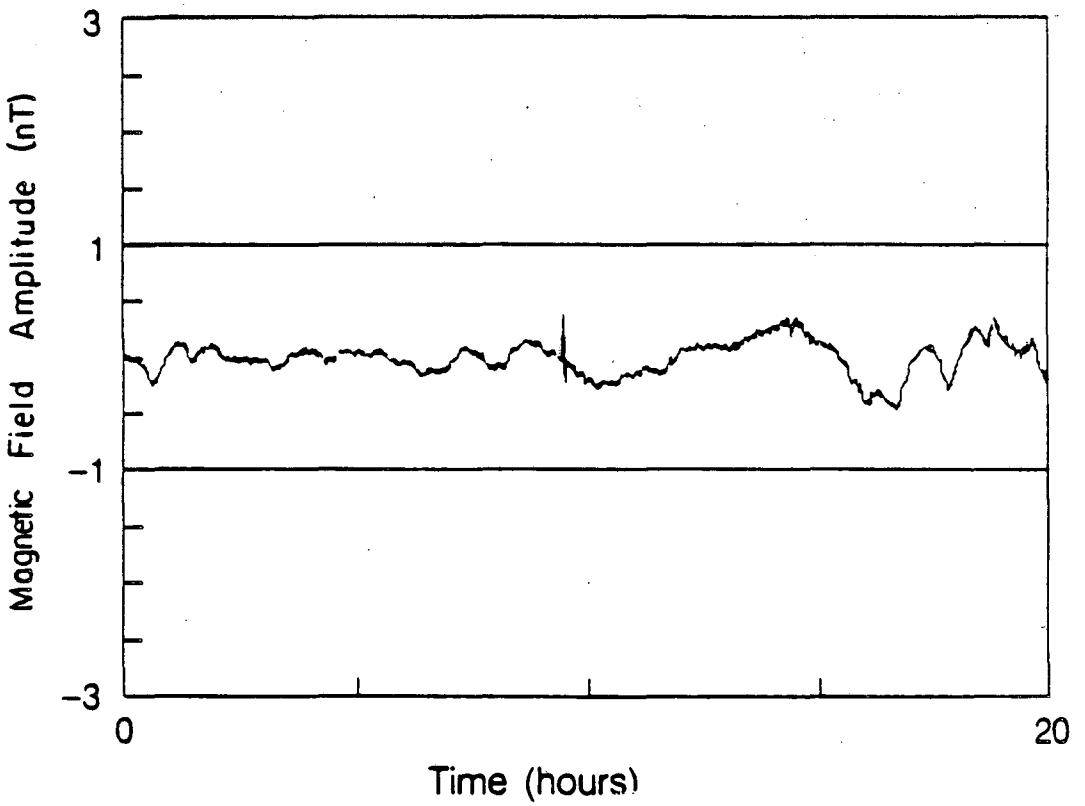

Fig. 4b

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