# CHAPTER III

# INSTRUMENTATION AND ANALYSIS

## III.1 Measurement

In this research we measured the natural low-frequency geomagnetic-geoelectric oscillations. Fluctuation of the magnetic field is caused by interaction of a beam of charged particles with earth's magnetosphere. The electric field variations in this case are caused by fluctuations in the earth's magnetic field. Induced electric currents flow in rocks and we can measure these electric field variations at the earth's surface.

### III.1-1 Magnetic Field Measuring

The measurement of magnetic micropulsations is considerably more difficult than the measurement of electric field oscillations. Only in recent years has equipment become available which makes it possible to detect such micropulsations of normal amplitude. Magnetometers have been constructed based on a variety of physical principles. Four types have been used extensively up to the present time to study magnetic oscillations; the magnetic balance, the flux-gate magnetometer, the induction coil, and the proton precession magnetometer.

Of the four methods for measuring magnetic field variation mentioned above, the magnetic balance is the oldest and simplest device, but is not sufficiently sensitive for study of Pc 1 oscillation. Moreover, it is sensitive to temperature changes, seismic accelerations, and lacks sensitivity to short-period magnetic variations.

Flux-gate magnetometers which are readily available and reliable respond to frequencies greater than 10 Hz, and measure only that component of the field parallel to the core. Their disadvantages are their high noise level, as compared with some other types, and their temperature sensitivity.

Proton precession magnetometers work on the principle of atomic resonance. They have a great advantage over the other types of magnetometers in that the measurement of the field strength is absolute, not subject to the many uncertainties of maintaining calibration that plague other types of magnetometers. Proton precession magnetometers are the best for measuring long term field changes. One major disadvantage is the complexity and cost of the equipment required to obtain an accurate measurement of the resonant frequency.

Induction magnetometers differ from other three types used in measuring magnetic field variations in that they measure the rate of change of field strength, rather than the field itself. From "Faraday's law of induction", the electro-motive-force (e.m.f.) induced in a coil of wire is:

$$\text{e.m.f.} = \frac{-d\Phi}{dt}$$

where $\Phi$ is the magnetic flux.

We will discuss this further in the next section. Induction coil magnetometers can have either an air core or a high permeability core. They have almost the same characteristics, such as the ability to measure signals with maximum frequencies more than 10 Hz and sufficient sensitivity to measure variations of $0.1\gamma$ (at 1 Hz). Induction coils with high permeability cores have an important disadvantage that air cored ones do not have. This disadvantage is harmonic distortion which is generated by induction coils with high permeability. Air cored coils must be much larger for the same sensitivity. Induction coil magnetometers are particularly effective for measuring geomagnetic oscillations in the frequency range from 0.1 to 5 Hz, a band containing the subgroups Pc 1 and Pc 2 micropulsations which we wanted to observe. We decided to use induction coils with air cores to measure Pc 1 because they are less expensive, effective in the range that we want to observe, and it is easy to find materials in this local, even though they are heavy.

a. Description of Equipment (Coil). The magnetic fluctuation field measuring equipment consists of three circular air-core coils each with 20,100 turns of AWG No. 34 copper wire on a two-meter diameter frame. The coils were wound semi-automatically by means of an electric motor and pulley arrangement (Figure 3 and 4). We divided the 20,100 turns into layers, each layer containing 200 turns.

Each layer of copper winding was bonded to the others with clear electrical varnish. When finished to 20,100 turns, the completed windings were covered with electrical tape, epoxy resin and a U-channel electrostatic shield of sheet copper was placed around the windings (Figure 5). Wooden sides were added for protection, the coil again covered with electrical tape, and finally the whole unit was painted with epoxy resin to give a hard waterproof finish. Waterproofing was done so the coils when emplaced could lie partially below the water table, a possible consequence of their large diameter as well as the high water table in the Bangkok area. A rubber tire was added to the coil circumberence to protect each coil. A finished coil weights roughly 45 kg., making it too heavy and bulky to be carried easily by two men, but two men can move it by rolling without much difficulty. These coils are sensitive to a range between 20 Hz to 0.001 Hz. Electrical connection between the coil windings and the measuring circuit is made via an Amphenol MS box receptacle (4 contact, socket type) mounted on the coil's inner circumference where it cannot be easily damaged. Pins A and C are connected to the start and the end of the windings, respectively. Pins B and D, shorted together within the box receptable, are terminals from the coil center tap, and connect to the ground of the measuring circuit.

One side of each coil is marked with a (+) sign to indicate that a positive field change, dB/dt, in that direction will result in a positive voltage at Pin A. Normally the three coils would be sited with their axes mutually perpendicular. We placed coils with their axes north-south, east-west, and vertical to the earth's main magnetic field (the main magnetic field of the earth tilts 11.5° to the rotation axis of the earth) making the (+) side facing in north, east and downward as in a right-handed coordinate system. Unfortunately, it has been found that the sign convention was reversed on coil #2, and when emplaced it should have its (+) side facing south, west, or upward.

The coil design was based on Campbell[1] (1959) and others, and is explained in more detail in appendix 1.

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[1] Campbell, op. cit., p. 7.

TABLE III-1

Coil Characteristics, Coils Horizontal on Ground and Held Vertical in Frame

| Coil | 2 | 3 | 4 |
|---|---|---|---|
| N (Turns) | 20,100 | 20,100 | 20,100 |
| R (k $\Omega$) | 44 | 41 | 47 |
| $\omega_o$ (rad/s) | 185.3 (175.8)* | 251 (251) | 128.8 (141.37) |
| fo (Hz) | 29.5 (28) | 40 (40) | 21 (22.5) |
| L (henries) | 734 (845.5) | 750.5 (517.5) | 1122 (1124) |
| C (nf) | 36 (35) | 19.7 (27.8) | 48 (41) |
| Q | 3.1 (3.4) | 4.6 (3.2) | 3.1 (3.4) |
| $n_{max}$ | 1.77 (1.92) | 1.76 (2.63) | 1.81 (1.98) |

* Numbers in parenthesis refer to measured or calculated values for the vertical orientation.

When the coils were finished we started to calibrate them. Table III-1 and Figures 6, 7 and 8 show the observed and measured coil characteristics. Calibration has shown that the resonant frequencies of these coils vary from 20 to 40 Hz, so that, as the frequencies of interest 0.1 to 5.0 Hz, the coils still behave as resistive circuit element with resistances of 44 to 47 k$\Omega$.

In theory the three coils should be identical but after construction, the resistance of each differs slightly. This is believed due to poor quality control of much of the wire that went into the coils. It was also found that inductances and capacitances varied from coil to coil. Moreover, these coil constants differed depending on whether the coil was lying flat on the ground or supported vertically (coil axis horizontal) in a wooden frame during calibration. When lying horizontal on the ground the coil appeared to have smaller inductance, hence Q, than when vertical, a condition believed due to mutual coupling between the coils and ground. However, the resonant frequency of the coils was little affected by coil orientation. Coil calibration procedures were adopted directly from Campbell (1959) with only minor modifications (see appendix 2).

b. The Measuring Circuit. The circuit of magnetic field measuring is shown in Figure 9a. The coil output goes to a calibration-filter circuit (Figure 10) via a three-conductor shielded cable. The filter is a simple, balanced, four-section low-pass filter to eliminate 50-60 Hz power-line and sferic pick up. The floating filter output is fed to a low-gain (X1000) differential amplifier (Tektronix, Model 122) which, because of its extremely high input impedance matching and also gives good common-mode rejection.

At the beginning of this work we measured at the MRDC Electronics Laboratory.* It is noisy test site, hence we found it necessary to include a 60 Hz notch filter following the preamplifier to reduce further the power-line frequency (Figure 11a). We later moved test site to the ASRCT TREND Site** and the filter was modified to notch 50 Hz (Figure 11b); the power-line frequency at TREND. On the output side of the notch filter is a voltage divider which attenuates the signal but which presents a low input impedance to the Astrodata 120 amplifier so that it can operate quietly at high gain. A gain setting of 5000 times for this amplifier is usually selected. The signal from the amplifier goes to a recorder (Brush Mark 260, six channels paper chart recorder) and this is the last step of the measuring circuit at Bangkok site. At TREND Site the output from coils pass through initial low pass filter, differential amplifier (Tektronix Model 122), 50 Hz notch filter, amplifier (Astrodata 120), pre-recording low pass filter*** and then the signal goes to recorder (Brush Mark 260). This measuring circuit is shown in Figure 9b.

Figure 12 shows the circuit of the Pre-Recording low pass filter and Figure 13 shows a detailed block diagram for one channel of the three magnetic field measuring channels. Chasis grounding as shown in this figure is extremely important.

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* The MRDC Electronics Laboratory, Petchburi Road, Bangkok uses 110 V., 60 Hz power line frequency.

** The TREND Site, Sakaraj, Nakhon Ratchasima uses 220 V., 50 Hz power line frequency.

*** At TREND Site there is high level of noise at 12 Hz, which came to disturb these signals.

Deviation from the arrangement of signal leads and chasis grounding might result in ground loops and an intolerable noise level.

As shown in the generalized block diagram (Figure 9a), timing of the chart record is accomplished by changing chart speed at regular intervals. Control for this operation comes from a frequency standard and divider circuit which can be programmed to open and close a relay at regular intervals. The normally open relay state causes the chart motor to move at an operator selected slow speed; either 1, 5, 25 or 125 mm/minute. With the relay closed the chart speed increases by a factor of 60. For our purposes we found that 1, 5 and 25 mm/second speeds are used allowing us to monitor continuously yet obtain a good hourly sample of geomagnetic activity and conserve chart paper. At TREND Site the speeds are 1 mm/second for 1 minute, 5 mm/second for 1 minute and 25 mm/second for 30 seconds in every hour.

c. <u>System Frequency Response</u>. System of frequency response at Bangkok site is determined primarily by the initial low pass filter and Tektronix preamplifier characteristics and is given in Figure 14. Frequency response of 60 Hz notch filter and attenuator is shown in Figure 15. The expected coil output in microvolts can be obtained by multiplying the average field strength in gamma $(1\gamma = 10^{-5}\Gamma)$ by the frequency of the excitation signal and by a geomagnetic coil constant which depends on coil diameter and numberof turns (see Eq. 3 in appendix 1). In our case, the coil constant is about 397 and the expected coil output is given by Curve 1 of Figure 16a. Multiplying this expected output by the system response (Figure 14) then give (Curve 2) the relative system sensitivity to Pc 2, 3 and Pc 1 micropulsations.

At TREND Site the system of frequency response is determined by the initial low pass filter, Tektronix preamplifier, 50 Hz notch filter, amplifier (Astrodata) and pre-recording low pass filter characteristics and shown in Figure 17a and 17b. In the same way we can find the average field strength in gamma. Figure 16b are shown the expected coil output in Curve 1 and average coil output after correction frequency response of the system already in Curve 2.

The expected signal-to-noise ratio can be estimated from curve 2 of Figure 16 and the calculated and measured noise level. One source of noise, the thermal noise level generated by a coil under normal operating temperatures is given by:

$$V_n\ (\mu v) = 1.26 \times 10^{-4}\ (R \times \Delta f)^{\frac{1}{2}}$$

and Vn is less than 1 $\mu$v even if the circuit resistance (R) is 2 or 3 M$\Omega$ because $\Delta$ f (the operating bandwidth) is so narrow.

A more serious source of noise is the flicker and shot noise in the input stage of the Tektronix preamplifier. We found that at frequencies of interest the noise amplitude increases as $\frac{1}{f}$. Measurements have shown a 4 $\mu$ v (rms) noise level (referred to input) is present at 1 Hz, but, this noise level is low enough so as not to seriously degrade the measurement of Pc 1 picropulsations. However, because of the inverse relation between frequency and noise level, in Pc 2, 3 micropulsations would have amplitudes greater than the amplifier noise unless flicker noise is greatly reduced. One approach for doing this is to make three simple modifications to the amplifier as described by Brophy in 1955 and used successfully by Campbell (1959). It is reported that the flicker noise level is reduced by an order of magnitude after the modifications. Similar modifications are planned for our amplifiers.

Because the coils are induction magnetometers, the time derivative of the magnetic field is measured, not the field itself. Integration of the signal could be handled electronically. This approach was not incorporated into the system. At present, integration of the magnetic field is done numerically in one subroutine of a comprehensive data analysis program that has been written for use in the research program and discussed in detail in the next section of this chapter.

### III.1-2 Electric Field Measuring

Measuring the electric field caused by induced currents consists of two parts; the electrode, which measures potential at any point of ground, and the measuring circuit.

a. Description of Equipment (Electrode). Since the earth's magnetic field is varying in time, currents may be induced in the earth which cannot be explained in terms of the direct current theory. We must make use of Maxwell's equations, which take into consideration the existence of induction currents. Magnetometers require great sensitivity in order to detect variations in the magnetic field in the order of tens of gammas with diurnal periodicity, and variations of the order of tens of milligammas with periods of a few seconds. The equipment for detecting variations in the electric field can be less sensitive. Electrode separation may be increased to compensate for lack of sensitivity and measure the required amplitudes. In tropical latitudes, it is necessary to be able to detect electric field oscillation amplitudes in the range from tenths of millivolts to tens of millivolts per kilometer. In measurement we use electrodes which are designed to avoid variations in electrode potential due to temperature changes. A lead plate buried in a shallow trench, and moistened with salt water, is a good simple electrode. Electrode potential, which is the potential drop between an electrode and the electrolyte in contact with it, depends on temperature for simple electrodes. Our signals are variations with periods ranging up to a day, and in the long time of measurements, changes of temperature will have occurred. Another possible disadvantage of such simple electrodes is the requirement that measurements be made soon as electrodes are emplaced. There is some advantage to using non-polarizing electrodes; electrodes which consist of a metal immersed in a saturated solution of one of its salts. Combinations commonly used are copper electrodes in solutions of copper sulfate and zinc electrodes in solutions of zinc sulfate.

In our measurements at the Bangkok site (MRDC Electronics Laboratory) we found that non-polarizing electrodes were suitable for electric variation fields measurement. We used the combination of copper electrodes in solutions of copper sulfate. Each electrode has a copper rod immersed in a six-inch high porous porcelain "pot" filled with a saturated solution of copper sulfate. A rubber stopper seals the pot and holds the protruding copper rod in place. Except around a small area at its base, the pot's exterior is coated with Silastic RTV compound, to reduce leakage of copper sulfate solution (see Figure 18a).

Two electrodes, separated by 200 meters, are buried 18-inches deep in covered holes, and electrical contact between electrode and ground is maintained by leakage of copper sulfate solution through the porous pot. The potential differences between the separated electrodes are amplified and recorded. Normally two orthogonal electrode pairs are emplaced, one pair north-south, the other east-west.

On the other hand, for our measurements at the TREND Site we found that a "lead plates" buried in a shallow trench, and moistened with salt water were suitable electrodes for this situation. Each lead plate has a surface area of about 80 square inches and thickness of $\frac{1}{4}$ inch (Figure 18b). We did not use copper electrode because it was not convenient to refill copper sulfate solution in the jungle station like TREND Site. At this station we placed two electrodes in 150 meters apart. In measuring electric variation field two orthogonal electrode pairs are emplaced, one pair in north-south direction, and the other in east-west direction.

b. Measuring Circuit. The equipment required for measuring the electric field variations starts with two electrodes. When signals go out from the electrodes they pass through a initial low pass filter to eliminate unwanted high frequency signals from the signal. In view of the small changes in voltage which are to be measured, the signal must pass through a Tektronix 122 low-gain preamplifier, and then to the Brush 260 recorder (Figure 9a).

In a noisy location, such as the Bangkok test site, a 60 Hz notch filter is added to that circuit. At TREND Site when signals go out from the electrodes they pass through 50 Hz notch filter, low pass filter, DC blocking and then to Brush Mark 260, recorder as shown in Figure 19. And overall response of electric field measuring system is shown in Figure 20.

c. Equipment Housing and Transportability. Except for the coils and electrodes, which must be buried, the equipment is housed in a small, windowless, but air-conditioned aluminum van. The van is transportable. It was designed to fit snuggly into the bed of a 2-1/2 ton turck, and this may be taken anywhere the truck can travel. For long-term field monitoring the van would be unloaded from the truck, either by means of a fork-lift or an "A" frame with block and tackle. Figure 21 show the rack mounted equipment inside the instrument van, and an exterior view of the van and surroundings at TREND Site.

Because of their large size, the coils have to be transported by a separate truck.

## III.2 Analysis of Magnetic and Electric Fields

The purpose of the analysis of geomagnetic disturbance field is to find the amplitude, spectral characteristic, times of occurrence and polarization of Pc 1 micropulsations. In this section we discuss the procedures used for analysis, which have been programmed in FORTRAN for rapid computer computation and graphic presentation.

### III.2-1 Digitizing of Data

The data is continuous and in this thesis our data is recorded in 24 hour per a day continuously one month. The first step in data analysis is the process of digitizing which consists of converting continuous data into discrete numbers. There are three things we must consider, the first of which is selection of segments of data that contain interesting details (Pc 1). The second is a selection of a sampling interval $\Delta t$. We must choose $\Delta t$ sufficiently small to avoid aliasing errors[2]. Third, we must make sure that the number of samples is sufficient to make our result significant (see appendix III).

### III.2-2 Data Filtration

Although the fields were electronically low-pass filtered prior to recording, numberical filterning by means of a digital computer is used to suppress those frequencies not of immediate interest or which obscure the important information. The effect of filtration is to enhance the frequency components selected for further study without causing any phase shift that would distort the data. The filter center

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[2] Bendat, J.S., and Piersol, A.G. 1966. Digital Computer Techniques, p. 278-320. Measurement and Analysis of Random data. New York: John Wiley and Sons.

frequency ($f_o$) and pass-band width ($\Delta f$) are chosen on the basis of a visual inspection of the original record. If the physical process is not stationary, that is, the spectral composition changes with time, each segment of the original data may require a separate set of filter parameters. The parameters $f_o$ and $\Delta f$ are read in and the appropriate impulse response function is calculated. This function, h, when convolved with the original data, $x_i$, produces the filtered output signal $x_o(t)$

$$x_o(t) = \int h(\tau) x_i(t-\tau) d\tau$$

with the information in frequency band of interest left undisturbed. The $h(\tau)$ is known as the filter impulse response. Meyerhoff[3] studies how to optimize, in a mean square sense, $h(\tau)$, when $h(\tau)$ is finite in length. According to this analysis, the filter we use, which has unit gain within the pass band and zero gain elsewhere, suffers from the socalled Gibbs[4] oscillations when $h(\tau)$ is by necessity truncated. That is, the actual frequency response of the filter has a maximum 9% overshoot on either side of the filter cut-off frequency. These oscillations in the frequency response cause slight errors in the output data which we can ignore so long as the frequencies of interest are near $f_o$ and not near $f_o + \Delta f$.

The operation is the digital counterpart of electronic filtering and is used to supplement the low pass electrical filtering done prior to recording. In face, digital filtering provides a flexibility that cannot be matched by electronic circuits.

### III.2-3 Integration of Filtered Data

If the data is magnetic field information, numerical integration of the raw of filtered data is necessary because the field derivative and not the field is parameter detected and recorded. Integration would not be required if the data were electric field information. After the integration step the field value is $\bar{x}_o(t)$

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[3] Meyerhoff, M.J. 1968. Realization of Sharp Cut-off Frequency Characteristics on digital computers part I, II. Geophysical Prospecting, XVI: 208-246.

[4] Meyerhoff, op. cit.

### III.2-4 Autocorrelation

The autocorrelation function[5] for random data describes the general dependence of the values of the data at one time on the values at another time. The function is calculated in preparation for obtaining the power spectra of the field via the Weiner theorem. The autocorrelation function is given in integral form as

$$R_x(\tau) = \lim_{T\to\infty} \int_0^T \bar{x}_o(t)\bar{x}_o(t+\tau)dt; \qquad \tau = o, 1, 2, m$$

when $\tau$ is number of lag. This expression means that the sum of lagged products is calculated up to some maximum lag $\tau_{max} = m$. The autocorrelation itself can establish the influence of values at any time over values at a future time.

### III.2-5 Power Spectrum

Power spectral density function[6] for random data describes the general frequency composition of the data in terms of the mean square value of the record in discrete, narrow frequency ranges. An important property of the power spectral density function lies in its relationship to the autocorrelation function. For stationary data the Fourier cosine transformation of the autocorrelation function gives the power spectrum density of the processed data.

$$\bar{G}_x(f) = 4\int_0^m R_x(\tau)\cos(2\pi f\tau)d\tau$$

This is the "raw" estimate of the true value of $G_x(f)$. Spectrum smoothing of the raw estimates of the power spectral density is done by various techniques in order to reduce the error in the spectral estimates. The technique used in this work, called "Hanning", is described in appendix IV.

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[5] Bendat and Piersol, op. cit., p. 23.

[6] Bendat and Piersol, op. cit., p. 23.

### III.2-6 Polarization of the Fields

On important feature of the fields which is worth studying is their polarization. We can select any two components and plot them together in an x-y plot, e.g. $H_x$, $H_y$; $H_x$, $H_z$; and $E_x$, $E_y$. This is done to determine the field's direction and ellipticity and how these might change with time.

### III.2-7 The Step of Analysis

There are many steps of analysis, each of which may be included or not. For example, if the original data have high frequency noise and we want the power spectrum and polarization of Pc 1, we would use all the steps explained in this section. If the original data have only frequencies in the range of interest, we can omit the filtering step. The steps of analysis depend on the original data and the output information desired.