

AFMAG—AIRBORNE AND GROUND*

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ABSTRACT

The existence of natural magnetic fields in the audio and subaudio frequency range has been known for some time. The primary source of energy for these fields is usually considered to be distant and local thunderstorms. Because of this origin, the fields are quasi-random with both amplitudes and directions changing drastically over short periods of time. Hence, use of these fields in geophysical prospecting has been extremely limited.

A new development, AFMAG, however, essentially eliminates the time variance in recording these fields without any sacrifice of the intelligence of their space variance. Since the space variance can be correlated with geologic features, AFMAG provides a new method of exploration with particular application to prospecting for conductive mineral deposits.

Instrumentation of the AFMAG method currently is available for both ground and airborne operation; the tilt of the plane of polarization of the natural magnetic fields is recorded simultaneously at two frequencies. Examples drawn from airborne and ground surveys show that the method has a much greater depth of exploration than its conventional cousin, the induction electromagnetic method. Numerous other advantages, such as the possibility of choosing discrete operating frequencies over a broad band from 1 cps to 1,000 cps, are discussed. The chief disadvantage of the method lies in a sometimes restricted daily measuring period during which the fields are of an amplitude too low to permit measurement with current instrumentation; this is not a serious problem and is being minimized as the technology improves.

INTRODUCTION

Electromagnetic surveys, both airborne and ground, have in recent years become the primary field activity in exploration for massive sulphides in most of Canada. Numerous specific techniques have been applied and most of these with success. However, all such methods bear one common inherent limitation: Depth of exploration is not great. On the ground this depth of exploration varies from 100 to 500 ft depending upon the technique employed. In the air it varies from 75 to 200 ft below surface. This limitation is imposed by the finite separation necessary between a transmitting coil and a receiving coil in order that the measurement of coupling between the two be reliable. The larger the separation between the transmitter and the receiver, the greater is the inherent depth of exploration; but so also are the requirements on signal-to-noise ratio in the receiver and transmitted signal strength made greater. Practical considerations associated with signal-to-noise ratio and signal strength so limit the useful depth of exploration to the maximum figures noted above of about 500 ft for ground equipment and about 200 ft (subsurface) for airborne equipment. These depths of exploration are not adequate for general world-wide coverage.

However, as Slichter (1955) has demonstrated, one of the main factors giving rise to a limited signal-to-noise ratio (atmospheric noise) may be put to good use as a source of energy to replace the artificially transmitted energy employed in

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conventional electromagnetic systems and thereby circumvent the depth limitation.

This has been done with AFMAG (Patent Pending), a product of ten years of research by the author and his associates.

The major problem to be faced in employing this natural energy is that it is very rapidly time-dependent. Separating the time-variance from the space-variance of these fields is a relatively simple theoretical problem as will be discussed below. Practically, however, the problem has been a difficult one; the difficulties were compounded by a world-wide lack of basic knowledge of the characteristics of the natural fields.

It is the object of this paper firstly to augment and review the state of knowledge of the natural audio and subaudio frequency magnetic fields with particular reference to the utility of this knowledge in employing AFMAG surveys and secondly, to discuss examples of airborne and ground AFMAG surveys. Some of the advantages and limitations of the method are thus made apparent.

NATURE AND ORIGIN OF NATURAL MAGNETIC FIELDS IN THE AUDIO AND SUBAUDIO FREQUENCY RANGE

Mode of Origin and Propagation

The rate of publication of articles on atmospheric "noise" in the audio and subaudio frequency range has increased markedly in the last five years. Although the amount of such data is still limited, we can conclude from it that the following are the chief sources of audio frequency atmospheric noise:

- (1) thunderstorms,
- (2) direct audio frequency energy from the sun filtering through the ionosphere,
- (3) the generation of audio frequency magnetic fields by interaction of the corpuscular radiation from the sun with the ionosphere in the presence of the earth's main magnetic field, i.e., the gyromagnetic effect (Aarons, 1956)
- (4) the generation of audio frequency magnetic fields by interaction of meteorites and the ionosphere (gyromagnetic effect),
- (5) man-made noise. This could include fields due to urban electrification gyromagnetic effect from ionized blasts such as nuclear explosions, jet aircraft "vapor trails," etc.

World-wide thunderstorms would appear to be by far the most dominant source of energy, but this is by no means an established fact. In any event, the energy, whatever its derivation, is propagated in a spherical wave guide bounded by the surface of the earth and the lower surface of the ionosphere. Attenuation of the wave is therefore determined by the height of the lower surface of the ionosphere and by the physical properties of the surface layers of the earth and ionosphere. Neither of these surface layers is homogeneous, and hence, propagation is irregular geometrically. Further, the electrical properties of the ionosphere and

the height of its lower surface are time variant. Therefore, the attenuation is time variant.

Thus, the writer believes (but has not fully proved) that selective attenuation of components is far more important than spatial origin in determining the direction of polarization of the natural fields at any point in space.

The word "polarization" here is meant to refer to a "mean polarization," since the fields at any point in space possess a quasi-random character. The vertical component of overlapping individual pulses, which constitute the mean field, is normally lacking because of attenuation. Some horizontal polarization is evident, but is much less definite than the vertical polarization. Polarization becomes much more pronounced near a highly conductive geologic entity and the vertical component can become appreciable. Since thunderstorm sources are irregularly distributed throughout the world, this degree of disorder is to be expected. Fortunately, some degree of order exists; the ratio of vertical to (mean) maximum horizontal components, at any point in space, remains sensibly constant with time except when thunderstorms exist overhead.

Diurnal, Short Period, and Intermediate Period Time Variations in Field Strengths

A typical 24-hour recording of the time variation of one component of the magnetic fields is shown in Figure 1. This recording was made with a narrow band-pass (500 ± 5 cps) tuned coil receiver oriented so as to detect the maximum horizontal component. Two features of this recording are worthy of note:

- (1) A sinusoidal diurnal variation in amplitude exists.
- (2) Irregular short period variations in amplitude are recorded and appear as sharp "spikes" throughout the recording.

It should be stressed that the detector employed was narrow band, and hence the recorded 500-cps envelope is smooth relative to the existing pulsations of the field. An indication of this relative smoothness is afforded by expanding the time base as in Figure 2.

The irregular short period variation is caused by the almost random occurrence and distribution of the sources, while the sinusoidal variation is caused by a regular time-variant attenuation associated with changes in the height and electrical characteristics of the lower surface of the ionosphere, as referred to earlier.

During the day, the lower ionospheric layer is the D-layer at a mean height of 60 km. This high-loss layer disappears at night and the more conductive E-layer at 90 km becomes the upper bounding surface of the earth-ionosphere wave guide. Hence, typically, field strengths are lower during local daylight hours than at night.¹

¹ Although the D- and E-layers are the accepted lower bounding surfaces of the ionosphere by day and by night, respectively, they are usually established as such by radar reflections and not by audio frequency measuring techniques. For this reason they are not necessarily the bounding surfaces for audio frequency energy, although most audio frequency propagation can be explained on this basis.

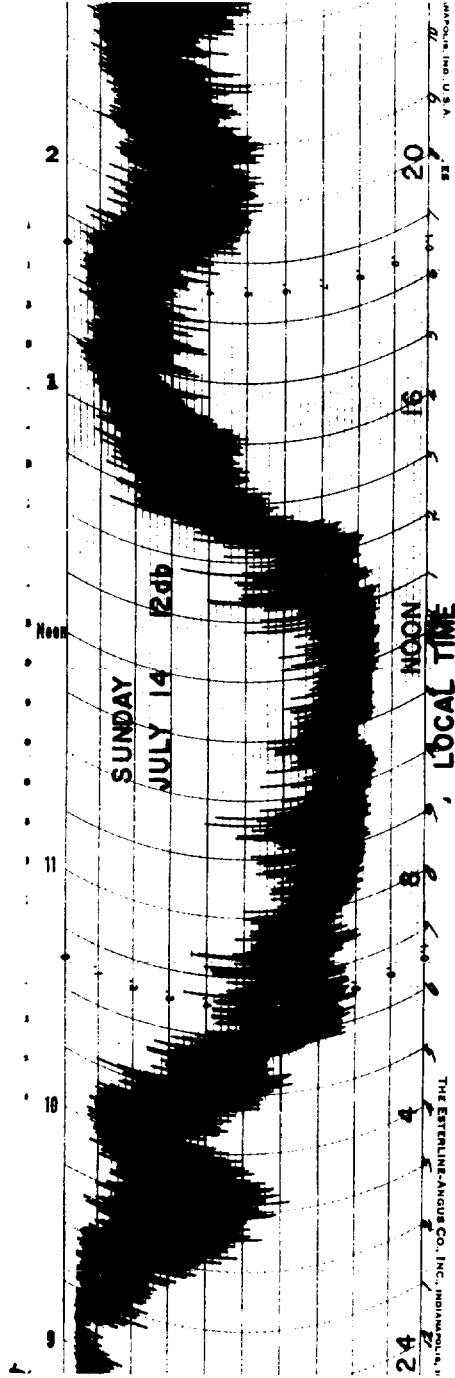


Fig. 1. Typical 24 hour recording of magnetic noise field. Location: Orangeville, Ontario. Date: July 14, 1957. Frequency: 500 CPS.

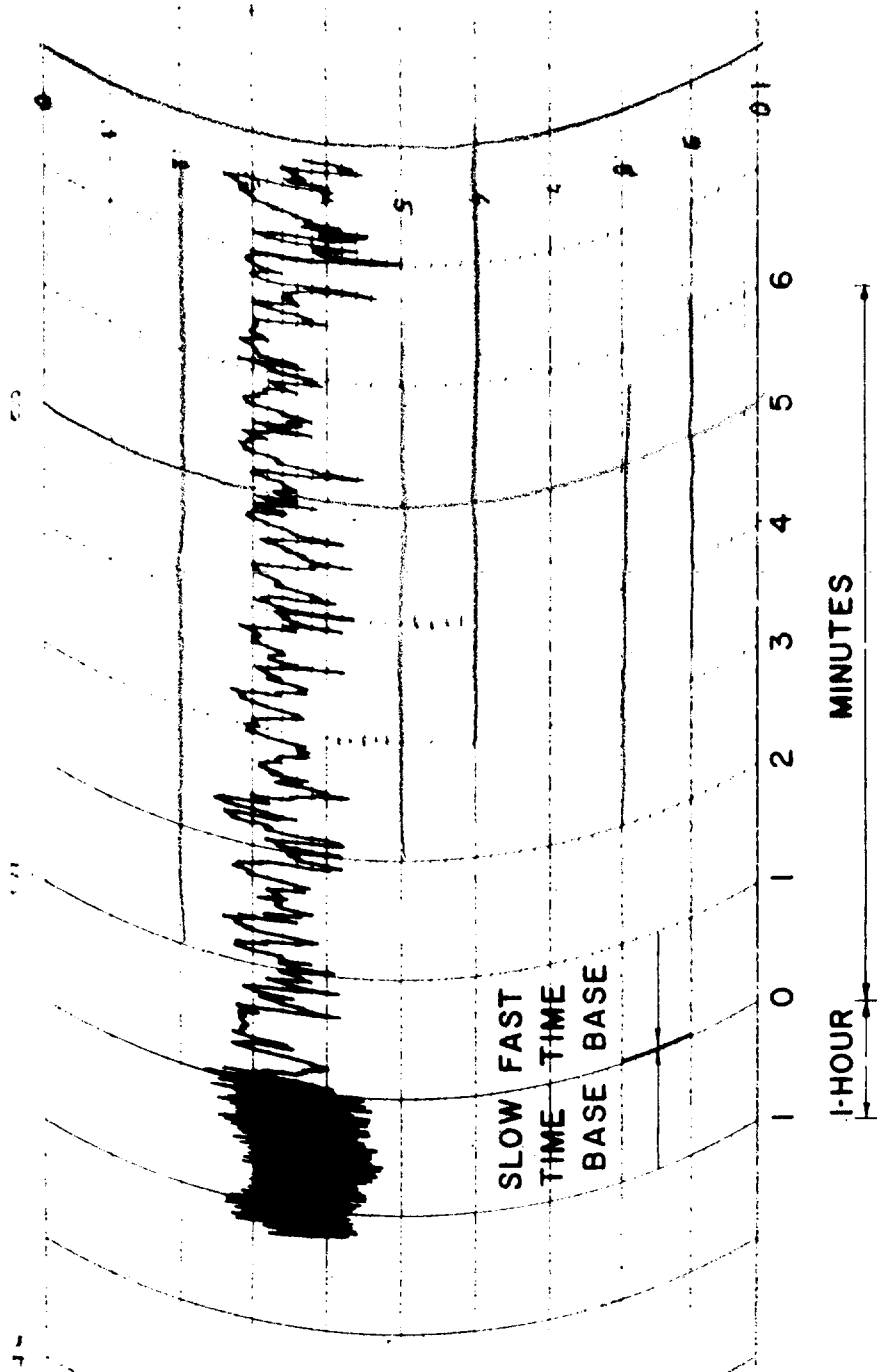


FIG. 2. Example of field strength variation, expanded time base. Location: Orangeville, Ontario. Date: September 23, 1958. Frequency: 500 CPS.

Superimposed on the short period and diurnal variations are irregular variations of intermediate periods. These may be caused by intermediate period time variance in the electrical properties of the ionosphere, in which case they may have the appearance of embayment "A" in Figure 3. Alternatively, they may be due to very local thunderstorms.

Local and Distant Sources

It is proposed that the total thunderstorm contribution to noise be considered as made up of local and distant parts.

The existence of these parts is clearly demonstrated by an analysis of Figure 4. The usual diurnal variation is present, but it is largely obscured by erratic and marked increases in intensity occurring between 9 A.M. and 12 noon for a station located at Lac La Ronge, Saskatchewan.

An illustration of the existence of distant sources is provided by recordings *A* and *B*, Figure 5. In this illustration, two stations over 2,000 miles apart detect almost identical patterns, although not necessarily identical amplitudes, for a period of several days. (Gain settings of the recorders at the two stations have not been cross-calibrated and, hence, a comparison of signal strengths is not available.) It is known that thunderstorms were not occurring near either site during the period of recordings. The two stations were Cross Lake, Ontario, and Tombstone, Arizona.

Although diurnal variation in field strength appears to be closely related to the development and dissipation of the D-layer of the ionosphere as the sun rises and sets, the correlation is not always obvious. For ideal correlation the daytime low in field intensity should be related to local time, and in many instances this holds true. For the recordings of Figure 5, an absolute time for the domain which includes the source of energy plus the two stations of observation needs to be considered. For example, events *A*, *B*, and *C* on the two recordings are separated by 2 hours and 25 minutes, 2 hours and 20 minutes, and 2 hours and 20 minutes, respectively. Since the two stations are situated 2 hours and 12 minutes apart geographically, the events *A*, *B*, and *C* occurred essentially simultaneously at the two localities. At this time of year (April), the nearest strong center of thunderstorm activity (World Meteorol. Organization, 1956) is probably in Central and South America (see Figure 6). Presumably the mean electrical characteristics and mean height of the ionosphere over a broad region spanning at least both North and South America must be considered. Note the disappearance of the regular diurnal pattern from 6 P.M., April 26, to 8 A.M., April 27 (times refer to the Tombstone record only, but the same phenomenon occurs on both recordings).

The "distant" sources are, in the literature, usually considered to be the three major world thunderstorm centers of Africa, South America, and the East Indies (see Figure 7). To provide a qualitative measure of the effect of the distance of one of these sources on the strength of the field at any point, the author made

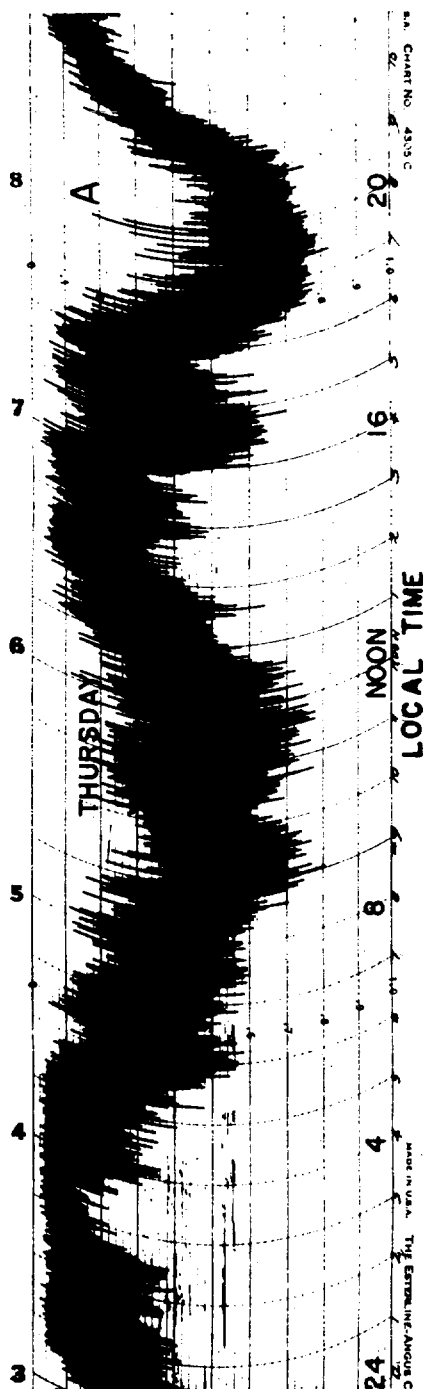


FIG. 3. Illustration of variation of magnetic noise field strength attributed to local variation in electrical properties of ionosphere. Location: Orangeville, Ontario. Date July 11, 1957. Frequency: 500 CPS.

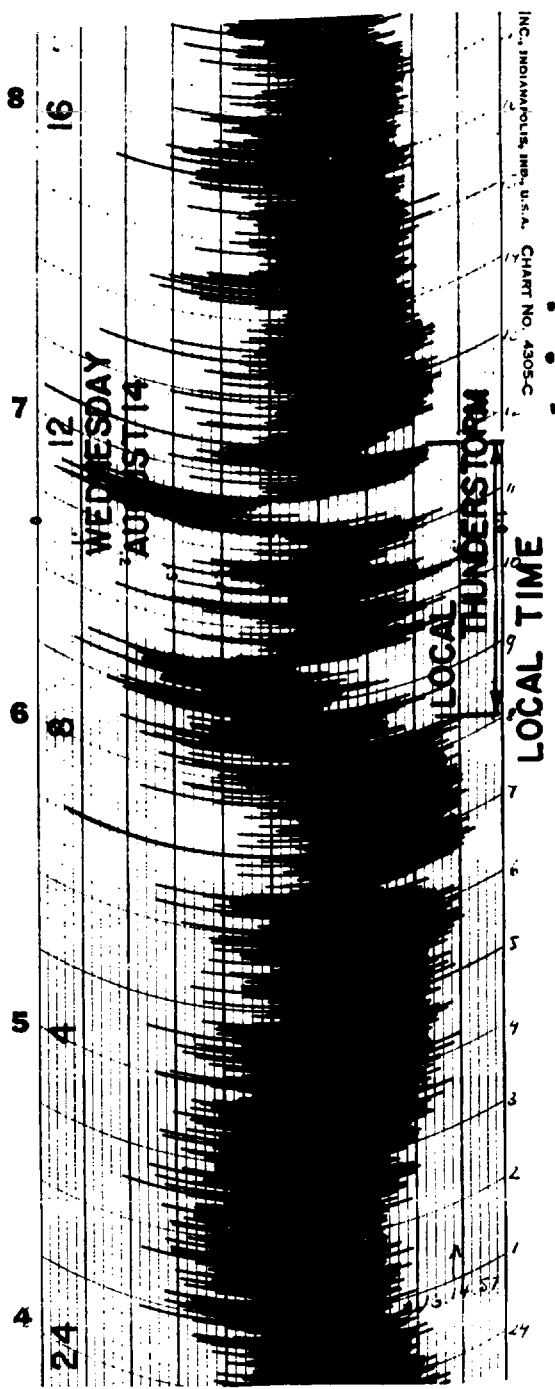
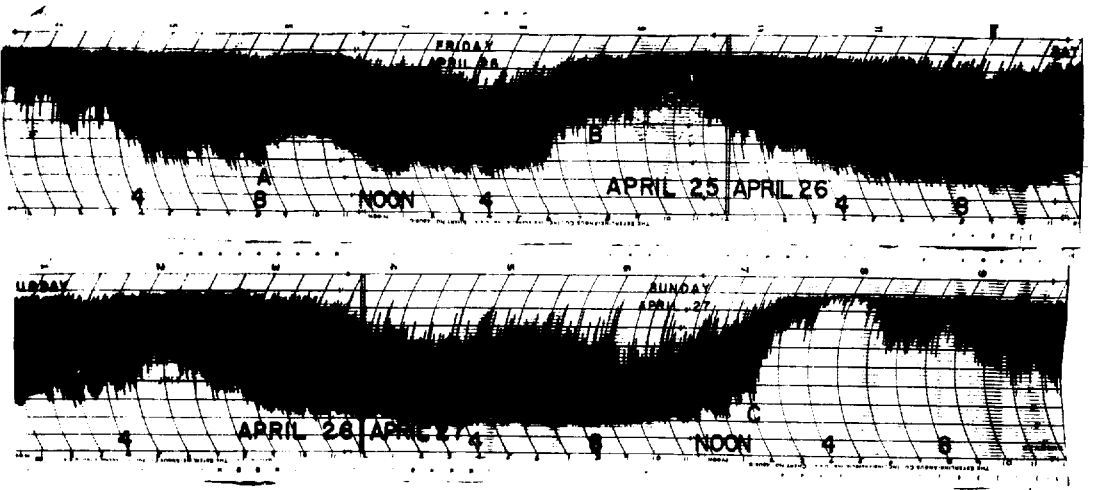


FIG. 4. Illustration of local thunderstorm contribution superimposed on distant thunderstorm contribution. Location: Lac La Ronge, Saskatchewan. Date: August 14, 1957. Frequency: 150 CPS.

A—CROSS LAKE, ONTARIO



B—TOMBSTONE, ARIZONA

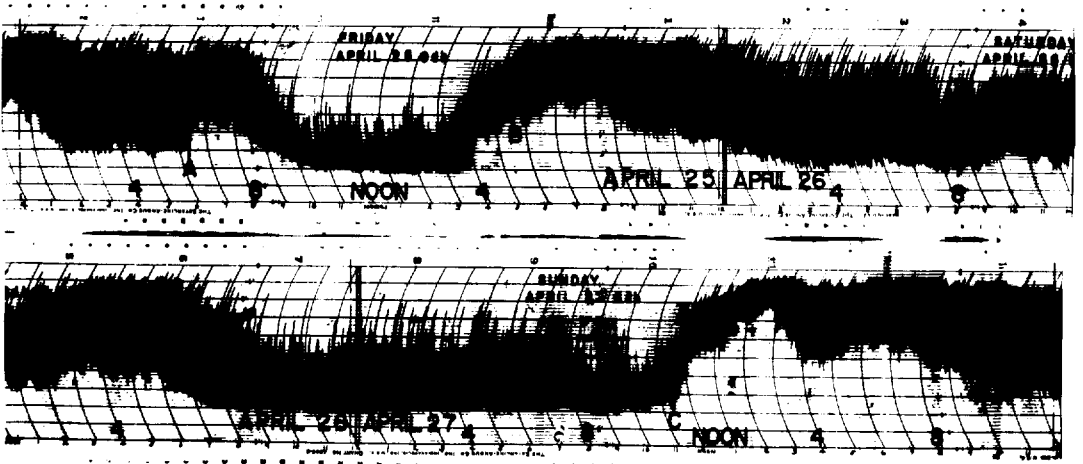


FIG. 5. Correlation of magnetic noise field strength between stations at Cross Lake, Ontario and Tombstone, Arizona for period of three days.

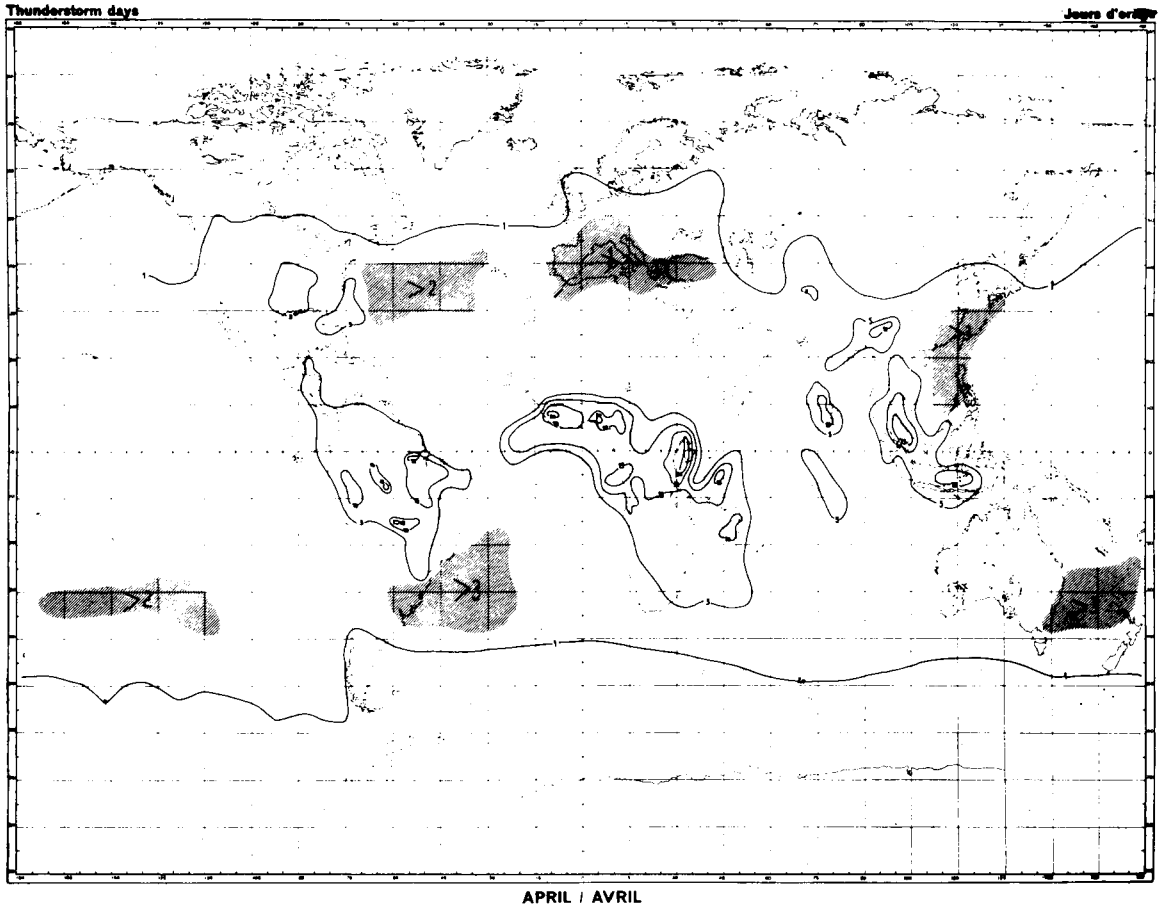


FIG. 6. World wide distribution of average number of thunderstorm days for month of April. (After World Met. Org.) Contour values 1, 5, 10, 15, 20.

measurements near Kitwe in Northern Rhodesia during the months of July, August, September, and October of 1957. July in Northern Rhodesia is a mid-winter month and seldom contains any thunderstorm activity (see Figure 8). At this time of year the center of the African thunderstorm activity is farther north. As October arrives, the thunderstorms in Northern Rhodesia become frequent and occur mostly about 4 P.M., local time. Violent bursts of lightning and thunder, accompanied by torrential rain, occur overhead most afternoons in the latter part of October (see Figure 9). Thus from July to October the thunderstorm energy center has moved south by perhaps 500 to 1,000 miles. A marked increase in audio frequency magnetic "noise" should, then, accompany this phenomenon. Such an increase may be observed by comparing the mean diurnal

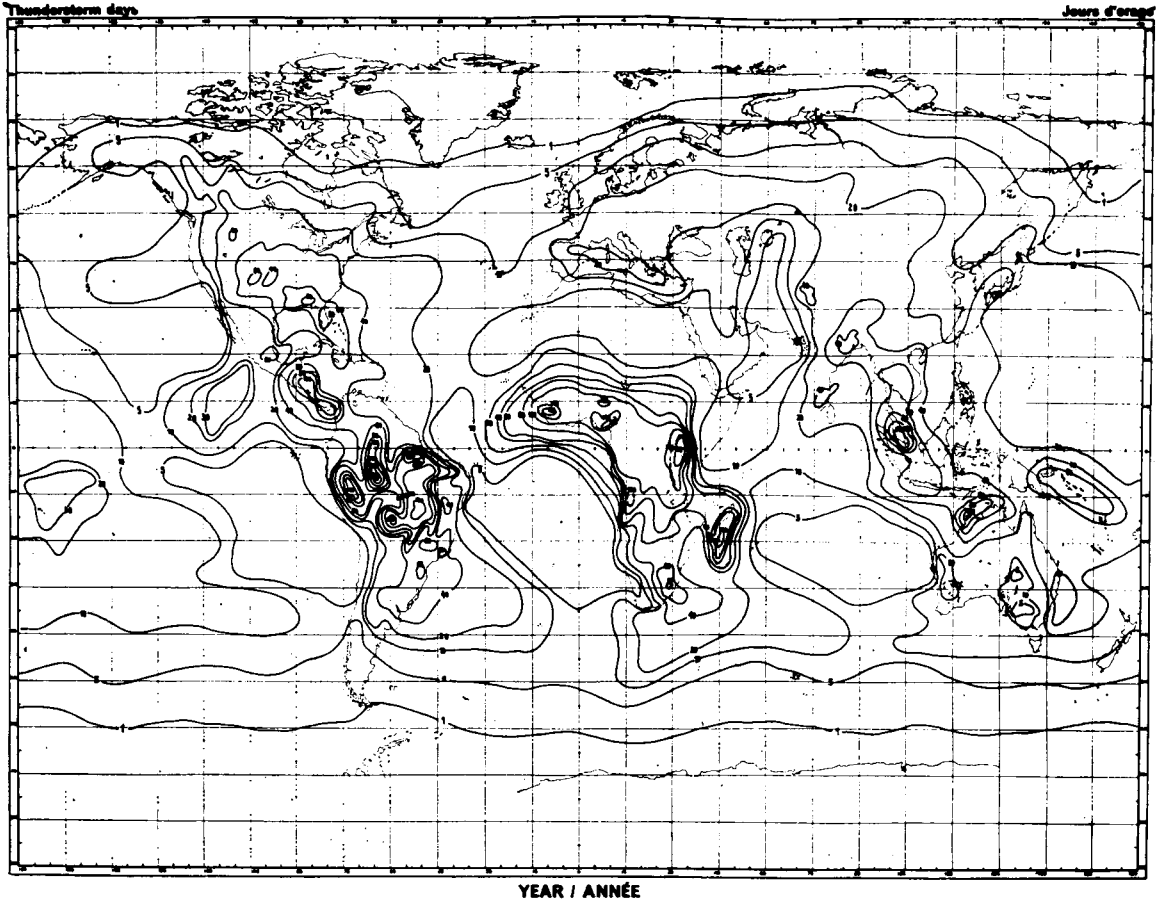


FIG. 7. World wide distribution of average number of thunderstorm days per year. (After World Met. Org.) Contour values 1, 5, 10, 20, 40, 60, 80, 100, 120, 140, 160, 200.

variations of magnetic noise at 175 cps for the months of July and October (see Figure 10). Note that, although there is a general increase in level throughout the day from July to October, the maximum increase occurs about 4 P.M., the time of the daily peak in thunderstorms. This feature is emphasized by plotting the difference of curves for July and October of Figure 10 as has been done in Figure 11. Obviously, the proximity of the 4 o'clock sources during October has led to a greatly enhanced "noise" level.

Secular Variations in Field Strength

Figures 1, 3, and 4 illustrate diurnal, intermediate period, and short period variations. By study of numerous graphs of this type, it is possible to establish that a secular variation in signal strength exists at any point in space. Perhaps

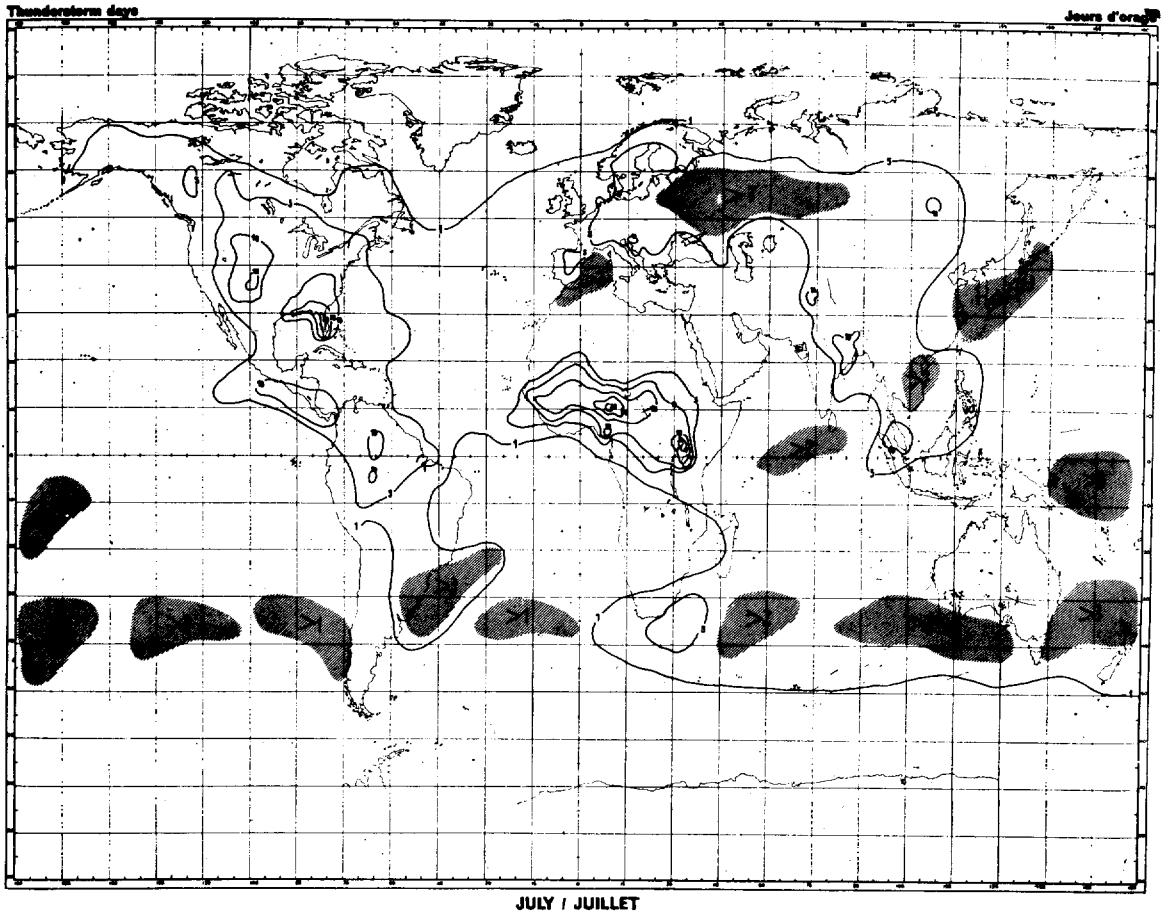


FIG. 8. World wide distribution of average number of thunderstorm days for month of July. (After World Met. Org.) Contour values 1, 5, 10, 15, 20.

the clearest illustration of the existence of secular variation is obtained by plotting the monthly mean field strength for any hour of the day. Such has been done for a station at Orangeville, Ontario, for the period February, 1957, to February, 1958, inclusive. The midnight and midday graphs of Figure 12 bear a marked resemblance to each other and portray a mean field strength during July, 1957, which is 20 db above the mean field strength for February, 1957, for the particular hours considered. The same general relationship holds true for all other hours of the day. Recordings have not been taken over a sufficiently long period to permit comment on the observed level increase from February, 1957, to February, 1958.

Source Spectrum and Frequency Selective Attenuation

One other facet of the origin and propagation of the "noise" fields is important to the application of AFMAG: frequency selective attenuation with

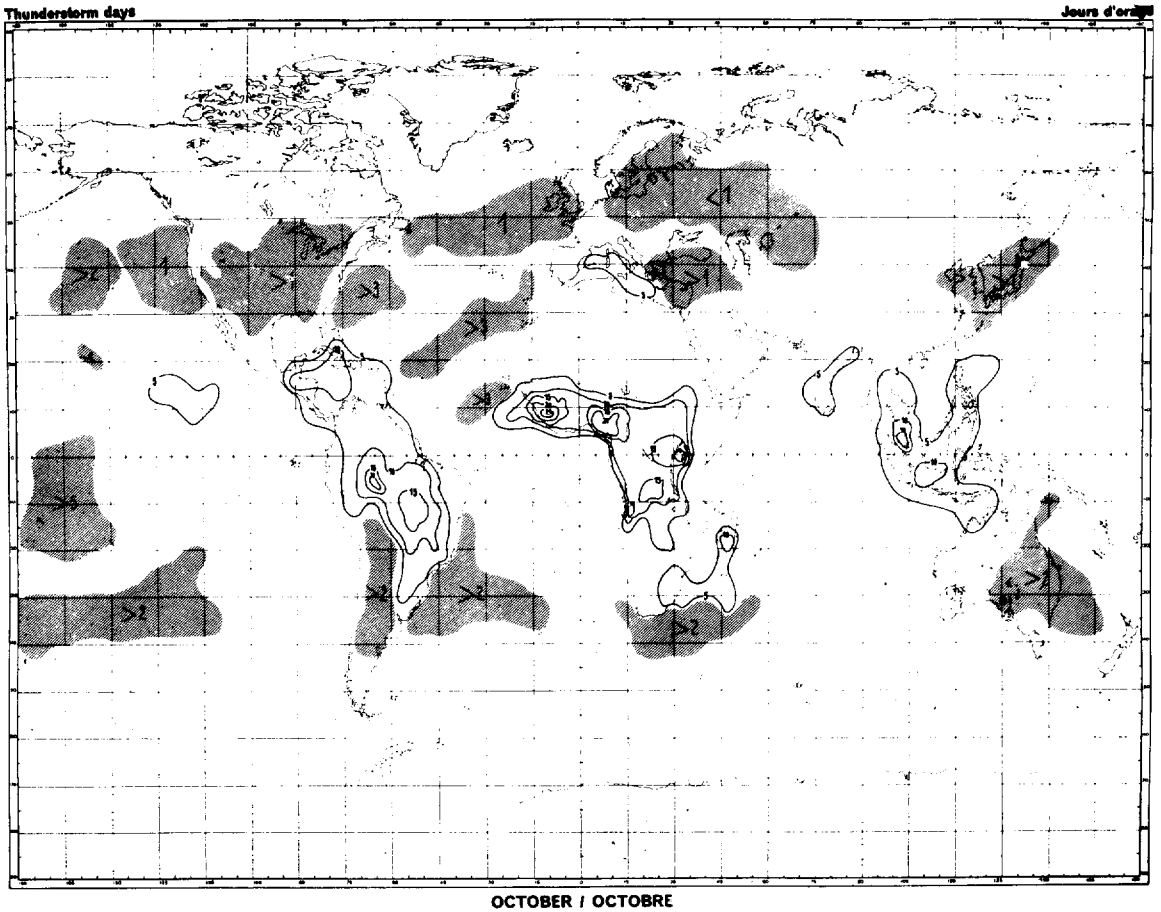


FIG. 9. World wide distribution of average number of thunderstorm days for month of October. (After World Met. Org.) Contour values 5, 10, 15, 20, 25.

distance, and frequency distribution of magnetic noise from a lightning discharge. Holzer, Deal, and Ruttenberg (1957) have studied attenuation in the range 45 cps to 6,000 cps and produced the data of Figure 13. Howe and Wait (1957) and Wait (1956) have developed a mathematical model of the earth-ionosphere wave guide which provides confirmation of these data. Watt and Maxwell (1957) plus Chapman and Macario (1956) have obtained experimental evidence which clearly illustrates the effects of both source spectrum and frequency-selective attenuation on the amplitude-frequency plot of atmospheric noise at any point in space (see Figure 14, after Chapman and Macario).

From Figures 13 and 14 we may conclude that if signal strength is a critical factor, then AFMAG should employ frequencies near the peak of the amplitude-

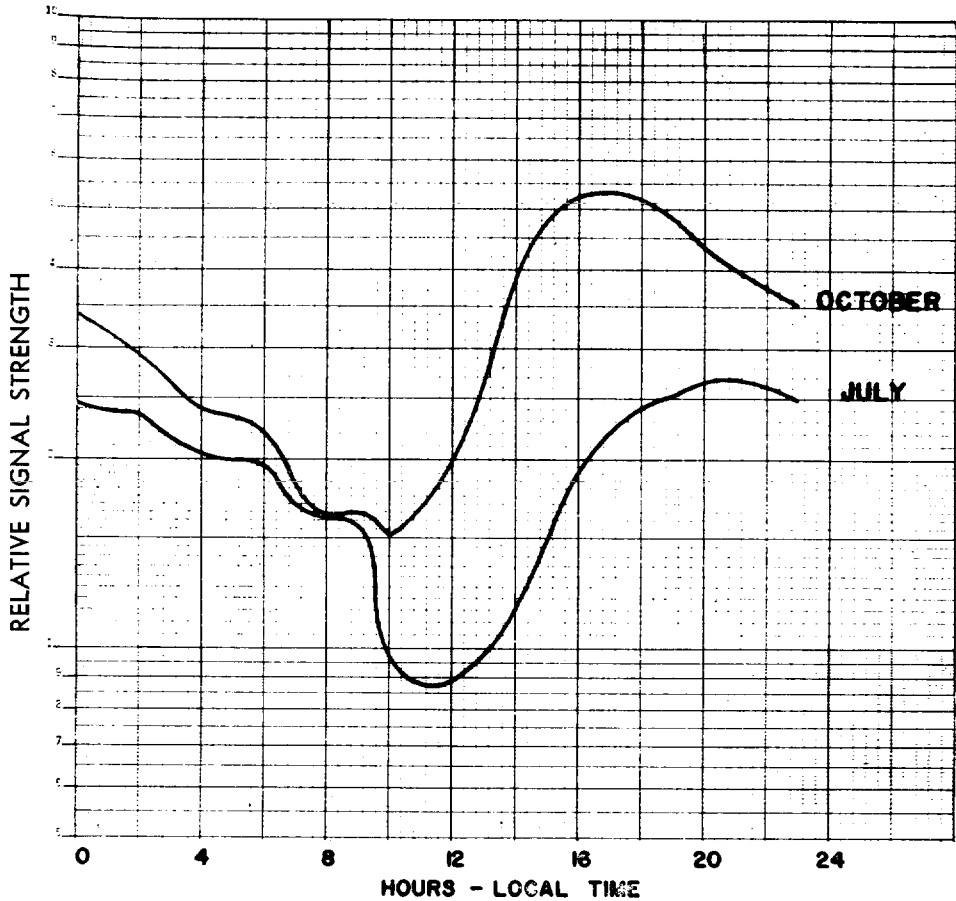


FIG. 10. Diurnal variation of natural magnetic noise obtained with coils tuned to 175 CPS. Kitwe, Northern Rhodesia—1957.

frequency plot. Little data are available from 45 cps down to 1 cps, but what is available suggests a decrease in signal strength with decrease in frequency in this region. Hence, a range of frequencies of from, say, 10 cps to 500 cps is suggested for use in prospecting.

AFMAG DESIGN FACTORS

Minimizing the Effect of Time Variations

The first and foremost problem to be faced in attempting to utilize the natural magnetic "noise" fields is effective elimination of short period time variations from the quantity measured. The short-period time variations in amplitude frequently produce 40-db changes in recorded signal level, whereas a sizeable ore

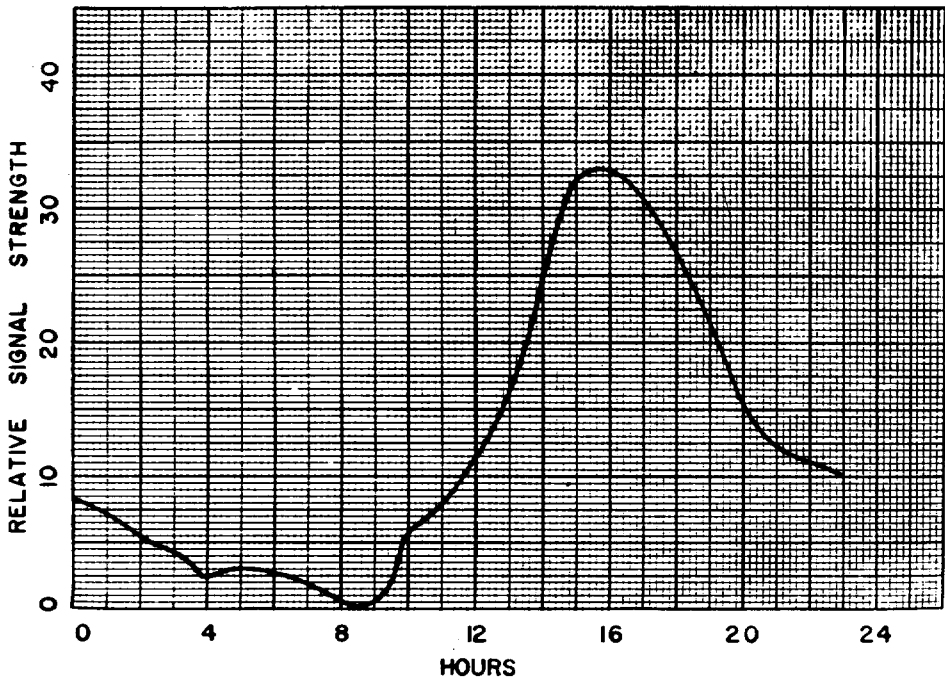


FIG. 11. Local thunderstorm contribution to diurnal variation of natural magnetic noise obtained with coils tuned to 175 CPS. Kitwe, Northern Rhodesia—1957.

body may produce no more than 6-db change in recorded level. It thus becomes imperative to introduce a comparator measuring technique wherein the time variations affect two detectors identically, yet space variations affect them differently. Cagniard (1953) accomplished this in the magneto-telluric method by "comparing the horizontal components of the magnetic and electric fields associated with the flow of telluric currents." It is accomplished in AFMAG by the simple expedient of measuring the tilt of the plane of polarization of the natural alternating magnetic fields (this is achieved by measuring the ratio of two components of the magnetic field).²

In the airborne version of AFMAG, the orientation of coils is that shown in Figure 15, and hence the components detected are those at 45° to the horizontal

² Cagniard's concept is that telluric currents are the primary source of energy, whereas the writer employs the concept of alternating magnetic fields caused by atmospheric electrical discharges as the primary source of energy. Under the latter concept, the existence of telluric currents is only a necessary phenomenon in the anomalous state and not in the normal state. This difference of concept is of considerable significance in the application and interpretation of AFMAG and magneto-telluric surveys, since Cagniard presupposes a horizontally uniform current sheet, whereas anomalies sought by AFMAG are those associated with deviations from a uniform or zero current sheet. Cagniard intended his method for use in uniform horizontally stratified sedimentary basins, whereas AFMAG is intended to locate variations from such horizontal uniformity.

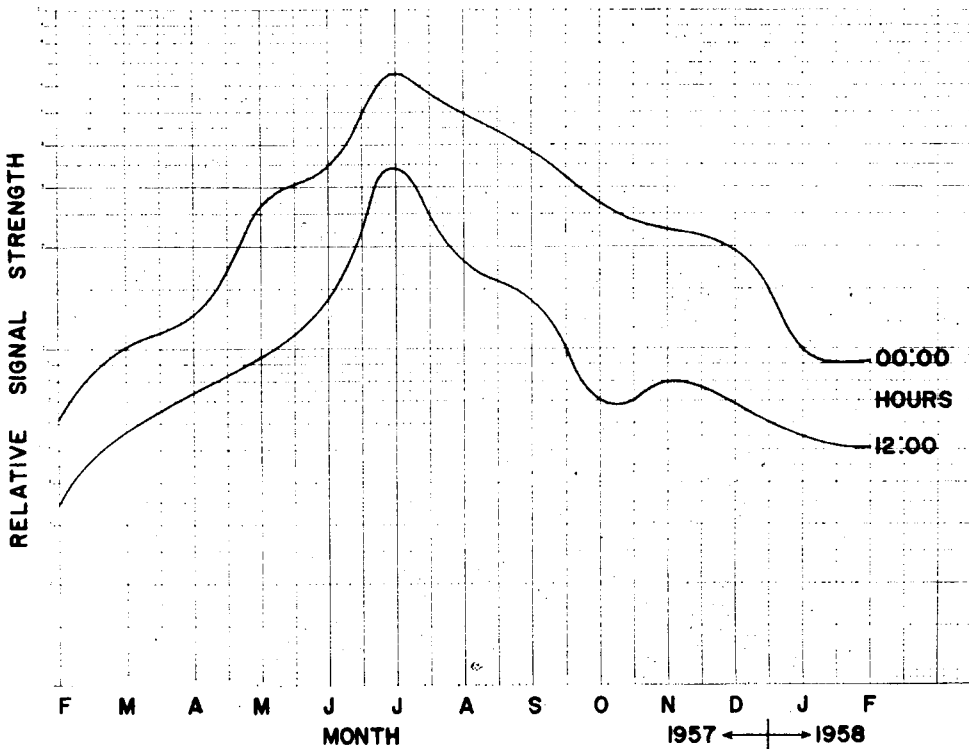


FIG. 12. Secular variation of natural magnetic noise obtained with coils tuned to 500 CPS. Orangeville, 1957-1958.

in the direction of flight. The manner in which these components are compared electronically is such that the deflection of a pen on a chart recorder is approximately proportional to α , the tilt of the plane of polarization. Since short-period time variations of signal strength affect both coil systems simultaneously, and to the first order by the same amount, the output of the comparator of Figure 15 approaches zero for such changes in amplitude of the natural fields. Time variations of amplitude are thereby eliminated to a first order from the quantity recorded.

On the other hand, should the direction of polarization in the vertical plane through the two coils vary with time, then these variations would be recorded. Fortunately, for all but very local noise sources, these polarization variations are of the second order and are of a shorter period than true anomalies; they may be largely eliminated by electronic smoothing. Nevertheless, they may preclude use of airborne AFMAG occasionally.

Also, of course, because it is impractical to construct two truly identical electronic systems, very large changes in signal strength are sometimes recorded despite the employment of the comparator system. Again, such changes are almost

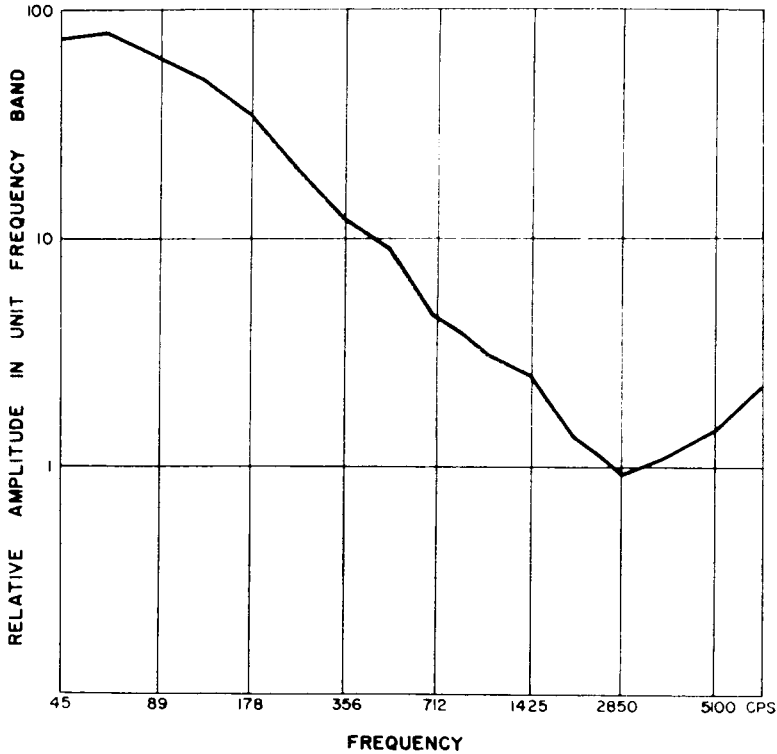


FIG. 13. Amplitude-Frequency plot of natural audio frequency magnetic noise. (After Holzer, Deal and Ruttenberg.)

always associated with a high proportion of local noise relative to distant noise and can be reduced by electronic smoothing.

Securing Adequate Signal-to-Noise Ratio

Up to this point in our discussion we have used the word "noise" to apply to natural alternating magnetic fields or "atmospheric noise." Conventionally the term "noise" also includes the following:

- (1) thermal agitation noise in the detecting coils,
- (2) thermal agitation noise in the input circuit of the first amplifier,
- (3) tube noise in the first amplifier,
- (4) noise mechanically induced in the detecting coils (this may include magnetostrictive effects; vibrations of the coils and/or nearby ferrous objects in the earth's main magnetic field, plus changes in the effective area of the coils),
- (5) aircraft noise (this may include the electromagnetic field of the ignition system plus the movement of the aircraft, as a metallic "anomaly," relative to the detecting coils),

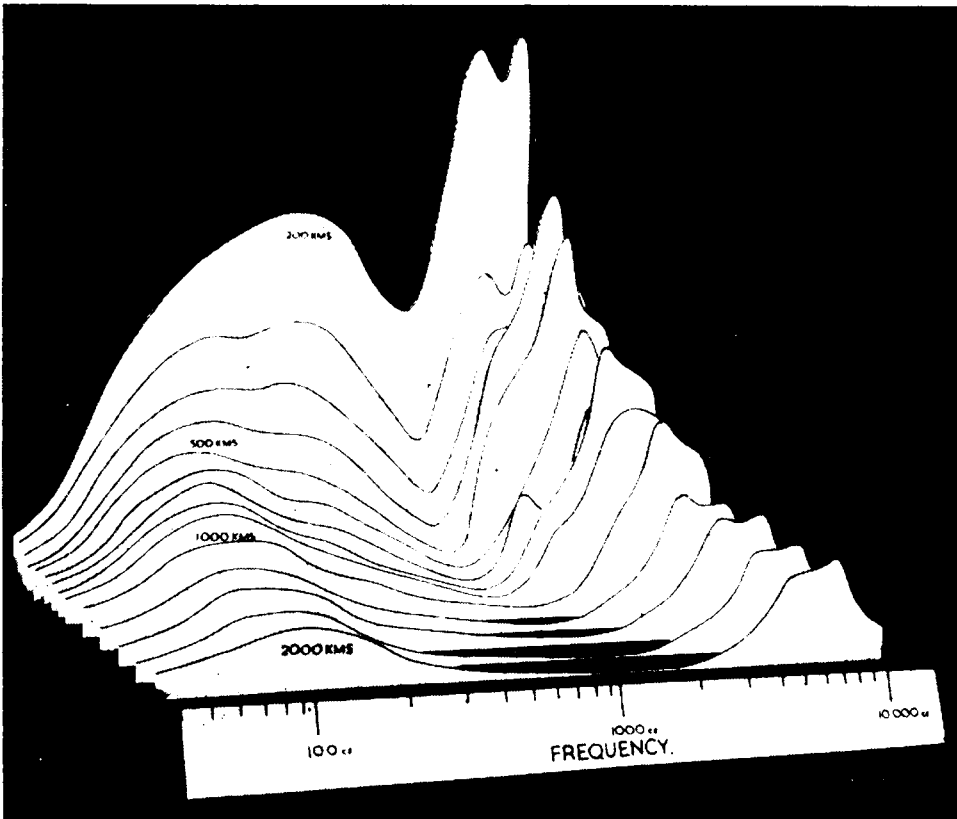


FIG. 14. Model showing source spectrum and attenuation of field of average daytime lightning stroke. (After Chapman and Macario.)

(6) geologic noise.

For the purposes of this discussion "atmospheric noise" is considered as the signal and the remaining six items as true noise.

Geologic noise is the background of minor anomalies of no significance upon which the significant anomalies are superimposed. This is an inherent limitation in any geophysical system and is usually removed by some form of human smoothing. In airborne AFMAG a minor amount of geologic noise normally is removed by electronic smoothing, but this is adjustable.

Aircraft noise is minimized by placing the detecting coils in a "bird" trailed some 200 to 500 ft beneath and behind the aircraft. Ignition noise is also suppressed by standard methods as far as possible.

Mechanically induced noise is minimized by:

- (1) ensuring that mechanical resonances lie well beyond the bandwidth of frequencies admitted by the high Q detecting circuits,
- (2) appropriate design of coils to ensure rigidity and no significant magnetostriction (if iron cores are employed).

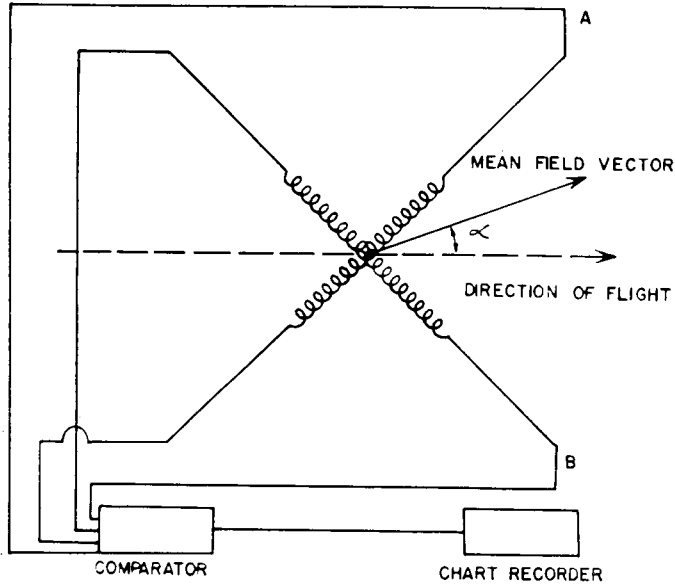


FIG. 15. Simplified representation of measurement of tilt (α) of plane of polarization in direction of flight by airborne AFMAG system.

Correct design of the input circuit and choice of tubes can ensure that tube noise in the first amplifier and thermal agitation noise in the input circuit are both small relative to thermal agitation noise in the coils.

Thermal agitation noise in the detecting coils is then left as the fundamental limitation on a high signal-to-noise ratio. An extremely high ratio of pickup factor (turns-area-frequency product) to resistance of an individual coil can eliminate this factor entirely, but only at the expense of an impractical weight of wire in the coil [see Slichter (1955)]. Thus coil thermal agitation noise theoretically remains as the basic limitation of the detecting system. When the atmospheric noise drops to a level which is of the order of only 6 db above the coil thermal agitation noise, then measurements of atmospheric noise are precluded. This does occur for both airborne and ground AFMAG as the atmospheric noise reaches its lows in secular and some diurnal variations. However, with airborne AFMAG, the vibration of the detecting coils in the very strong earth's main magnetic field frequently, if not usually, produces noise which is somewhat above the level of the thermal agitation noise of the detecting coils. Hence, in practice this factor usually dictates the times at which the airborne system becomes in-operative. This is understandable when one considers that the earth's main field is, say, $6 \times 10^4 \gamma$ whereas the thermal agitation noise is at a level which would permit detection of a field of less than $10^{-5} \gamma$. Mechanical and electrical discrimination cannot always be adequate to work against a factor of nearly 10^{10} . Of course, the more turbulent the air, the greater and more rapid is the angular rota-

tion of the detecting coils in the earth's main magnetic field and consequently the greater is this particular noise contribution.

Secular variations in field strength limit the annual period of applicability of the method. Up until the last six months, the use of ground AFMAG has been limited to the period April 1 to November 1, and airborne AFMAG from about May 1 to October 1 in Northern Canada. Recent equipment improvements suggest that use of ground AFMAG may be extended appreciably beyond these limits. Naturally, in regions closer to year-round thunderstorm sources, AFMAG conceivably could be employed without interruption. Experience with early model AFMAG units in Northern Rhodesia suggested that even under local midwinter field conditions, six hours of daylight operation were to be expected on the average.

Dynamic Range Requirements on Amplifiers and Detectors

The field intensities at any point in space can vary by several tens of times over periods of a fraction of a second. Narrow band pass circuits reduce these extreme variations considerably (Fulton, 1957), but even so, the dynamic range of voltage from the pickup coils places strenuous requirements on linearity of amplifiers and detectors. This is particularly true in a comparator system where any non-linearity existing must be identical in the two channels in order not to result in poor cancellation. Various electronic dodges may be introduced to overcome this difficulty but each leads to additional complexity and/or difficulties. Thus dynamic range of signal strength can, on rare occasions, lead to difficulty of measurement.

In this regard, distant sources would appear to produce fields of lesser dynamic range than local sources. However, this point requires further study before any quantitative information can be offered. Quite possibly the more regular fields of distant sources are due to the greater number of initiating events. The time interval between individual pulses and the dynamic range of these pulses both require consideration in prospecting instrumentation. Obviously a long interval between pulses can lead to difficulties in measurement or to erroneous recordings since if the time interval were infinite, only the meaningless ratio of thermal agitation noises in the two detecting coils would be measured. This difficulty has been experienced at times of extremely low field strengths.

Choice of Frequencies for Prospecting

It may be said that the AFMAG method is similar to a conventional inductive electromagnetic method with the transmitter removed to infinity. This analogy provides a useful concept for interpretative procedures. Typically, inductive electromagnetic systems employ a frequency of 400–1,000 cps if of the single frequency type, and of 400–1,000 cps and 2,000–5,000 cps if of the dual frequency type. It is known from work in these frequency ranges that an increase in the transmitter-receiver spread is equivalent to an increase in the frequency when tracing long linear conductors. For instance, at a spread of 200 ft a poorly con-

ductive fault zone may not be detectable at 1,000 cps. On the other hand, increasing the spread to 600 ft or the frequency to, say, 2,000 cps may raise the response of the fault above the lower limit of detectability. Other similar examples might be cited. Hence to provide the same range of responses, AFMAG should operate, because of its effective infinite spread, with somewhat lower frequencies. On the other hand, the frequencies should not be lowered too far or significant anomalies will begin to drop out. Hence nominal operating frequencies of 500 cps and 150 cps have been chosen and are employed simultaneously in one instrument.

In order to minimize pickup of fields of power lines, the actual operating frequencies are adjusted to 150 cps and 510 cps to avoid harmonics of 60 cps power line fields and to 175 cps and 475 cps to avoid significant harmonics of 25 cps and 50 cps power line fields. Even so, AFMAG surveys may meet with some interference near power lines—and for that matter near some telegraph and telephone lines. Of course, in some instances, the artificial fields of power lines can be used to advantage to replace the natural fields. Conductivity analysis of buried conductors, normally provided by comparing the ratio of the 150 cps to the 510 cps responses, is more difficult to apply in these power line areas.

For some problems, use of still lower frequencies may be desirable. This seems to be feasible, at least down to 10 cps, as indicated earlier. Beyond that range possibly lies hope for application of AFMAG to deep petroleum exploration. Even with frequencies currently employed, exploration for saline domal structures at depths as great as 3,000 to 5,000 ft would appear to be practicable.

RESULTS OF FIELD SURVEYS

Ground Surveys

Numerous examples of ground surveys and field techniques were presented in an earlier paper by the author and his associates (Ward et al 1958). The reader is referred to these results which demonstrate fairly well the advantages and limitations of ground AFMAG surveys. Hence only one illustration is presented herein of results obtained with ground equipment; Figure 16 contains dual frequency AFMAG dip angle profiles obtained over a tabular pyrite-pyrrhotite sulphide body. Standard interpretative procedures used on data from vertical coil electromagnetic surveys may be applied (with some modifications) to data from AFMAG surveys. Thus the following analysis is derived:

(a) The lateral positions of the conductor-axes are located readily from the tilt angle "crossovers" at the two frequencies. The shift between the two crossovers is indicative of inhomogeneity of the conductive body.

(b) Conductivity is estimated semi-quantitatively by recording the ratio of peak-to-peak tilt angle amplitudes at the two frequencies. For this example, the ratio is

$$\frac{7 + 35}{23 + 34} = 0.74.$$

(c) Depth to the top of the conductor can be estimated from the slope of the

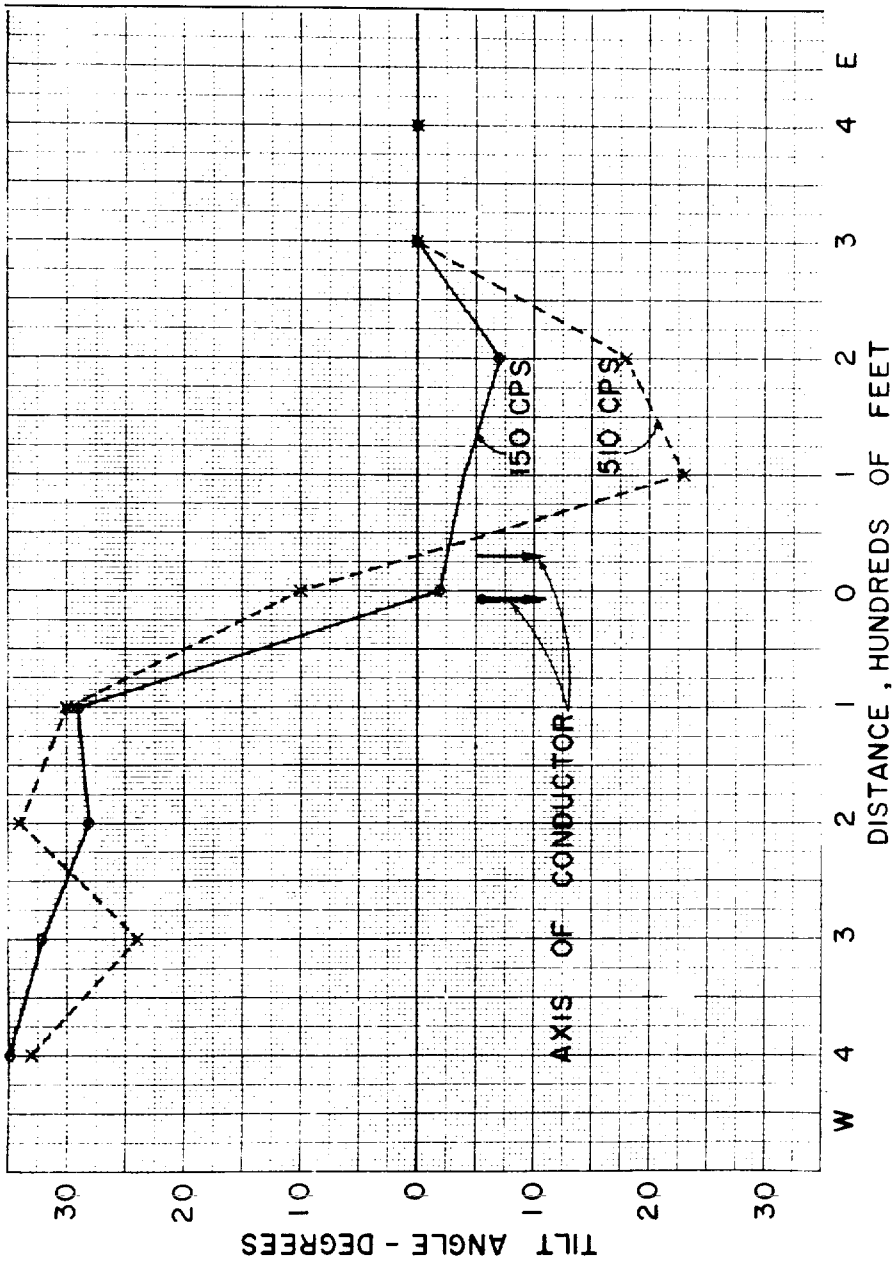


FIG. 16. Dual frequency AFMAG tilt angle profiles over sulphide zone.

“crossover.” A depth perhaps as shallow as 25 ft is interpreted from Figure 16.

(d) Depth extent affects the slope of the profile beyond the peak and can be estimated provided the profile is of sufficient length.

(e) The effective dip of the conductive body at each frequency is determined by measuring the asymmetry of the profile at that frequency. An expression of this is, 7/30 at 150 cps, and, 23/34 at 510 cps, both indicating a dip to the east. Comparison with scale model experiments leads to a quantitative interpretation of these latter figures. Usually a gross inhomogeneity of the sulphide body would lead to such a marked difference in dips interpreted from the two profiles. In this example, however, the effect of an adjacent conductor near 4+OOE probably is also affecting the two profiles to a different degree and hence rendering the normal analysis invalid. However, the example is included because it is a good one for demonstrating the principles of interpretation.

Airborne Surveys

As discussed in the earlier paper (Ward et al 1958), the technique of measurement on the ground is first to determine the mean azimuth of polarization, then to determine the tilt of the plane of polarization in that azimuth. This procedure is repeated at discrete intervals and the tilt angle readings plotted up in profile form.

Airborne operation requires modification of this procedure. Rather than determine, by horizontal polarization measurement the azimuth in which tilt angle readings are to be recorded, the tilt angles are measured in the direction of flight.

The flight direction is chosen perpendicular to strike of regional geologic features, which in turn tend to align the noise fields perpendicular to themselves. Thus the measurements are, on the average, made in the azimuth of mean polarization. It should be borne in mind here that the horizontal polarization is not a definite direction for all noise pulses, but is a mean direction for them. Hence the compromise adopted for the airborne system is a reasonable one.

The tilt of polarization, which is clearly defined and is zero in the normal state, is recorded continuously on a paper tape. In fact, two such recordings are made, one for each of the two operating frequencies. In addition, the signal strength at each of the two frequencies is monitored continuously so that gain settings can be made appropriate to the noise field levels. These signal strength recordings also afford the interpreter the opportunity to study abnormal behavior of the noise fields and so assess the importance of such field characteristics as dynamic range and interval between pulses.

Centering of the tilt angle recordings on the paper tapes is made arbitrarily at the start of each flight line in an area assumed to present only zero tilt angles. Obviously some centering or zero error can arise by this procedure, but since only changes in the tilt angles are indicative of buried conductors, the absolute level is relatively unimportant. In any event the absolute level can often be determined by inspection of the paper tapes. In addition the centering control is calibrated in terms of equivalent change in tilt angles.

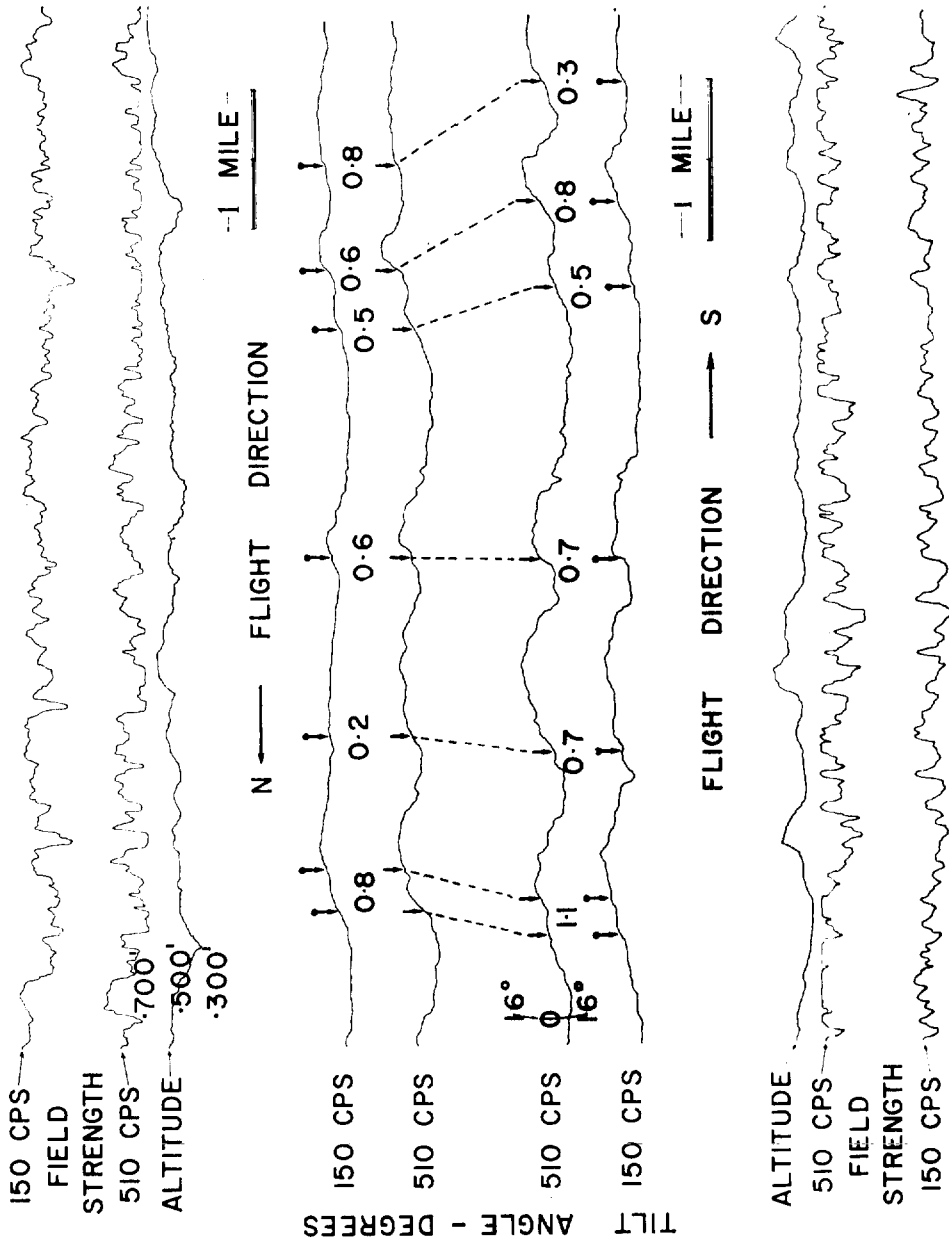


Fig. 17. Typical adjacent airborne AFMAG recordings.

Mean terrain clearance, as measured by a radio altimeter is continuously recorded. The customary positioning by strip film is employed.

Typical Recording

Two adjacent paper tape recordings from an airborne survey are shown in Figure 17, where some of the items discussed above are indicated. The locations of conductive bodies are determined by noting the mid-point of an inflection in the tilt angle profile as has been done on the tapes. Only an inflection from negative on the left to positive on the right is significant according to the convention adopted for recording the tilt of the plane of polarization (opposite convention normally adopted for ground data). Semi-quantitative estimates of conductivity are again provided by measuring the ratio of peak-to-peak amplitudes of the anomalies at the two frequencies, i.e.,

$$\frac{150 \text{ cps}}{510 \text{ cps}}$$

These values will range from 0 to 1, as the conductivity increases from very poor to excellent. Such values are noted on the paper tapes. Depth and depth extent estimates are made according to the criteria discussed for the ground survey data. Dip estimates could be made but are seldom necessary in interpretation of these airborne profiles.

Decrease of Anomaly with Aircraft Height

To determine the decrease of response of a long linear conductor with altitude, the test depicted by Figure 18 was made. It is interesting to note that the anomaly is detectable at aircraft altitudes as great as 3,000 ft (bird height approximately 250 feet less in all cases). The amplitude fall-off law is of the order of the inverse first power of altitude as predicted by theory. For conductors approaching a more spherical shape the fall-off should be governed by an inverse cube law and hence a conductive ore lens of the order of one-quarter mile in maximum dimension would cease to give a recognizable anomaly signal at altitudes of the order of 1,000 ft or greater. This would appear to be borne out by experimental evidence over the Mattagami orebody in Northern Quebec.

In contrast, airborne electromagnetic surveys seldom record a response when the aircraft is at an altitude in excess of 750 ft. Thus, as much as another order of magnitude in depth of exploration for massive sulphide bodies is available with AFMAG compared to conventional electromagnetic surveys.

Comparison of Airborne AFMAG and EM Data

A comparison of airborne AFMAG and airborne electromagnetic anomalies over the Whistle Mine, near Sudbury, Ontario, is provided in Figure 19. Note that the influence of the ore zone is measured at a much greater lateral distance

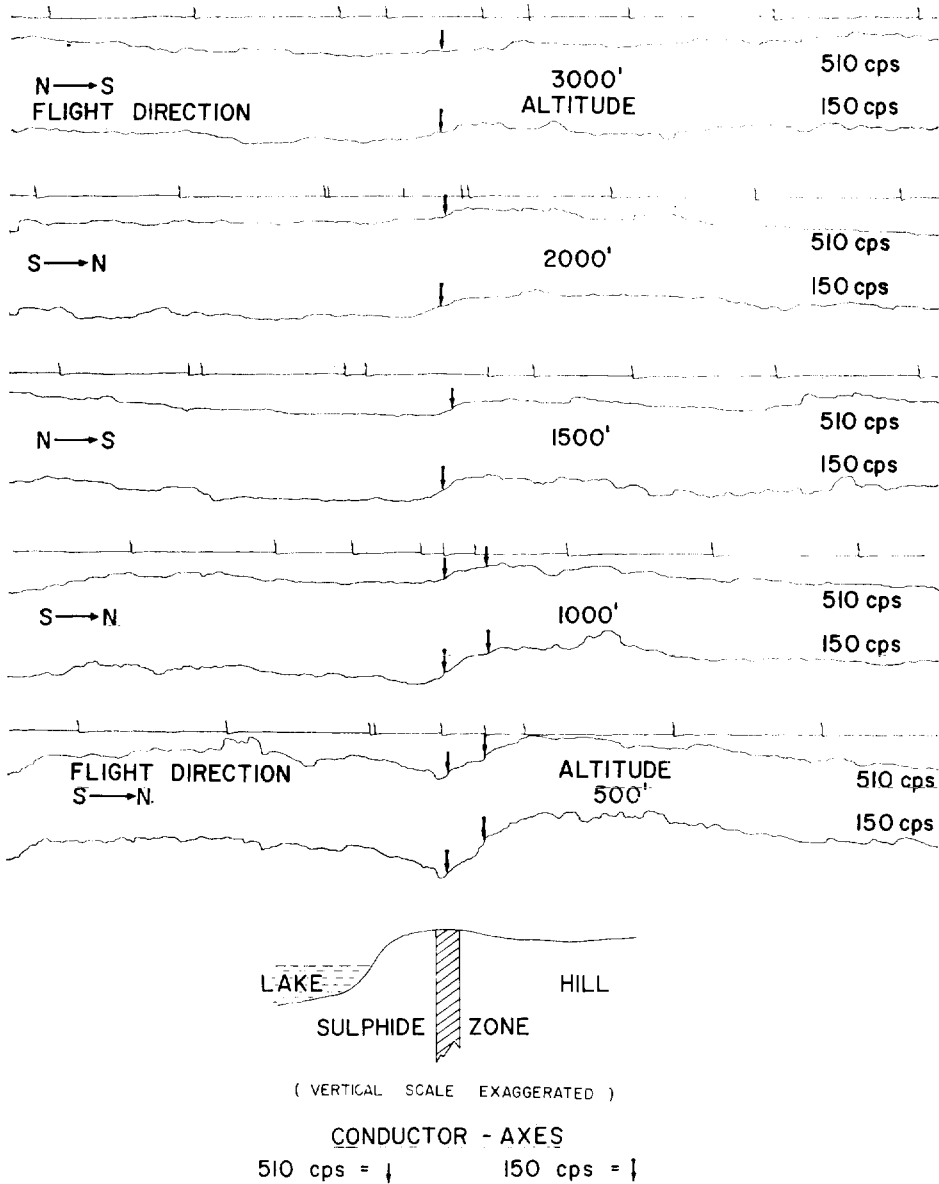


Fig. 18. Variation of anomaly with aircraft altitude over long linear conductive body.

from it with AFMAG than with a conventional airborne electromagnetic system. Thus, greater lateral range is indicated; this leads to a greater probability of detection of such orebodies. Note also the greater percentage of total field that the anomaly is with AFMAG as opposed to EM.

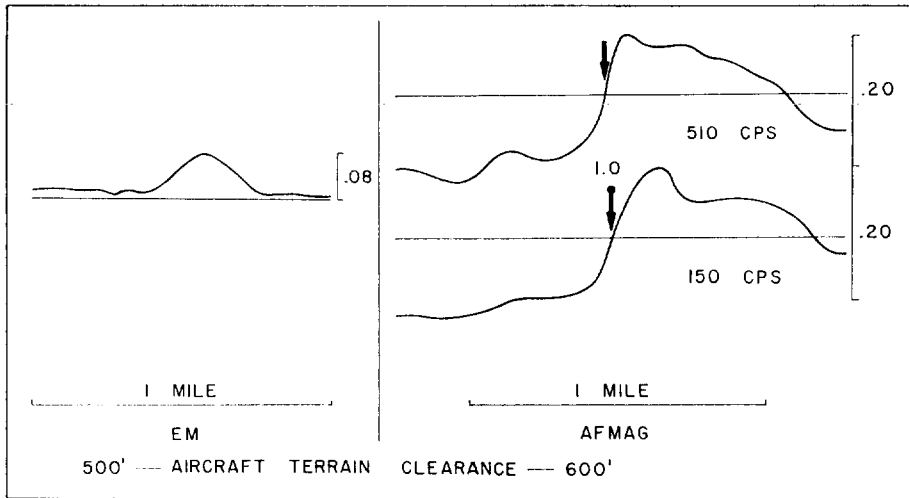


FIG. 19. Comparison of airborne EM* and airborne AFMAG responses over Whistle Mine, Sudbury District.

* After Slichter, 1955.

CONCLUSION

Although there is much to be learned concerning the basic theory, application, and interpretation of AFMAG, production airborne and ground surveys with the system over the past three years have demonstrated its utility as a means of locating and evaluating buried conductors.

On the basis of the evidence presented in Figure 18, it would appear practical to explore for mining targets in mountainous terrain where aircraft terrain clearances of necessity must be extremely variable and sometimes large. Similarly, depths of exploration in areas of deep oxidation or areas of deep valley fill are adequate to reach targets which up to now have been excluded from aerial electrical prospecting. It seems reasonable to speculate that such petroleum exploration targets as saline domal structures, in view of their large size, may be detectable at depths of the order of 3,000 to 5,000 ft. No experimental work has been performed in this respect as yet.

AFMAG may provide a greater probability of detection of certain ore zones when investigations are carried out on a standard grid pattern.

To achieve these major advantages requires, at present, a concession in the times of the year during which the method may be fruitfully employed. In particular, the winter months in temperate climates are not currently satisfactory operating times, unless observations are made at night. A few summer days or portions thereof similarly may be unsuitable for observations because of excessive reduction in the strengths of the natural fields. These problems are not of significant importance in tropical and sub-tropical areas where the system is likely to have its greatest application.

ACKNOWLEDGMENTS

The author wishes to make it clear that the development of airborne and ground AFMAG equipment is almost entirely the work of his former associates, Messrs. W. O. Cartier, H. A. Harvey, G. H. McLaughlin, and W. A. Robinson. To them he is indebted for the opportunity to be associated with such a development and for constant counsel.

American Metal Climax, Inc. financed a large portion of the research on this project. Thanks are due to the management of the Mining and Exploration Department of that company for permission to publish some of the data contained herein.

Hunting Airborne Geophysics Limited have kindly permitted publication of part of the data for Figure 19. Mr. D. G. MacKay and Dr. Norman Paterson were particularly helpful in this respect.

Crossland Licensing Corporation Limited, owners of the pending patent rights on AFMAG, have furnished some of the data for this paper and approved its publication.

Mr. Robert G. Lee assisted in presentation of the drawings and editing the manuscript.

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COMMENTS ON "AFMAG-AIRBORNE AND GROUND"

BY S. H. WARD

Dr. S. H. Ward has kindly shown me the manuscript of the preceding paper and has invited me to comment on the origin of the natural audio-frequency

signals used by his AFMAG system. He lists five possible sources of signals. Of these, the only natural sources of practical importance in the frequency range under consideration are lightning strokes. Man-made noise may be important in the vicinity of cities or industrial areas.

Dr. Ward correctly states that signal attenuation is greater during the day in the presence of the D region of the ionosphere than at night when the D region disappears. This leads to a characteristic diurnal variation of signal strength with larger amplitudes at night than during the day provided that the frequency band used is above 100 cps and provided that there is no large area of thunderstorm activity within roughly 3,000 miles of the receiving station. Figure 3 is a good illustration of the effect of relatively close thunderstorm activity on the simple diurnal oscillation described above. After the nighttime maximum, the received signal strength decreases in part, at least, due to the development of the D region after sunrise. Instead of remaining at a low value throughout the day, the signal strength once more rises shortly before noon due to the development of the usual summer thunderstorms in the eastern part of the North American continent. The record shows a secondary maximum in the afternoon hours when North American thunderstorm activity is at its peak. As storm activity in the mid-continent subsides, there is a rapid drop in signal strength to a minimum (marked A) close to local sunset. With the disappearance of the D region the curve once more rises toward its nighttime maximum. I do not believe that there is evidence to support the interpretation of the embayment A as an increase in signal attenuation around sunset.

It is interesting to note that the "normal" diurnal pattern described above disappears if the frequency range lies between 5 and 100 cps. The signal attenuation, of the order of 1 db per 1,000 km at 100 cps becomes even lower as the frequency decreases and signals in this range are received from lightning strokes in all parts of the world. For the special case of a receiving station nearly 90 degrees from the nearest thunderstorm region, the mean signal amplitude is roughly proportional to the total number of thunderstorms in progress over the world. This leads to a diurnal oscillation on universal rather than local time. The maximum is at 20 hours U. T. and the minimum near 4 hours U. T. On the North American Continent, the phase of the diurnal oscillation below 100 cps is nearly opposite the normal local time oscillation.

My criticisms of the interpretation of the typical signal records do not, of course, extend to Dr. Ward's most ingenious development and use of the AFMAG system.

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AUTHOR'S REPLY*

Dr. Holzer's comments are very appropriate and much appreciated.

The interpretation of diurnal variations of field strength is often subject to certain speculations. Dr. Holzer's extensive work in this field has minimized the speculations necessary, so that his interpretation of Figure 3 would sound more logical than my own.

However, in interpreting any such records it is absolutely essential that the effect of instrumentation on the recorded variations be appreciated fully. For the diurnal records produced in this report, an instrument with a time constant of the order of six seconds was employed. Widely separated individual bursts of energy might be smoothed from the record entirely. Thus during the time of embayment *A* of Figure 3 there might well have been some substantial local activity producing pulses more widely separated than those occurring earlier during the day.

In one recent example, obtained subsequent to writing this paper, a very local thunderstorm, involving largely "sheet" lightning, produced a record with a decrease similar to embayment *A* for the duration of the storm. Presumably in this latter event, the increased ionization of the very local atmosphere led to attenuation of signals from sources more than a very few miles away. At the same time the long time constant of the instrument removed any obvious indication of the individual lightning flashes occurring overhead. Speculating still further one might assume that had the lightning been largely of the "fork" type, then the attenuation might not have been so evident since ionization possibly would not have been so all pervading locally.

Provided one is prepared to so speculate, then an explanation for embayment *A*, similar to that originally given, may yet be valid. However, I am now inclined to favor Dr. Holzer's explanation.

Finally, it should be borne in mind that narrow-band, tuned coils and amplifiers were employed for the records contained in this paper. Thus these records should not be compared directly with records obtained with broad-band equipment.

* Received by the Editor July 2, 1959.