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The McPhar Vertical and Horizontal Loop Electromagnetic (VHEM) Unit as a tool in Geological Exploration

Pentti Lassila

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THE McPHAR VERTICAL AND HORIZONTAL LOOP

ELECTROMAGNETIC (VHEM) UNIT

AS A TOOL

IN GEOLOGICAL EXPLORATION

by

PENTTI LASSILA

A THESIS

SUBMITTED TO THE FACULTY

OF THE

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AT THE

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GRAND FORKS, NORTH DAKOTA

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ABSTRACT

The McPhar VHEM is an efficient and useful electromagnetic unit used in conjunction with geologic exploration to locate shallow-depth ground conductors which may contain economic minerals.

It consists of two battery powered lightweight units, a transmitter and receiver, each with a set of two enclosed coils. It operates on an alternating current with two frequencies of 2400 cps and 600 cps.

Both vertical loop (VL) and horizontal loop (HL) procedures may be used with the same set of instruments.

With VL, two techniques, VL Broadside and VL Standard are used; VL Broadside for locating the anomaly, and VL Standard for tracing out its length. The process is to pass the instruments parallel over the conductor and thus obtain a VL profile curving from negative to positive with the crossover at zero over the conductor.

The basic principle of VL is that an induced current sets up a secondary magnetic field around any conductor within range. The receiver detects the dip of the resultant vector of the primary and secondary fields so produced.

HL procedure is primarily used to determine the nature of the anomaly. With this method the receiver follows the transmitter in line and perpendicularly across the conductor.

The principle of HL is to measure the secondary field relative to the primary field. The instruments are interconnected by a cable which allows the required voltage to balance out the secondary field. This voltage is recorded
as percent of normal voltage. When the in-phase (IP) readings are plotted, generally a symmetrical profile results with two positive shoulders and a large negative central lobe. The out-of-phase (OP) curve tends to be rather flat, especially with good conductors.

From the HL profiles several interpretations can be made. High IP/OP ratios indicate good conductivity. The profile width between zero readings denotes conductor width. Asymmetry generally indicates dip.

The readings after any necessary corrections are generally plotted on graph paper either as individual profiles or as a composite profile plan map.

The main error with VL is transmitter disorientation with respect to the receiver position. This results from variances in sound direction caused by rough topography between the operators. The error may be corrected by running both instruments on measured lines, by decreasing separation between instruments or by a pace and compass method. Disorientation error can be critical with weak and/or complex anomalies.

Some error with the HL procedure may be caused by static or instrument noise due to poor insulation and grounding of the various instrument components. However, HL error mainly results from short cable effects and differences in the elevation between the instruments. Short cable error can be best corrected by adjusting for it directly in the field with the help of a correction chart.

Also, error due to elevation differences between the
instruments can be eliminated in the field by always setting the coils of both instruments parallel to each other when taking HL readings.

Certain types of complex weak conductors can cause problems in the field with VL Standard. These types include irregular broad strongly magnetic zones; crossing conductors in jounts, fractures and/or faults; warped, curved conductors; and intermittent conductors. To alleviate difficulties in pinpointing these conductors a decrease in instrument separation is recommended.

The essential criteria of a good conductor is that the conducting material be continuous. Pyrrhotite and graphite are usually excellent conductors. The conductivity of other sulfides may vary from negligible to good, depending upon the type of environment in which the anomaly lies.

Accurate interpretation of VL profiles is usually difficult due to the large number of variables which may be involved in the conduction and the high probability of at least some error being introduced into the readings. However, controlled model and field studies are very useful for defining the conditions for particular trends.

HL profiles can be used to interpret conductivity, width and approximate dip and depth of burial. Dipping conductors cause asymmetry in a profile. A high central lobe results if the traverse is at an acute angle to the conductor or, if conductor is wide. Magnetite promotes high profile shoulders. A high IP/OP ratio indicates a good conductor.
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INTRODUCTION

General

Geological exploration, particularly in recent years, is becoming increasingly reliant on more diverse and sophisticated techniques and equipment. This report on a relatively new and useful exploration tool, the McPhar Vertical and Horizontal Loop Electromagnetic (VHEM) unit, hopefully will add some further knowledge to this expanding field.

The main emphasis is not only on field techniques and the limitations of the unit, but also on the evaluation and interpretation of the resulting data. Less emphasis is placed on the description, technical operation, theory and the basic operational principles behind the equipment.

Purpose

The purpose of this report is three-fold. First, it is intended as an explanation and analysis of the more important aspects of the equipment as an exploration tool. Secondly, it is intended to be of value as an instructional aid to the novice VHEM operator. Thirdly, it hopes to offer, to the experienced operator, some further insight into the various aspects in the practical field operation of the equipment. Since these objectives are interrelated, they have been incorporated into the text as a single unit.

Acknowledgements

I wish to express my thanks to the Anaconda Company for making available to me much of the material used in this
report. Also, I am greatly indebted to the many workers on the Anaconda staff and others who contributed to make this writing possible.

In particular, I wish to thank Mr. E.H. Brinley under whose supervision I worked for several years and gained experience and knowledge in the operation of the McPhar VHEM unit. Also, I want to thank Mr. J.D. Corbett who was a major contributor in the early application of the equipment to exploration as well as the author of Anaconda's VHEM operation manual from which a considerable amount of information for this paper has been obtained, both directly and indirectly, and from which the basis for many of the illustrations also have been taken. The information I received through conversation with Jack Betts also was very helpful. I want to thank Al Boerner for helping me get together material for the report. I am also indebted to the many VHEM operators with whom I have worked.

I wish to express my thanks to Dr. John R. Reid for his suggestions, guidance and supervision in the preparation of this paper. I am also indebted to Dr. F.R. Karner for his critical reading of the manuscript.

Credit should also be given to McPhar who engineered, designed and constructed the unit.

Previous History

Since the Second World War much progress has been made in geophysical equipment, resulting in particular types of equipment designed for specific purposes. The McPhar VHEM came into being when Anaconda asked McPhar if it would
consider designing a lightweight VHEM type EM unit. McPhar, which already had the component circuits and had given some thought to producing such a unit, agreed to engineer the project. The final product came into field use in 1959.

LIMITATIONS AND ADVANTAGES

The McPhar VHEM unit is particularly suitable to areas such as the Canadian Shield where most conductive minerals are primary minerals, overburden is generally shallow, access often difficult, the foliage thick and brushy and the terrain although locally rough is regionally fairly flat. This environment is suitable to the relatively short horizontal range of the unit (about 600 feet under optimum conditions) and the resulting fairly shallow vertical range (about 300 to 350 feet), which will not reach the more deeply buried conductors as will other more penetrating but cumbersome types of EM equipment.

This unit, within its limits, has several advantages over most other EM equipment. It is compact and lightweight. Both transmitter and receiver can be carried by shoulder straps by their respective operators through brushy country with relative ease. Also, the transmitter power supply, in the form of long lasting and/or rechargeable batteries, is incorporated into the instrument. Only two men are required to operate the unit. It is reliable and has few maintenance problems, and most of these are fairly simple. Both vertical loop and horizontal loop surveys can be done with the same set of instruments, requiring only a
single reference cable 300 feet or less in length between the two instruments for horizontal loop. Readings usually take only a fraction of a minute. A minimum of cut or blazed traverse lines is necessary. Satisfactory results have been obtained in reconnaissance work with no lines at all, using only compass and flagging to mark station locations.

Used in conjunction with geological exploration, this unit has proved to be a remarkably efficient and useful tool in locating hidden shallow-depth ground conductors or anomalies which may contain potential ore deposits.

INSTRUMENT DESCRIPTION AND OPERATION

The McPhar Vertical and Horizontal Loop Electromagnetic (VHEM) equipment consists of two small (3"x 7"x 20") light-weight units consisting of a transmitter (12 lbs.) and a receiver (10 lbs.) complete with earphones and three separate horizontal loop reference cables of 100', 200', and 300' lengths. It operates on an alternating current with two frequencies of 600 cps and 2400 cps. It has a practical range of 200 to 300 feet in thick brush-covered rough topography, to about 600 feet on open areas such as on lake ice. Each instrument is carried by two shoulder straps and held in front of the operator when taking a reading (Fig. 1).

Each instrument is enclosed in a weather-resistant bakelite case. The battery power supply is self-contained in the instrument. In the case of cold weather, however, the transmitter may be switched to an external supply
Figure 1. --Diagrammatic sketch illustrating instrument positioning for VL and HL procedure.

(s = separation between transmitter and receiver
  t = transmitter station
  m = station for which reading is recorded
  r = receiver station)
attached by a cable and carried inside the operator's coat. The alternating current is supplied to the transmitter from the battery through an electronic oscillator. The various operating components of the unit are illustrated in Figure 2. The coil arrangement is the same in both instruments (Fig. 3).

The transmitter may be switched to either frequency by a two-way spring-loaded lever (Figs. 1 and 2). During the vertical loop procedure (hereafter termed VL) the transmitter is held horizontal with the aid of a level bubble and with the two-way operating lever facing away from the operator (Fig. 1a). However, during the horizontal loop procedure (hereafter termed HL) the transmitter is held vertical with the operating lever toward the top and facing away from the operator (Fig. 1b).

The receiver adjustments for volume, tuning and frequency may be made with the appropriate knobs (Fig. 2). During the VL procedure the readings are read in degrees of tilt from the receiver clinometer, with the instrument positioned as shown in Figure 1a. If the bottom of the receiver points towards the north or east, the reading, by convention, is classified negative; for south and west, positive. It should be noted that the bottom of the receiver normally always points toward the conductor in VL procedure (Figs. 4 and 5.). An exception is for banded magnetite, in which case it points away from the anomaly. The reading is taken at the position of tilt of the receiver (angle from the vertical) when a null in tone is obtained
Figure 2. --Diagrammatic sketch illustrating the external components of the receiver and transmitter. (Modified after J. D. Corbett, Fig. I-4, 1959).
Figure 3. --Diagramatic sketch of the VHEM unit coils. (After J. D. Corbett, Fig. I-2, 1959).
Figure 4. Schematic diagram of the vertical loop (VL) field.

(I_p - primary AC current in transmitter loop
H_p - primary magnetic field in space due to I_p
I_s - secondary current in conductor due to I_s
H_s - secondary magnetic field due to I_s
H_R - resultant magnetic field; the vector addition of H_p and H_s at coil location
\( \alpha \) - dip angle
\( \theta \) - tilt angle in degrees as read from the clinometer)

Note: the clinometer scale indicates the angle (\( \theta \)) of tilt of the receiver coils from vertical.

(Modified after J. D. Corbett, I-4, 1959).
Figure 5. --Diagrams illustrating the receiver positions and corresponding coil plane positions and the resulting profile curves of a VL Standard and Broadside traverse over a conductor.
through the earphones by the operator. With the receiver in a vertical position, a null should occur when the clinometer reads zero if the unit either is out of range of a conductor or directly over it.

The operation of the HL procedure consists of three basic steps:

1) positioning and orientation of the instrument coils (receiver and transmitter)
2) setting (tightening) the reference cable for precise separation
3) balancing the in-phase (IP) and out-of-phase (OP) components of the resultant field against the reference (standard) field.

In the HL procedure the receiver is held vertical, but the rheostat knobs are toward the top and facing away from the operator (Fig. 1b). The two rheostat knobs are turned or balanced until a sharp null is obtained. Polarity (plus or minus) for each rheostat is determined by a switch beside each knob. Both the IP and OP rheostats with their respective polarity are read directly in percentage (+ or -) from the circular scale on each rheostat knob flange (Fig. 2).

For the HL procedure a reference cable of either 100, 200 or 300-foot length, depending on conditions, is connected between the instruments by two cable jacks (Figs. 1b and 2). In the HL system the point of measurement (m) for any cable length is midway between the receiver and transmitter coils. The station recorded for each reading on an HL traverse should be this midpoint (m) and not at the receiver position (r).
(Fig. 1b). Some operators may prefer to record the station at the receiver position and later, when plotting the data, translate the station reading the required distance in the direction of the traverse. However, the latter method tends to lead to incorrect location of the stations on the profile map when these stations are plotted.

Calibration adjustments for the in-phase (IP) component background, in the HL system, may be accomplished by rotating a small shaft covered by a small snap-hole plug in the transmitter (Fig. 2). Rotation of the shaft will change the in-phase reading but not appreciably the out-of-phase (OP). The instrument should be calibrated for normal background close to, but preferably not exactly on zero. At zero the polarity changes and therefore it tends to be a broad null zone, thus making the exact null position difficult to pinpoint. A background calibration slightly off zero (3 or 4%) will alleviate this problem. The receiver should be calibrated if the normal background for IP exceeds 10%. For this purpose a base station near the field camp should be established as a background check point. However, once set, it is usually not necessary to recalibrate the instrument for the rest of the season.

It should be noted that while each HL cable has six or seven feet of extra length to allow for irregularities in topography, it is essential, when running an HL survey, that the distance of 100, 200, or 300 feet between the two instruments be kept as uniform as possible to minimize error.
WORKING PRINCIPLE OF THE McPHAR VHEM UNIT

Introduction

There are three main fields of geophysical prospecting. They are:

a) Natural Earth Potentials
b) Applied Currents
c) Induced Currents (Electromagnetic Methods)

This report deals with the Electromagnetic (EM) Methods and in particular the Horizontal Loop (HL) and Vertical Loop (VL) procedures used with the McPhar VHEM unit.

Description

The principles behind the McPhar VHEM unit are very adequately summarized by J.D. Corbett, (1959).

General Working Principle of Electromagnetic Methods

A transmitter loop...excited by an alternating current \( I_p \), produces in the space around it a primary alternating magnetic field \( H_p \). This \( H_p \) field excites or induces an alternating current \( I_s' \) in the receiver coil, and similarly an alternating current \( I_s \) in any conductors in the vicinity. The coupling involved resembles that in an alternating current transformer, the only real difference is that a transformer uses an iron core for tighter coupling. The current \( I_s \) induced in a nearby conductor will set up a secondary magnetic field \( H_s \) about itself which tends to oppose the primary field. The receiver coil detects the algebraic sum of the primary and secondary fields.

The inductance of the conductor, which is the inertia due to creating or destroying the secondary magnetic field \( H_s \), is such as to shift the secondary magnetic field 180°, or directly opposed to the primary field. Because
Figure 6. --Schematic diagram illustrating the general working principle of electromagnetic methods. (After J. D. Corbett, Fig. I-3, 1959).
of the finite resistivity of the conductor, however, this 180° relationship is altered and the quadrature, or commonly the out-of-phase component is produced. The horizontal loop method takes advantage of this out-of-phase component to give a crude measure of the relative conductivity of the conductor involved.

At any given frequency, the electromagnetic response of a conductor is proportional to its size, shape, conductivity, and orientation with reference to the primary field. By varying frequency, targets of various sizes and/or conductivity can be made to respond. As a corollary, the response of a given conductor at two different frequencies can also give a rough estimate of relative conductivity. This principle is applied in the vertical loop method of exploration.

General experience, both theoretical and empirical, have shown that the higher frequencies excite swamps, water, alluvium, and shear zones while the very low frequencies require large targets of good conductivity. The low frequencies, too, are difficult to handle insofar as they require heavy bulky equipment to achieve any range of detectable propagation. For these reasons the frequencies used in Canadian prospecting are a compromise and generally fall between 400 and 4000 cps (exceptionally 110 or 60 cps) (Corbett, 1959, pp. I-3, 4).

Vertical Loop Principle

The transmitting loop is orientated so that the coil plane is vertical which gives, theoretically, maximum coupling with a steeply dipping conductor. The primary magnetic field (Hp) due to the alternating current (Ip) through the coil induces a secondary current (Is) in a conductor \[ \text{Fig. 4} \]. This secondary current causes a secondary field (Hs). The receiver detects the resultant (HR) of these two fields.

A null (no induced signal) is obtained at the receiver station whenever the receiver coil is parallel to the resultant field. The primary field at the receiver is always horizontal so that if no conductor is present there is no secondary field and the receiver will give a null at zero degree dip \[ \text{tilt} \]. If a conductor is present the resultant field will not be
horizontal and when the null position is ascertained, a dip [tilt] angle can be read directly from the clinometer (Corbett, 1959, p. I-5).

It should be noted that since a null is obtained at the receiver whenever the receiver coil is parallel to the resultant field, and since the conductor is below the receiver, the receiver bottom always points toward the conductor during null in tone, as is shown in Figure 4.

The vertical loop method measures only the dip angle of the resultant field with respect to a horizontal plane, and does not directly measure a phase or amplitude variation. A phase shift of the secondary field due to the finite resistivity of the conductor has the effect of producing broad nulls, or minima over a conductor (Corbett, 1959, p. I-5).

F.S. Grant and G.F. West (1965) also noted, with inference to broad nulls, that:

If a secondary magnetic field exists, it is generally displaced from the primary field in phase as well as in direction. Thus, the total field may be elliptically polarized and cannot be represented by a single vector. The receiver cannot then be nulled completely but it will sense a minimum signal when it contains within its plane the major axis of the polarization ellipse (Grant and West, 1965, pp. 446-447).

Horizontal Loop Principle

As the name implies, the coil plane is orientated in a horizontal position, which theoretically, gives maximum coupling with horizontal conductors. In practice, however, it has been found that the horizontal loop method is sensitive to narrow vertical conductors.

The primary field (Hp) induces a secondary current (Is) in a conductor, which in turn creates a secondary field [Fig. 7]. As the receiving coil remains horizontal, both the primary and secondary fields cut the plane of the coil inducing a voltage in it. This voltage is proportional to both the intensity and cosine of the field.
Figure 7. --Schematic diagram of the Horizontal Loop (HL) field.

(Id - primary AC current in transmitter coil
Hp - primary magnetic field due to Ip
Is - secondary current in conductor due to Hp
Hs - secondary magnetic field due to Is
Ip' - current induced in receiving coil by Hp
Is' - current induced in receiving coil by Hs
W - reference cable)

(After J. D. Corbett, Fig. I-5)
direction with respect to the vertical, and is balanced against a reference voltage taken directly from the transmitter by means of the interconnecting cable.

In the absence of any conductors, the reference is balanced against that induced by the primary field. The balancing circuit is calibrated so that when a secondary field is present, the voltage necessary to cancel it is read in terms of percent of the normal voltage required.

Because there is a phase shift due to the finite resistivity of the conductor, both in-phase and quadrature (out-of-phase) components are required to cancel the resultant net voltage (Corbett, 1959, p. I-6).

Conductivity

The conductivity of an anomaly may be approximately determined from certain ratios of the HL and VL profiles. The theoretical calculation of conductivity from two frequencies is discussed by J.D. Corbett (1959) as follows:

Because of the variation in response for a given frequency over conductors of varying conductivity, the selection of one single frequency to cover all areas is impossible. Two frequencies, more or less arbitrarily chosen from the proper range, are considerably better. In addition, and probably more important, two frequencies enable an empirical estimate of conductivity to be made ...

Fig. 8. Consider first the in-phase and quadrature components of a single frequency (the solid lines for a higher frequency). The conductivity estimate is the ratio (R) of in-phase to quadrature response.

As the conductivity increases to the right, the ratio increases. A similar situation holds for the lower frequency, but the conductivity, shape-size factor must be greater to give an identical ratio. Hence, the higher frequency will normally give a better response and ratio for a given conductor.

The ratio \(R_0\) of lower to higher quadrature responses gives another estimate of conductivity, which is different from R.
Figure 8. --Diagrammatic sketch illustrating conductivity determination from ratios of two frequencies:

(In-phase quadrature system) (Modified after J. D. Corbett, Fig. I-6, 1959).
Still another ratio which is most applicable to the vertical loop survey is the ratio \( r \) of low to high in-phase amplitude.

As these are all theoretical considerations and the shape of the actual curves are unknown, it is impossible to set limits on any ratio insofar as positive evaluation of conductivity is concerned. Empirical data over a period of time may enable interpretative separation of graphite or sulphide because of a difference in conductivity, as in Bathurst, on the basis of ratio, but it is a non-predictable factor in any new area (Corbett, 1959, p. I-7).

Experience indicates that a rough idea of the magnitude of conductance may be obtained from the profiles, but they reveal little about the materialistic nature of the conducting body. This is because of the large number of unknown factors that may be a contributing cause to the conductivity.

The general range of conductivity of a number of common materials is shown in Table I. Conductivity is the reciprocal of resistivity and is measured in terms of mhos per meter, centimeter, foot, etc.

**SURVEY TECHNIQUES**

**Recording Data**

The receiver operator is in charge of the crew and records all the notes except in certain situations where a note-taker may be included in the crew for increased operational speed. The operator should therefore be aware that certain information must be recorded for location and plotting purposes. A list of such information is given on Table II. Figures 9a, 9b and 9c illustrate how the data are recorded.

Depending on the type of survey conducted, various
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<td>Bituminous Coal</td>
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<td>Lignite</td>
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(After J.D. Corbett, Fig. I-7)
### TABLE II

A List of the Essential Information (with Examples) That Must be Recorded on VL Broadside, VL Standard and HL Surveys

<table>
<thead>
<tr>
<th>ESSENTIAL INFORMATION</th>
<th>EXAMPLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. The local area</td>
<td>Id</td>
</tr>
<tr>
<td>2. Anomaly designation (usually by number)</td>
<td>Anom. 60</td>
</tr>
<tr>
<td>3. Traverse designation (usually by letter)</td>
<td>VL Trav. A</td>
</tr>
<tr>
<td>4. Technique (VL Broadside, VL Standard or HL)</td>
<td>VL Brdsd. A</td>
</tr>
<tr>
<td>5. Separation between transmitter and receiver</td>
<td>Sep. 200'</td>
</tr>
<tr>
<td>6. Date</td>
<td>Sept. 7/60</td>
</tr>
<tr>
<td>7. Page of the notes</td>
<td>Page 3</td>
</tr>
<tr>
<td>8. Location of the start of the traverse, either by description (see VL Brdsd., Fig. 9a), or at a particular location on a line (claim line, blazed line or picket line)</td>
<td>Start at 3 W. on P.L. 6 N.</td>
</tr>
<tr>
<td>9. Direction of the traverse</td>
<td>Going N. 60 W.</td>
</tr>
<tr>
<td>10. The relative position of the transmitter and receiver in VL procedure (not necessary in HL procedure if, by convention, the receiver always follows the transmitter along the line of traverse)</td>
<td>O N. 30 E. of Δ (also see Figs. 9a, 9b, and 9c)</td>
</tr>
<tr>
<td>11. Initials of the receiver (O) and transmitter (Δ) operators</td>
<td>O S.R., Δ A.J.</td>
</tr>
<tr>
<td>12. The readings and their stations</td>
<td>(see Figs. 9a, 9b, and 9c)</td>
</tr>
</tbody>
</table>
**Figures 9 a, b, and c. -- Examples of EM notes illustrating the method of recording field information and instrument readings for VL Broadside and Standard, and HL survey.**

<table>
<thead>
<tr>
<th>STATION</th>
<th>LOW</th>
<th>HIGH</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traverse starts on blazed line</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>250' N 60°W of blazed and flagged tree on NW bank of Pine Creek</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>400' West of beaver dam</td>
<td>Going N 60°W</td>
<td></td>
<td></td>
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<tr>
<td>0:00</td>
<td>0</td>
<td>0</td>
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<tr>
<td>1:00</td>
<td>0</td>
<td>0</td>
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<tr>
<td>2:00</td>
<td>+1</td>
<td>+2</td>
<td></td>
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<tr>
<td>2:50</td>
<td>+7</td>
<td>+10</td>
<td></td>
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<tr>
<td>3:00</td>
<td>+4</td>
<td>+5</td>
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<tr>
<td>3:50</td>
<td>-3</td>
<td>-4</td>
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<tr>
<td>4:00</td>
<td>-10</td>
<td>-12</td>
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<tr>
<td>4:50</td>
<td>-6</td>
<td>-9</td>
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<tr>
<td>9:00</td>
<td>+1</td>
<td>-1</td>
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</tbody>
</table>

**Notes:**
- 3425W on VL Travo.
- 3480 flagged outcrop at 4100W
- Possible trenching area
- Stream 5+30W
- Flow South
- Steep rise

**Correction:** -10 +4 +12 -6
other useful information may also be recorded. When taking
VL Broadside and Standard notes (the VL technique is
explained on pages 36 to 44), it may be worthwhile to note
general topographic features which may be important in the
evaluation and interpretation of the anomaly profiles, and
in determining the method of approach for further work.

Notations might include such items as:

- cedar swamp, open muskeg, sharp 30-foot ridge
- (outcrop), probably deep gravel overburden,
- 40-foot cliff or bluff, 25-foot deep gully,
- steep hillside, flooded beaver pond.

These notations are particularly important in cases
where one or several of the following situations exist:

1) In reconnaissance type surveys where geological
mapping, either before or at the time of the
VL survey, is sparse. In such a situation it
may sometimes also be useful to note some of
the general geology, e.g.: pink granite
typical; mostly metasediments; shear zone in
basic volcanics; granite and metasediment
contact.

2) In the immediate vicinity of any anomaly or
conductor. Here, it is essential that possible
trenching locations and any old pits or trenches
be noted, particularly when tracing a conductor
by VL Standard. It is usually advisable to
"walk-out" the anomaly after it is traced out
and check for areas where it may cross outcrops

or shallow overburden to determine if and where trenching is possible. A special note should be made of these locations (See Fig. 9b). Trenching, if possible, is almost always much quicker and cheaper than diamond drilling in the initial determination of the nature of the conductor.

3) If an HL survey is to follow a VL survey. Since rough topography often poses greater problems with HL than VL, a knowledge of topographic features can be important in determining the best locations for HL lines as well as which cable length to choose.

**Plotting the Data**

The recorded readings for both the VL and HL survey are usually plotted on graph paper (Figs. 10, 11, 12 and 13). An example of the general layout of data involved in the exploration of an anomaly is illustrated by the case history shown in Figures 12, 13, 14 and 15. First, a VL profile plan map was made. Plotted on this map were the VL Broadside and Standard profiles, the anomaly trace, and the picket line system which was used for location control in the field (Fig. 12). A similar profile plan map was then made for the HL survey on the same picket line system (Fig. 13). Following this, a geological map was produced on the same scale (Fig. 14). A profile of the drill hole, which was placed through the anomaly at what appeared to be most conductive zone, was drawn last (Fig. 15). Most of
Figure 10. --Diagram illustrating the method of plotting VL data (from notes in Figures 9a, 9b, and 9c).
Figure 11 a and b. —Diagram illustrating the differences between HL profiles plotted from notes which a) have not been adjusted for background and b) which have been adjusted for background. Also shown is the magnetic relationship (Mag. A) which is the cause of the abnormally high shoulders on the HL profile. The trench 1 contains bands of quartzite and magnetite (strongly magnetic) with intertingering thin stringers of pyrite and pyrrhotite.
Figure 12. --A case history in which is illustrated the method of plotting VL Broadside and Standard traverses on a VL profile plan map.
Figure 13. --Case History; illustrates the method of plotting HL traverses on a HL profile plan map. Only the low frequency is plotted. Note the fairly low magnitudes but high ratios of the profiles (R = IP/OP) indicating a good but probably fairly deeply buried conductor. Also see Figure 15.
Figure 14. -- Case History; a geology map of the area shown in figures 12 and 13.
Figure 15. --Case History; illustrates the relationship of the H. L. profile on P. L. 12W, to the conductor as it is disclosed by the drillhole section. The graphite indicated in the drill-hole section is an excellent conductor. (After E. Burgan, 1961)
the basic relationships between instrumentation and the resulting profiles is illustrated by Figures 5, 16, 17 and 18.

VL Broadside notes may be plotted as a separate profile. However, VL Standard notes are always plotted on a profile plan map. The profile plan map usually includes basic geomorphic features, such as swamps, streams, ponds and cliffs, as well as a plan of the traverses, anomaly traces and trenches with VL profiles superimposed (Fig. 10). Generally, it is advantageous to plot both the VL Broadside and VL Standard profiles on the same map (Figs. 10 and 12). Usually both frequencies are plotted for VL.

In HL surveys the recorded results are usually plotted as separate profiles (Fig. 11), but may also be plotted on an HL profile plan map (Fig. 13). Often only one frequency (usually 2400 cps) is plotted since it generally contains the essential information. The ratio \( R = \frac{IP}{OP} \), usually is the best indicator of the conductivity of the anomaly.

The background often varies somewhat from place to place and therefore an adjustment must be made to give an approximate background average of zero. This may be done by adding, in each column of the notes, the background readings and dividing their respective sums by the number of readings added. This gives a correction factor which is then algebraically subtracted from every reading in its respective column. The corrected readings are then plotted. The correction factor usually can be estimated with sufficient accuracy (±1) that no calculation is necessary (Fig. 9c).
The comparative results of non-adjusted and adjusted background readings from the notes in Figure 9c (IP and OP, 2400 cps., only) are illustrated in Figures 11a and 11b. In Figure 11a, a space results between the IP and OP background giving a false ratio R of 4.5, thus indicating falsely a strong conductor. In Figure 10b the background of IP and OP coalesce or match giving the more accurate ratio R of 2.0, thus indicating the true but much weaker conductor than in Figure 11a.

Scale

The following scale for VL and HL survey is commonly used (Figs. 10 and 11):

Horizontal scale: 1" = 100'
Vertical scale, VL: 1" = 20° (VL is measured in degrees)
HL: 1" = 20% (HL is measured in percentage, see pages 6 and 11).

Various other (usually smaller) scales may be used to fit those of other maps, particularly if overlays are used. However, it is important that the ratio of the horizontal scale to the vertical scale be kept constant. For example, if the horizontal scale is reduced to 1" = 400', the vertical scale must be reduced to 1" = 80°, and 80%, for VL and HL respectively. Thus, although the scale is smaller, the profile form remains the same and can be compared with other profiles in the same perspective.

Sign Convention

Determination of the sign (- or +) for VL survey, as
mentioned on page 6, has been arbitrarily chosen to be negative when the receiver bottom points in a northerly or westerly direction. It is again asserted that in the VL procedure the bottom of the receiver always points in the direction of a normal conductor as is explained on page 16.

A problem arises as to which sign to use when traverses are N 45° W or S 45° E. The choice may be arbitrary but should conform with other traverses in the area. Also, the axis of anomalies often curve. This situation is exemplified in Figure 16a by a hypothetical anomaly with an exaggerated curving of the anomaly axis. In this type of situation to avoid confusion, the sign, once established, should always be kept the same on each side of the anomaly to the completion of that anomaly trace, regardless of the direction. In Figure 16a, for example, if the anomaly trace by VL standard progresses from A to B, the right side of the anomaly remains positive and the left side negative. If, however, the anomaly trace had progressed from B to A, the signs would be reversed but the profiles plotted would remain exactly the same, except possibly for some differences in magnitude. For this reason the minus sign must be used for the receiver bottom pointing north and east, and a plus sign for south and west. If, for example, a minus sign were used for the receiver bottom pointing toward north and west, a false reverse cross-over could result in the westerly direction (Fig. 16b).

**VL Procedure**

When working a VL procedure the receiver and transmitter
Figure 16a. --Diagrammatic profile plan map of a hypothetical anomaly illustrates the use of sign convention on a curved axis anomaly.

Figure 16b. --Illustration of how a false crossover may result if the minus sign is used when the receiver bottom points north and west.
are positioned relative to each other as is shown in Figure 1a. The VL procedure includes VL Broadside and VL Standard techniques.

**VL Broadside Technique**

In the VL Broadside technique the receiver and transmitter advance broadside to the conductor with the intent of passing as nearly in line over it as possible (Fig. 17a, e and f). Since the strike of the anomaly is usually unknown, the Broadside approach often traverses the anomaly at an angle (Figs. 17b, c, d, and g). However, the direction of approach is not critical unless the approach angle is extremely acute, because most anomalies can be detected except at extremely acute angles (Figs. 17c, d and g). A typical reverse crossover such as results when VL Broadside is passed over banded magnetite is shown in Figures 17f and g. The essential purpose of VL Broadside is to find the anomaly.

Usually, with this technique, the receiver operator traverses along a picket or blazed line and controls by voice the movements of the transmitter operator who generally travels by pace and compass according to the receiver operator's instructions. The common separation between the transmitter and receiver is 200 feet but this may be shortened to about 150 feet in rough topography where problems with instrument orientation are encountered. Separation may also be lengthened to 300 or 400 feet in swampy or flat areas where overburden may be deep. As much as 600 feet separation can be used in special situations.
Figure 17a. --Diagram illustrating a VL Broadside traverse perpendicular to the conductor and the typical resulting curves for a weak conductor and a strong conductor.

Figure 17b. --Diagram illustrating a VL Broadside approach 1), at an angle across a conductor and 2), a perpendicular approach with the transmitter leading the receiver. The resulting curve is the same for both cases. Note the greater profile magnitude at X as compared to the point at Z.
Figure 17c. --Diagram illustrating an acute angle VL approach over a conductor and the resulting positive curve.

Figure 17d. --Diagram illustrating an acute angle VL approach over a conductor and the resulting negative curve.
Figure 17f. --Diagram illustrating a VL Broadside perpendicular to banded magnetite and a typical reverse crossover profile that results.

Figure 17g. --Diagram illustrating an acute angle VL Broadside approach and the resulting curve over banded magnetite.

Figure 17e. --Diagram with two profiles illustrating a VL Broadside traverse crossing multiple conductors.
such as on lake ice where vocal communication between the operators is possible over longer distances.

Since VL Broadside is the first technique applied, this procedure is mainly a reconnaissance type and therefore only a minimum of location control such as blazed lines is used. On some reconnaissance work, a crew of four (the receiver and transmitter operators, a geologist and a line cutter or blazer) may work together as a unit. Once a conductor or indication of a possible conductor is noted, a Standard traverse is run in a semi-circle around the receiver to pinpoint the strike of the conductor.

It is essential that all indications of a conductor, however small, be checked out by VL Standard because it is not the strength of the conductor but the value of the economic minerals in it that determines the value of a prospect. Poor conductors may be rich in economic minerals.

**VL Standard Technique**

VL Standard technique is used to trace the conductor along its length. The technique here is to place the transmitter on the crossover located by VL Broadside and have the receiver traverse perpendicularly across the conductor farther down (Figs. 10 and 18a to f). The resulting plotted curve is similar to that of a VL Broadside but is usually of greater amplitude (Fig. 5). The transmitter is next brought to the new crossover and the receiver is again moved across the conductor at an equal distance away. This procedure is repeated along the anomaly trace until the conductivity disappears (Fig. 12).
Figure 18a. -- Diagram illustrates a VL Standard with the transmitter on the conductor and the resulting profile curve for 1), a weak conductor and 2), a strong conductor.

Figure 18b. -- Diagram illustrating the type of curves resulting with VL Standard when the transmitter is offset from the conductor. Note the difference in magnitude in the profile curve, and the shift in crossover position for transmitter locations at A and B. For a vertical conductor the crossover position would be the same for both curves.

Figure 18c. -- Diagram illustrating the type of profile curves that may result in VL Standard if the receiver traverses at A, an angle towards the transmitter and B, at an angle away from the transmitter.
Figures 18 d, e, and f. --Diagrams of plan views and profiles illustrating the resulting types of curves which may be obtained by VL Standard when the receiver traverses across two conductors of various conductivity with the transmitter positioned on one conductor.
Separation is usually 200 feet but may be reduced or extended the same as for VL Broadside and for the same reasons. A separation of as close as 75 feet may be used to pinpoint the near surface location of the conductor with greater accuracy for trenching purposes. The plotted result of a VL Standard survey is illustrated in Figures 10 and 12.

The strike of the conductor from the VL Broadside crossover should be first determined so that an organized plan of approach by Standard technique can be established. Lack of control and inaccuracy of locations due to haste in the initial stages can later lead to a considerable confusion when all the data are plotted. This is particularly true where complex (curved, warped, irregular) and/or multiple conductors are encountered (Fig. 17e). It may be advisable to trace the conductor several hundred feet and establish a straight line parallel along it in order to tie in the Standard traverses and then run the Standard survey which is to be plotted on the map.

When more than one conductor is in close proximity (Fig. 17c and 18d, e and f), it may be advisable either to use a shorter separation or trace the anomaly by steps. For example, the separation may be 200 feet but the amount of advance from one Standard traverse to the next may be only one hundred feet.

The primary purpose of VL Standard is to trace the conductor along its length in anticipation that it will cross a trenchable area. Also, a general idea of magnitude of conductivity can be determined from the amplitude of the.
profiles and the ratio \( r = \frac{\text{high frequency}}{\text{low freq.}} \) of the two frequencies used. This helps to determine the most advantageous location(s) to run an HL traverse(s).

**HL Technique**

The object of an HL survey usually is to try to determine certain characteristics of the anomaly such as conductivity, width, dip and depth of burial. The instrument positioning for an HL traverse is illustrated in Figure 1b. HL is usually run on a cut line (picket line) with the transmitter leading the receiver (Fig. 19). The separation between the instruments is kept uniform by measured distances on the lines (pickets) or, as usually is the case, by using a marked position on the HL reference cable. At each station the cable is tightened for accuracy, the receiver is positioned at the cable marking, and a reading is recorded. Both frequencies (600 cps and 2400 cps), as well as the in-phase (IP) and out-of-phase (OP) for each frequency are generally recorded at each station. As earlier mentioned, a 100, 200, or 300 foot cable may be used. A comparison of the HL curves resulting from the use of these the cable lengths is illustrated in Figure 20.

The intervals between stations at which readings are taken vary with respect to the length of the cable used and the position of the instruments relative to the conductor. In general, the longer the cable length the longer may be the interval. The reason for this is, that to maintain accuracy, the same number of stations should be taken over a short cable length as that of a long cable length. In
Figure 19. --Diagram of an ideal HL profile illustrating some of the mechanics involved in the development and interpretation of the profile.

\[ Q - Q' = \text{Conductor width minus reference cable length} \]
\[ \text{OP} = \text{OP} \]
\[ \text{IP} = \text{IP} \]
\[ m = \text{Station recorded by receiver operator (center of cable)} \]
\[ X = \text{Interpreted conductor width} \]
\[ R = \frac{\text{IP}}{\text{OP}} = 3 \]

\[ \Delta = \text{transmitter} \]
\[ \Phi = \text{receiver} \]

Figure 20. --HL curves from a field study comparing profiles resulting from the traverses with 100, 200, and 300 foot cable over the same conductor on the same line. (Modified after J. D. Corbett, Fig. V-4, 1959).

IP and 2400 cps only
\[ Z = \text{separation between receiver and transmitter} \]
order to do so, the interval between stations must be
decreased for the shorter cable.

For most purposes the station interval for background is
100 feet. However, this interval is shortened when the
instruments move into range of an anomaly. A particularly
critical zone is that where either the receiver or trans-
mitter passes over the anomaly. It is this zone that the
shoulder on the plotted curve drops from positive to minus
on one side of the conductor and back from minus to positive
on the other side (Fig. 19). The distance between the
points where the curve passes through zero is used to deter-
mine the conductor width. This distance (Q to Q' in Figure
19) minus the cable length gives the calculated conductor
width. Therefore it is important that sufficient points
are taken in this zone to give a high degree of precision
to the plotted curve and so give an accurate estimate of
the conductor width. Usually in this situation readings
are taken at 25 foot intervals for 200 and 300 foot cable
lengths and at 10 or 15 foot intervals with 100 foot cable.
Otherwise 50 foot station intervals for the 300 foot cable
and 25 foot intervals for the 200 and 100 foot cables should
be used when within an anomaly range.

The receiver operator should keep an eye on the
readings taken as he goes along so that he will detect any
significant change from the background and reduce the
station intervals accordingly. Often, when using 100 foot
intervals, it is advisable to go back 50 feet to take an
extra reading for greater precision when a significant change
does occur. A significant change usually may be considered to be three or four percent if background is smooth, and greater than five or six percent if the background is irregular.

The choice of cable length depends largely on the terrain. The 200 foot cable has been found to be most acceptable for general use since it has considerable depth penetration (to about 100 feet) and is much easier to handle than the 300 foot cable. The 300 foot cable is usually used on lake ice or on fairly level ground where overburden (or water) is thought to be of considerable depth. The 300 foot cable has a practical depth range of about 150 feet. It should also be noted that in general, the longer the cable length used, the weaker signal and the broader will be the null.

The 100 foot cable is often used where overburden is shallow and the terrain irregular so that a close spacing and better visual control between the receiver and transmitter operator are important (Fig. 21c). The 100 foot cable also has a great advantage over the longer cables where several parallel conductors are closely spaced (less than 250 feet apart). With it anomalies as close as 100 feet apart can be well separated, while with the longer cable lengths an overlap of the resulting curves occurs, thus making interpretation difficult (Figs. 22 and 23). Figures 20 and 22 to 26 illustrate some of the basic types of curves encountered in HL surveys.

Sometimes only the HL technique might be used when
Coils of both instruments are held parallel to each other.

Coils of both instruments are held vertical. The receiver operator estimates $h$ and later applies the corresponding correction factor when the notes are plotted. This method is generally used in critical areas where elevations of the stations have been taken.

A shorter cable (1) may be preferable in rough terrain to keep the $\bigcirc$ and $\triangle$ in view of each other.

The receiver operator estimates $h$ (15') and steps back the required amount (2') to compensate for short cable.

Figures 2 a, b, c, and d. — Diagrammatic sketches illustrating methods used in the correction for elevation and short cable effects.
Figure 22a. --An HL profile from a case history in the field illustrates the type of HL curves that may be expected over multiple narrow conductors with the 200 foot cable. Note that the anomalies a, b, d, and e appear, from the profile, to be one wide highly conductive anomaly.

Figure 22b. --An HL profile of an HL traverse done with a 100 foot cable on the same line as in Figure 22b. Note that most of the anomalies are now differentiated as separate identities.
Figure 23 a, b, c, and d. --Diagrammatic sketches illustrating a generalization of the cumulative effects of closely spaced parallel conductors. (After J. D. Corbett, Fig. IV-6, 1959).
checking an area for possible anomalies. This may be done where a precut picket-line system has been used for geological mapping or other uses and a check for possible conductors over the system is desired. There are two main reasons for using HL only: a) the HL technique tends to detect weak conductors better than the VL Broadside technique; b) both the transmitter and receiver operator can walk on a cut line, thus facilitating a more efficient operation.

**Crossing an Anomaly at an Acute Angle with HL**

A high center or peak may occur in the profile curve when an HL traverse crosses an anomaly at an acute angle (Figs. 24A and B). In general, the height and form of this peak depends on the angle of the traverse approach to the anomaly, as well as on the conductor width. If the conductor is fairly narrow (less than two-thirds the cable length) the height of this central node or peak will increase as the approach angle is decreased to about forty-five degrees. If the approach angle is decreased beyond forty-five degrees the vector of effective conductivity is reduced and the peak will approach zero as the traverse becomes parallel to the conductor. As the width of the conductor is increased the low lobes which develop on each side of the peak (Fig. 24B) tend to disappear so that only a positive hump remains on the HL curve when the conductor width becomes greater than the cable length. If the conductor is dipping, asymmetry in the profile will develop (Fig. 24A and C).
Figure 24 A. --Sketch from a field study illustrates the type of HL profile which results when an HL traverse is passed at an angle (about 45°) over a dipping conductor.

Figure 24 B. --Sketch from a field study illustrates the type of HL profile which results when an HL traverse is passed at an angle (about 45°) over a vertical conductor.

Figure 24 C. --Sketch from a field study illustrates the type of HL profile which results when an HL traverse is passed perpendicular to a dipping conductor (same conductor as in Figure 24 A).

Figure 24 D. --Sketch from a field study illustrates the type of HL profile which results when an HL traverse is passed perpendicular to a vertical conductor (same conductor as in Figure 24 B).
Figure 25 a, b and c. Profiles from a case history showing the relationship of Magnetometer, HL and VL Broadside profiles over a strongly magnetic 20 foot band of magnetite.
Figure 26. —Diagrams of hypothetical HL profiles to show some comparisons of conductivity and depth of burial relationships.

EXELLENT CONDUCTOR

MODERATE CONDUCTOR

POOR CONDUCTOR

R = IP/OP = degree of conductivity

d = depth to top of conductor

z = separation between transmitter and receiver
It is important, particularly if only HL is used (see page 47), that any zones with significant deviation of an undetermined nature from the normal background should be checked by VL for a possible anomaly. For example, the true nature of the conductor in Figure 24B is illustrated in Figure 24D, in which case the HL traverse was passed through the same point but perpendicularly over the conductor. Note that in this case (Fig. 24D) a strong normal type HL curve develops. Weak anomalies may give only a small deviation from normal background, particularly if the HL traverse passes nearly parallel to the conductor. They may, therefore, be difficult to identify.

CAUSES, PREVENTION, ESTIMATION AND CORRECTION OF ERROR

Error with VL Procedure

With the VL Procedure, essentially all significant error in taking readings is due to disorientation of the transmitter coils with respect to the receiver location. Disorientation of the transmitter is that situation when the axis of the transmitter coil is not perpendicular to a line directly from the transmitter to the receiver. The cause of transmitter disorientation in the field is due to the inability of the transmitter operator to detect the true direction of the voice from the receiver operator. Since all communication between operators is by voice, rough or irregular terrain causes problems with both sound direction and audibility. Ridges, knoles or scarps between
the operators may deflect, echo, bend and/or decrease the
volume sound waves as they travel from one operator to the
other. Therefore, as the sound reaches the transmitter
operator, it may appear to be coming from a direction other
than its true original source, and so misleads him to
disorient the transmitter.

Disorientation can be prevented by three methods.
Firstly, it can be eliminated if both instruments are run
on premeasured parallel lines (picket lines) so that the
relative positioning of the instruments is definitely
established. Secondly, it may be reduced by decreasing
the separation between the instruments and thus increasing
the vocal control between the operators. Thirdly, it can
be essentially eliminated by having the transmitter operator
walk to within visual distance of the receiver operator
and than pace directly back to the transmitter station
location by compass. The transmitter operator then can
use compass direction to orient his instrument (this method
fails in strongly magnetic areas).

The two-picket-line method, although theoretically the
best, is seldom used due to the high cost both in money and
time consumed in cutting and measuring such lines. It should
be considered that VL Broadside is essentially a reconnai-
ssance type method.

Decreasing the separation for better vocal control is
the most common method. In areas such as the Canadian
Shield, if the topography is rough, outcropping of rock is
common and the overburden is generally shallow. Therefore
the use of a closer separation between the instruments is
not likely to miss any anomalies that may be present.

The third method is used mainly in areas where eskers,
glacial moraine and/or other unconsolidated sediments may
be present and it is therefore desirable to maintain a
wide separation (200 feet or more). This method has the
disadvantage that it tends to slow down the rate of traverse
progress considerably. Therefore, only those stations on
which off-zero readings occur and disorientation is strongly
suspected are usually checked in this manner.

Disorientation is not usually critical with strong
conductors. The primary aim of VL is to locate the anomaly,
and if the conductor is strong, the cross-over point on
the conductor can be recognized even if considerable error
is present in the readings, unless the traverse approach
is at an extremely acute angle to the conductor (Fig. 17C).

With weak conductors, however, error due to instrument
disorientation can become a serious problem, particularly
if the conductors are complex. The disorientation results
in readings being off zero, thus giving a false impression
that an anomaly is present. Since such readings must be
checked by VL Standard (see page 40), considerable work
results that would be otherwise unnecessary. Furthermore,
the same difficulty of instrument orientation that was en-
countered with VL Broadside may also be encountered with
VL Standard. To counteract this situation, one of the three
methods of error prevention mentioned above can be used.

It should also be noted that the degree of error is
accentuated by an elevation difference between the instruments. The rate of increase in error, when plotted as a graph, forms an upwarping curve similar to the curves in Figure 28, as the elevation difference between the instruments increases. For example, ten degrees of disorientation for 200 foot cable may give two degrees of error on flat ground, seven or eight degrees of error with thirty foot elevation difference, and perhaps twenty-five degrees of error with a fifty foot elevation difference. It is obvious from this situation that excessively rough topography can, by causing instrumentation error, greatly restrict the use of VL methods.

**Error with HL Procedure**

Two main causes of error are encountered with HL Procedure: 1) poor insulation of the interior parts of the instruments against outside grounding; and 2) error indirectly resulting from elevation differences between the instruments.

Electrical static or other interference due to external grounding of the internal instrument assemblage can be sufficient to make HL operation virtually impossible. Therefore it is important that this internal assemblage be insulated as well as possible from outside contact. The internal parts should also be well grounded to each other to prevent eddy currents and a resulting capacitance from forming within the instrument. This capacitance creates its own magnetic field which then interferes with the resultant field set up by the primary and secondary coils.
and any conductor that may be within range. This causes irregular shifting of the null point making it difficult, if not impossible, to obtain an accurate HL reading. In order to reduce these interference effects it is important that the instrument be kept dry as possible and that care be taken by both operators, when recording readings, that body contact to susceptible areas of interference on the instrument be kept to a minimum.

With the HL procedure elevation differences between the instruments are even more critical than with VL procedure, particularly if the conventional method of instrument positioning is used (Fig. 21b). When using the conventional method, the receiver operator records the readings, estimates the differences in elevation between the receiver and transmitter, and later applies the appropriate corrections from a correction chart when he plots the notes (Fig. 28).

Error with HL also results if short cable is caused by irregular topography (Fig. 21d). Correction for short cable and elevation error is illustrated in Figures 27 and 28.

A study of the short cable error chart in Figure 27 (for 200 foot cable only; equivalent charts for 100 foot and 300 foot cables have not yet been developed) yields three main conclusions. Firstly, it is obvious that the out-of-phase (OP) for either 2400 cps. or 600 cps. is not significantly effected by short cable effect. Secondly, the error for the in-phase (IP) for both frequencies remains constant.
**Figure 27.** --Chart from a field study illustrating the amount of error caused by short cable effect (0 to 20 ft.) when using a 200 foot HL cable.

**Figure 28.** --Chart showing HL topographic corrections for 100, 200, and 300 foot cables. Note: all corrections are positive and must be added to the corresponding readings noted in the field. (After J.D. Corbett, Fig. IV-1, 1959).
at 1½% per foot. Thirdly, a decrease in separation causes the error to be positive. This regularity in the degree of short cable error makes correction simple.

For calculating short cable correction the chart in table III may be used. With one method the receiver operator first estimates the vertical distance (h) that the HL cable has been displaced (Fig. 21d). Later, when the data is plotted, table III and the chart in Fig. 27 may be used to correct the readings. A more efficient method of correction is to estimate (h) and, by using the figures from the chart in table III, correct the error directly in the field as is shown in Figure 21d. This method keeps the HL readings at their true level in the notes, thus enabling the EM operator to more precisely determine if anomalous conditions are encountered. However, if uncorrected readings are recorded as in the first method, he may have difficulty deciphering them in the field.

A study of table III will show that as the cable length is increased, the short cable effect (d) for the same degree of cable displacement (h) decreases. Also the rate of increase in (d) increases with (h). This implies that a particularly humpy type of topography can seriously limit HL work because it induces excessive short cable error. In some situations the cause of error may be alleviated by using a shorter cable (Fig. 21c). Short cable effect for an (h) of less than 10, 15, or 20 feet can be ignored for 100, 200 and 300 foot cable lengths respectively. Elevation differences between the instruments also significantly
### TABLE III

A Short - Cable - Distance Correction Chart Showing the Amount of Short Cable (d) for Various Heights (h)

<table>
<thead>
<tr>
<th>h</th>
<th>d</th>
<th>h</th>
<th>d</th>
<th>h</th>
<th>d</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.5</td>
<td>5</td>
<td>0.3</td>
<td>5</td>
<td>0.2</td>
</tr>
<tr>
<td>10</td>
<td>2.0</td>
<td>10</td>
<td>1.0</td>
<td>10</td>
<td>0.6</td>
</tr>
<tr>
<td>15</td>
<td>4.6</td>
<td>15</td>
<td>2.3</td>
<td>15</td>
<td>1.4</td>
</tr>
<tr>
<td>20</td>
<td>9.3</td>
<td>20</td>
<td>4.0</td>
<td>20</td>
<td>2.8</td>
</tr>
<tr>
<td>25</td>
<td>13.4</td>
<td>25</td>
<td>6.4</td>
<td>25</td>
<td>4.2</td>
</tr>
<tr>
<td>30</td>
<td>20.0</td>
<td>30</td>
<td>9.2</td>
<td>30</td>
<td>6.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>35</td>
<td>12.6</td>
<td>35</td>
<td>8.4</td>
</tr>
<tr>
<td>40</td>
<td>16.4</td>
<td>40</td>
<td>10.8</td>
<td>45</td>
<td>13.6</td>
</tr>
<tr>
<td>45</td>
<td>21.4</td>
<td>50</td>
<td>17.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>26.8</td>
<td></td>
<td></td>
<td>55</td>
<td>20.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60</td>
<td>23.0</td>
<td>65</td>
<td>29.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>70</td>
<td>34.6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

**Diagram:**

- **b = cable length**
- **h = cable displacement (vertical) at center (maximum)**
- **d = amount the horizontal distance is shortened due to h**
effect only the IP readings.

The required correction for elevation error of each cable length is shown on the chart in Figure 28. Here again the rate of error increases with the increase in elevation difference. With an elevation difference of 20, 40 and 60 feet for 100, 200 and 300 foot cables, respectively, the degree of error becomes critical if the conventional method of operation is used. Therefore, when elevation differentials greater than those mentioned above are encountered, all stations should be accurately surveyed rather than estimated. Not only does error result from the elevation difference, but the equipment becomes very sensitive to misalignment, thereby compounding the probability of error.

An alternative method is illustrated in Figure 21a. In this situation both instruments are oriented so that their coils are parallel to each other. This method has the great advantage over the conventional methods in that all the elevation error is automatically eliminated. In this situation orientation of the instruments at all times is the equivalent to that of running an HL traverse on an even level surface. However, problems do arise. The main problem is that the operators may have difficulty in keeping both instruments tilted at the same angle. This is especially true in brushy areas where visibility, even on a cut line, is often short, and the EM operators may have to orient by voice alone. Therefore the 300 foot cable is rarely used, rather, the 100 foot cable is commonly employed.
with this method in areas where visibility is limited.

INTERPRETATION

VL Standard on Complex Conductors

Certain types of anomalies can cause difficulties in the determination of weak conductors by VL Standard. The problem arises when low readings which have been picked up by VL Broadside are checked by VL Standard for a conductor over complex anomalies such as: 1) irregular broad strongly magnetic zones; 2) crossing conductors in joints, fractures and/or faults; 3) warped curved conductors; and 4) intermittent parallel or interfinger ing lense-like conductors. It is the nature of these types of anomalies not only to cause weak and confusing readings (3 to 6 degrees) and doubtful crossovers, but the conductor(s) also may appear to shift with a change in the positioning of either instrument, or with a change in the separation between the instruments. This makes it very difficult to define the course of such anomaly traces accurately.

It must be considered that the EM operator in the field is working wholly with unknowns that may be infinite in variety, and when complexities arise, he often has very little idea of what type of situation he may have encountered until he has at least partially worked out and solved the problem in the field. Also, if the topography is irregular, as often is the case with complex anomalies, such a situation can become extremely difficult to solve because of the high probability of error caused by instrument disorientation.
In some areas broad and irregular strongly magnetic zones exist which cause low readings, usually with broad nulls, for which no true crossover, not even a shifting one, can be found.

If the complex anomalies are good conductors, they can usually be traced to some extent and definite crossovers can be located. Also if the anomaly is banded magnetite, reverse crossover can usually be determined by some maneuvering around with VL Standard.

When the EM operator suspects, after some preliminary VL Standard, that he has encountered a complex type anomaly situation, there are certain techniques that he may immediately use in the field to try to determine the characteristics of the anomaly. He should first reduce the separation between the instruments. This will reduce both the horizontal and vertical range of instruments so that the conductive effect of the anomaly or anomalies can be isolated to simpler and shorter near-surface zone. Here the conductor(s) can be better differentiated. Secondly, once a strike along at least part of the conductor has been established, it is essential that some type of straight blazed line, or preferably a measured picket line, be cut as nearly parallel as possible to the anomaly for location control. Thirdly, if the operator can roughly determine the strike of the conductor, he may run one or several HL survey lines perpendicular to this strike and over the conductor. An HL traverse running perpendicularly across the strike of an anomaly often gives a much clearer picture.
of the nature of the conductor than VL methods.

It has been found from experience that whenever a conductor is located, its strike should be determined for at least some distance before notes are taken for the purpose of plotting VL Standard profiles. The reason for this is that if the approximate orientation of the conductor is known, a well organized and properly oriented sequence of VL Standards can be planned. The notes can then be easily and accurately plotted. This is particularly true where complex and/or multiple conductors are encountered.

Again it must be stressed that the purpose of the VHEM survey is to find economic minerals. Defining anomalies is only of secondary importance. Therefore, if outcropping is abundant and a crossover on a trenchable area is found, it may not be necessary to detail the anomaly unless economic minerals are found in the trench. However, where overburden is such that trenching is not feasible and the alternative is to use a diamond drill, it is imperative that as much interpretive information as possible be first acquired by VHEM methods. This information will help to determine whether or not diamond drilling is advisable. When diamond drilling is anticipated, it may be expedient to run a traverse with all three cable lengths so that a more complete analysis of depth, width and probable dip of the conductor can be made. This information should indicate the best location and orientation for drilling.
Conductivity and its Causes

When considering the conductivity of anomalies with respect to VHEM, the important criteria is not so much that the anomalous substance be very highly conductive, but rather the conductivity be continuous. The common minerals which have this criteria are mainly vein type sulfides and graphite. A range of the conductivity of various materials is given in table I.

Some of the more common metallic minerals shall first be considered individually as conductors. Grant and West (1965) give an interesting and informative review on the conductivity of such metallic minerals from a study of specimens mainly representative of Precambrian mineralization. Some of the principal observations and comments mentioned are presented here. The minerals are listed in the order of decreasing conductivity.

Pyrrhotite \([\text{FeS (Fe}_7\text{S}_8])\) is an excellent conductor both in mineral form and as an ore, with a fairly constant conductivity of about \(10^4\text{mhos/m}\). Field evidence substantiates the high conductivity. The conductivity of pyrrhotite mineralization, as given on Table I (\(10^{-1}\) to about \(10^{+1}\) mhos/cm), is probably much too low.

Graphite (C) is an extremely good conductor and has the remarkable ability to remain connected (continuous) even when it is present only as a few percent. Therefore very little graphite is needed to produce a good conductor. The molecular structure of graphite is of a platy or layered nature so that it imparts a conductivity of about \(10^6\) mhos/m.
in the basal plane and about $10^2$ mhos/m across it.

**Pyrite** ($\text{FeS}_2$) which is one of the most common sulfides has a highly variable conductivity which averages about $10^2$ mhos/m.

**Chalcopyrite** ($\text{CuFeS}_2$) and **arsenopyrite** ($\text{FeAsS}$) are similar to pyrrhotite but they have a lesser mean conductivity of about $2 \times 10^2$ mhos/m.

**Galena** ($\text{PbS}$) in crystal form is an excellent conductor ($10^4$ mhos/m) but the cubic habit usually breaks the conductivity thus making it a poor linear conductor. However, other conductive minerals mixed with it may provide sufficient connection between the grains or crystals to create a substantial conductor.

**Magnetite** ($\text{Fe}_3\text{O}_4$) like galena, has highly conductive crystals which tend to remain as distinct euhedral grains making it also a poor conductor.

**Hematite** ($\text{Fe}_2\text{O}_3$) and **sphalerite** ($\text{ZnS}$) are essentially insulators but with the presence of impurities they may reach a conductivity of about 10 mhos/m.

Several other sulphides, including **bornite** ($\text{CuFeS}_4$), **chalocite** ($\text{Cu}_2\text{S}$), **covellite** ($\text{CuS}$), **molybdenite** ($\text{MoS}_2$) as well as the non-sulphides, **pyrolusite** ($\text{MnO}_2$) and **ilmenite** ($\text{FeTiO}_3$) may have conductivities between 1 mho/m and $10^3$ mhos/m. (F.S. Grant and G.F. West, 1965, pp. 397-399).

The McPhar VHEM unit is probably sensitive to conductors as low as 1 mho/m with HL and about 10 mho/m with VL, providing these conductors are of a substantial size (over 300 feet long, at least a few feet wide and at shallow depth).
Apparently the degree of conductivity mentioned above pertains to the minerals as they are massive linear form. However, in the field the mineralization may vary from finely disseminated nonconductive bodies to massive vein-like highly conductive bodies.

In the field sulphides are rarely found as purely separate identities. Usually they occur in varying degrees of mixture. Most often a combination of pyrrhotite, pyrite and/or magnetite will occur together as a mixture of as narrow separate bands or zones in an anomaly. Galena and sphalerite are also commonly found together. Only graphite tends to occur as a solitary unit, and even it is often mixed with some pyrite and/or pyrrhotite.

Economic minerals such as the copper sulphides are of course rare, at least in massive quantity.

One aspect which can be an important contributing factor to conductivity is the structural environment in which the sulphide body rests. As was earlier mentioned, the criteria of a good conductor is that the media must not only be conductive but it must also have conductive continuity. Some substances such as galena and pyrite may have high crystal conductivity but often are discontinuous because of the crystal habit and therefore make poor linear conductors. However, if they happen to be in a structural environment such a shear zone where permeating waters may act as an electrolite, at least partial electrical conduction occurs between the crystals, and a moderate to good conductor may result where one otherwise would not be
present. Therefore, massive pyrite may constitute a very weak conductor, but paper-thin layers of pyrite on the aqueous bedding planes of sheared shale or slate can produce a substantial conductor.

Permeability, porosity, microstructure, grain size, ionic content of the fluids contained in the rock and even the temperature are all contributing factors to conductivity. Clays for example, under favorable conditions may be strong enough to give a weak HL anomaly. Therefore it may be important to record general geomorphic and structural features so that they may be used as an aid in anomaly interpretation (see pages 20 to 25).

In general, conductivity as it can be sensed with the VHEM unit depends on:

a) the conductor length and width
b) the depth of burial
c) continuity of the conductor
d) the conductivity of the conducting media
e) the structural environment of the conductor
f) composition and shape of the conductor
g) the position of the instruments as they are related to each other and to the anomaly.

Interpretation of VL Profiles

The interpretation of VL profiles, even at best, is of doubtful accuracy due to the large number of variables and many types of error that may enter into the development of such profiles.
Consider the variables associated with instrumentation. Firstly, error due to disorientation may have entered into the readings (pages 55 to 58). Secondly, mislocation of instrument positioning with respect to the conductor will affect resulting profile (Figs. 17b and 29f). Thirdly, the direction of the traverse approach to the conductor will affect the shape of the VL curves (Figs. 17b, c, d and e). Fourthly, the distance of separation is reflected in the amplitude of the VL profile (Figs. 29e and g).

Secondly, consider the characteristics of the conductor itself. The causes of conductivity have already been discussed (pages 67 to 70). The degree of conductivity primarily affects the amplitude of the profiles. Various other aspects such as dip (Figs. 29c and d), and irregularities such as zones and bands of different conductivity affect mainly the shape or form of the profiles. Because of these factors, very little information, other than the location and approximate conductivity, is revealed with reasonable degree of certainty by VL. However, certain tendencies which do exist can be accurately tested by model studies (Figs. 29a, b, c and d). Others may be tested by controlled field studies (Figs. 29e, f and g).

VL procedure does give a fairly accurate location of the anomaly (within ten feet in shallow overburden to about twenty-five feet in deep overburden). Also a fair idea of the conductivity may usually be determined from 1), the amplitude of profile and 2), from the ratio between the high and low frequency. A high frequency and a ratio (r = low 71
TABLE IV

A List of Symbols and Their Definitions Used in the Following Sketches Illustrating the Interpretation of Various VHEM Profiles

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>d</td>
<td>depth; often considered a unit distance</td>
</tr>
<tr>
<td>z</td>
<td>horizontal distance or separation; along strike for VL Standard between coils for VL Broadside or HL</td>
</tr>
<tr>
<td>d/z</td>
<td>ratio of depth (d) to horizontal distance or separation (z) expressed generally as a decimal</td>
</tr>
<tr>
<td>t</td>
<td>thickness</td>
</tr>
<tr>
<td>f</td>
<td>frequency in cycles per second</td>
</tr>
<tr>
<td>a</td>
<td>separation between coils</td>
</tr>
<tr>
<td>y</td>
<td>length of conductor</td>
</tr>
<tr>
<td>oo</td>
<td>infinity</td>
</tr>
<tr>
<td>→</td>
<td>approaching</td>
</tr>
<tr>
<td>Δ</td>
<td>transmitter</td>
</tr>
<tr>
<td>O</td>
<td>receiver</td>
</tr>
<tr>
<td>ω</td>
<td>angular frequency (omega)</td>
</tr>
<tr>
<td>σ</td>
<td>conductivity (sigma)</td>
</tr>
<tr>
<td>ρ</td>
<td>resistivity (rho)</td>
</tr>
<tr>
<td>α</td>
<td>alpha</td>
</tr>
<tr>
<td>μ₀</td>
<td>permeability of free space (mu)</td>
</tr>
<tr>
<td>π</td>
<td>3.1416 (pi)</td>
</tr>
</tbody>
</table>

\[ \alpha^2 = \mu_0 \sigma \omega \frac{1}{z} = \text{the conductivity response parameter of the conductor} \]

\[ \omega = 2\pi f = \text{angular frequency} \]

(After J.D. Corbett, 1959)
Frequencties is greater at low conductivity and approaches zero at an infinite conductivity. It should also be noted that the greater is the difference between frequencies the greater is the separation between the resulting curves. (After J.D. Corbett, 1959).
Figure 29b. --Curves from a VL model study illustrating the increase in magnitude as the depth/separation ratio (d/z) decreases. (After J.D. Corbett, 1959).
Figure 29c. --Curves from a VL Standard model study illustrating the effect of a dipping conductor on various ratios of $d/z$. (After J.D. Corbett, 1959).
Figure 29d. --Curves from VL Standard model study illustrating the effect on the resulting curves of conductors with 90°, 60°, and 30° dip respectively. (After J.D. Corbett, 1959).
Figure 29 e. --Curves from a field study illustrating the difference in magnitude of the profiles for 100 and 200ft. separation. Note also the difference between 2400cps and 600cps. (After J.O. Corbett, 1959).
Figure 29 f. --Curves from a field study illustrate the effect of the transmitter being offset from the conductor. (After J.D. Corbett, 1959).
Figure 29g. --Curves from a field study illustrating the variation in magnitude resulting from different distances of instrument separation. (After J. O. Corbett, 1959).
freq./high freq.) close to one indicates a strong conductor. If the amplitude is fairly low but the ratio equals nearly one then the conductivity probably is good but the anomaly may be at considerable depth. If the amplitude is high but the ratio is low, say 0.5, then a fairly poor but near surface conductor is indicated (Fig. 29a).

Dipping conductors tend to cause asymmetry in VL profiles (Figs. 29c and d). The effect of dips greater than 45° are usually not significant. However, as the angle of dip decreases below 45° the curve becomes prolonged and gains in amplitude on the down dip side, while on the up-dip side it tends to decrease in amplitude and becomes forshortened (Figs. 29c and d).

The effects of separation and transmitter offset with VL Standard are illustrated in Figures 29e and f. Separation effects with VL Broadside are illustrated in Figure 29g.

**Summary of the Concepts of VL Interpretation**

Jack Corbett (1959) has adequately summarized the basic concepts of VL interpretation as follows:

1. For an infinite conductor, the larger the separation, the greater the amplitude of the anomaly.

2. For a limited conductor the amplitude will increase with separation up to a point which depends upon the size, shape, and conductivity of the body.

3. For any conductor the amplitude and symmetry of the plotted profile depends upon the relative location of both transmitter and receiver and upon the direction of traverse with reference to the strike of the conductor.
4. In the VL Standard technique, the magnitude of the anomaly curve, but not the crossover location, is dependent upon the transmitter location.

5. In general, the steepness of the VL crossover is an indication of the depth to the top of the conductor, i.e. the flatter the crossover the deeper the body.

6. In general the distance between positive and negative peaks is an indication of the width of a conductor, i.e. the greater the distance the greater the width.

7. In general, the fall-off back to zero on either side of the peaks is an indication of depth extent, i.e. the slower the return to zero, the greater the depth extent of a body. (J.D. Corbett, p. III-3, 1959).

Interpretation of HL Profiles

Several aspects of HL profiles have already been discussed. These include: the determination of conductor width (page 46 and Fig. 19); effect of different cable lengths (Fig. 20); close spaced multiple conductors (page 47 and Figs. 22a and b); dipping conductors (page 51 and Figs. 24A and C); curves resulting from an HL traverse approach at an angle to the conductor (page 5a and Figs. 24A and B).

In the interpretation of HL profiles it should be considered that since the coupling coefficient is independent of which coil carries the current, the profile will be the same whether the leading coil receives or transmits. Therefore, a profile over a uniform vertical conductor will be symmetrical regardless of the direction of the traverse.

A high frequency will usually evoke a better response and ratio for a given conductor than will a low frequency.
This is particularly true with weak conductors. The response of magnetite bands tends to produce profiles with high narrow positive shoulders (Figs. 11 and 25). If the magnetite should happen to be offcentered from the conductor the resulting curve will tend to be asymmetrical with the higher shoulder on the magnetite side of the anomaly. Therefore, unless a magnetometer survey is also run on the same traverse line so that magnetic and conductive relationships can be compared, the anomaly may wrongly be interpreted to be a dipping conductor. An asymmetrical profile also may result when the conductor consists of several variably conductive parallel bands, with the bands on one side being more conductive than those on the other. A detail VL Standard check with fairly close instrument separation may resolve whether it is such a multiple closely banded conductor or a single but dipping conductor.

The relationship of the IP/OP ratio and the profile amplitude with respect to strength of conductivity and depth of burial is illustrated by the profiles in Figure 26.

Summary of the Concepts of HL Interpretation

1. The amplitude of an HL curve is dependent on the strength of the conductor, the separation between the coils and the depth of burial.

2. The degree of conductivity is best indicated by
the ratio of in-phase over out-of-phase (IP/OP).

3. Banded magnetite promotes the development of high shoulders on the HL profile.

4. Asymmetry may be caused by a dipping conductor, an offset magnetite band or by the variance in conductivity of several parallel bands which may make up an anomaly.

5. The higher frequency tends to detect weak conductors better than a low frequency.

6. In general, HL can detect weaker conductors than can VL.

7. Error due to short cable tends to increase the HL readings whereas error resulting from elevation differences tends to decrease the HL readings.
BIBLIOGRAPHY
