ELECTROMAGNETIC METHODS

Introduction

Electromagnetic methods in geophysics are distinguished by:

1. Use of differing frequencies as a means of probing the Earth (and other planets), more so than source-receiver separation. Think “skin depth”. Sometimes the techniques are carried out in the frequency domain, using the spectrum of natural frequencies or, with a controlled source, several fixed frequencies (FDEM method ---“frequency domain electromagnetic”). Sometimes the wonders of Fourier theory are involved and a single transient signal (such as a step function) containing, of course, many frequencies, is employed (TDEM method - “time domain electromagnetic”). The latter technique has become very popular.

2. Operate in a low frequency range, where conduction currents predominate over displacement currents. The opposite is true (i.e., has to be true for the method to work) in Ground Penetrating Radar (GPR). GPR is a wave propagation phenomenon most easily understood in terms of geometrical optics. Low frequency EM solves the diffusion equation.

3. Relies on both controlled sources (transmitter as part of instrumentation) and uncontrolled sources. Mostly the latter is supplied by nature, but also can be supplied by the Department of Defense.

- EM does not require direct Contact with the ground. So, the speed with EM can be made is much greater than electrical methods.

- EM can be used from aircraft and ships as well as down boreholes.

Advantages

- lightweight & easily portable.

- Measurement can be collected rapidly with a minimum number of field personnel .
- Accurate
- Good for groundwater pollution investigations.

Limitations :

- Cultural Noise

Applications

1. Mineral Exploration
2. Mineral Resource Evaluation
3. Ground water Surveys
4. Mapping Contaminant Plumes
5. Geothermal Resource investigation
6. Contaminated Land Mapping
7. Landfill surveys
8. Detection of Natural and Artificial Cavities
9. Location of geological faults
10. Geological Mapping

Type of EM Systems

- EM can be classified as either :

1. Time – Domain (TEM) or
2. Frequency- Domain (FEM)

- FEM use either one or more frequencies.
- TEM makes measurements as a function of time .
- EM can be either :
  - a- Passive, utilizing natural ground signals (magnetotellurics)
  - b- Active , where an artificial transmitter is used either in the near-field (As in ground conductivity meters) or in the far-field (using remote high-powered military transmitters as in the case of VLF Mapping 15-24 KHZ).

Factors Affecting EM Signal

The signal at the Receiver depends on :

1) the material 2) Shape 3) Depth of the Target

4) Design and positions of the transmitter and receiver coils .

The size of the current induced in the target by the transmitter depends on

1) Number of lines of magnetic field through the Loop (magnetic flux) 2) Rate of change of this number 3) The material of the loop.

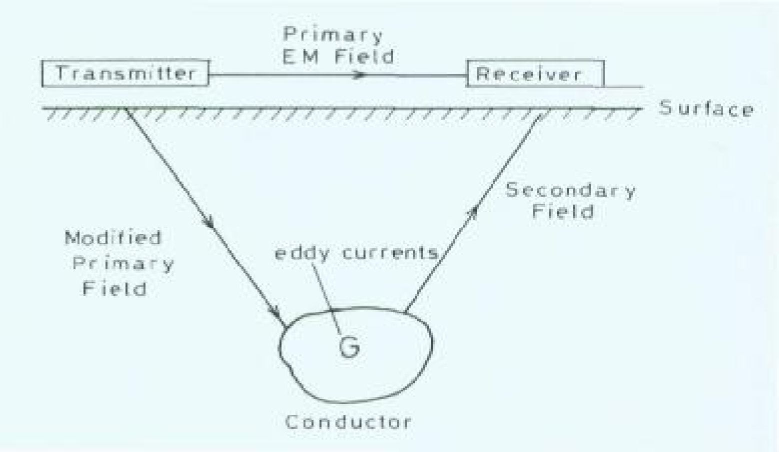
Magnetic flux Depends on :

1) The Strength of the magnetic field at the Loop 2) Area of the Loop 3) Angle of the loop to the field

Flux Ø = Magnetic field X cos Ө X area X number of turns .

Principle of EM surveying

- EM field can be generated by passing an alternating current through either a small coil comprising many turns of wire or a large loop of wire .
- The frequency range of EM radiation is very wide, from < 15 HZ (atmospheric micropulsations) , Through radar bands (10^8 – 10^{11} HZ) up to X-ray and gamma >10^{16} HZ .
- For geophysical Applications less than few thousand hertz, the wavelength of order 15-100 km , typical source- receiver separation is much smaller (4-10 m)



The primary EM field travels from the transmitter coil to the receiver coil via paths both above and below the surface.
In the presence of conducting body, the magnetic component of the EM field penetrating the ground induces alternating currents or eddy currents to flow in the conductor.
The eddy currents generate their own secondary EM field which travels to the receiver. Differences between TX and RX fields reveal the presence of the conductor and provide information on its geometry and electrical properties.

Depth of Penetration of EM

Skin Depth : is the depth at which the amplitude of a plane wave has decreased to 1/e or 37% relative to its initial amplitude $\mathbf{A_o}$.
Amplitude decreasing with depth due to absorption at two frequencies

$$\mathbf{A_z = A_o e^{-1}}$$

The skin depth S in meters $= \sqrt{2 / \omega\sigma\mu} \quad = \quad 503 \sqrt{f\sigma}$

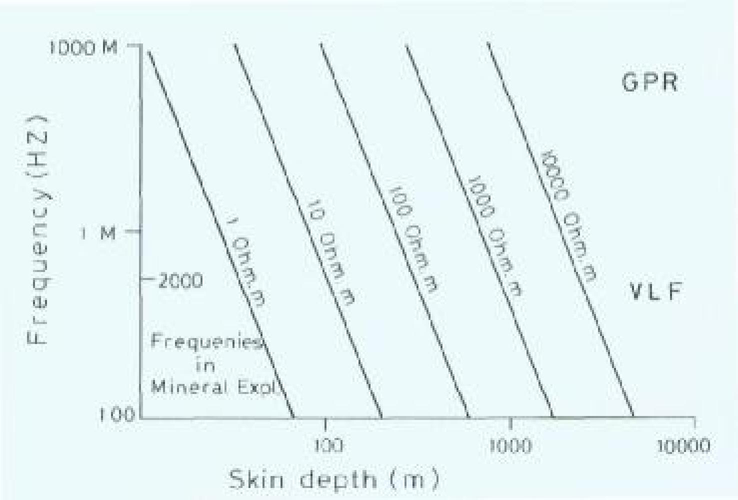
$\omega = 2\pi f \quad = \quad 503 \sqrt{\rho / f} \quad = \quad 503 \sqrt{\rho}\, \lambda / v$

σ : conductivity in s/m

μ : magnetic permeability (usually ≈ 1)

λ : wavelength , f : frequency , v : velocity , p : Resistivity thus, the depth increases as both frequency of EM field and conductivity decrease.

Ex. In dry glacial clays with conductivity $5x\ 10^{-4}\ sm^{-1}$, S is about 225 m at a frequency of 10 KHZ .



Skin depths are shallower for both higher frequencies and higher conductivities (Lower resistivities).

Magnetotelluric Methods (MT)

Telluric methods: Faraday's Law of Induction: changing magnetic fields produce alternating currents. Changes in the Earth's magnetic field produce alternating electric currents just below the Earth's surface called Telluric currents. The lower the frequency of the current, the greater the depth of penetration.
Telluric methods use these natural currents to detect resistivity differences which are then interpreted using procedures similar to resistivity methods.

MT uses measurements of both electric and magnetic components of The Natural Time-Variant Fields generated.
Major advantages of MT is its unique Capability for exploration to very great depths (hundreds of kilometers) as well as in shallow Investigations without using of an artificial power source .
Natural – Source MT uses the frequency range 10^{-3}-10 HZ , while audio – frequency MT (AMT or AFMAG) operates within 10-10^4 HZ .

The main Application of MT in hydrocarbon Expl. and recently in meteoric impact, Environmental and geotechnical Applications.

$$\mathbf{P_a = 0.2 / f \;|E_x / B_y|^2 = 0.2 / f \;|E_x / H_y|^2 = 0.2 / f \;|Z|^2}$$

E_x (nv/km) , B_y , orthogonal electric and magnetic components.
B_y : magnetic flux density in nT .
H_y : magnetizing force (A/m) .
Z : cagniard impedance.

The changing magnetic fields of the Earth and the telluric currents they produce have different amplitudes. The ratio of the amplitudes can be used to determine the apparent resistivity to the greatest depth in the Earth to which energy of that frequency penetrates.

Typical equation:

apparent resistivity = $\frac{1}{5f}\left(\frac{E_x}{H_y}\right)^2$

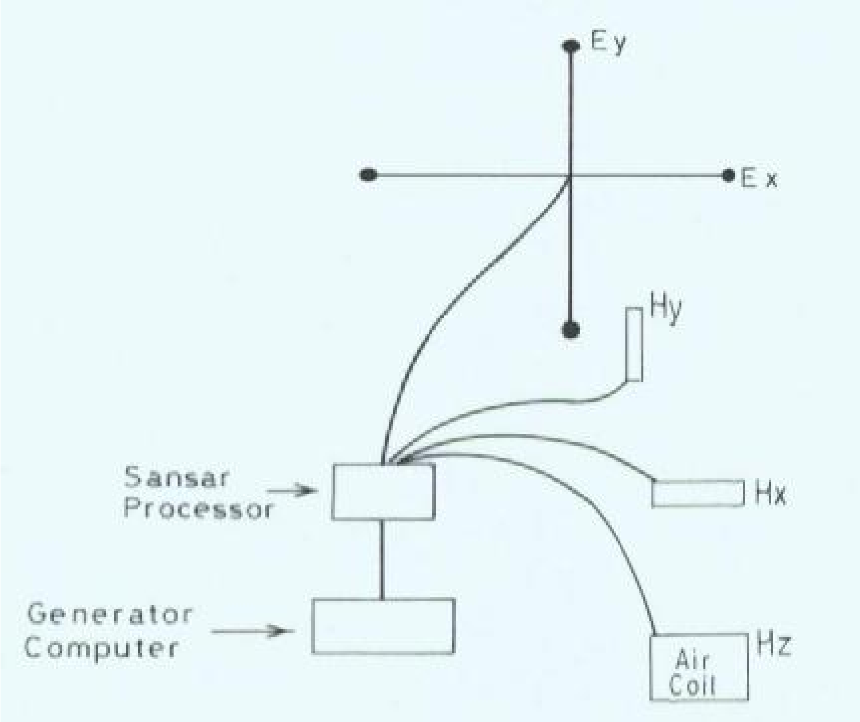
where E_x is the strength of the electric field in the x direction in millivolts
H_y is the strength of the magnetic field in the y direction in gammas
f is the frequency of the currents

Depth of penetration = $\frac{1}{2\pi}\sqrt{\frac{5\ (\text{apparent resistivity})}{f}}$

This methods is commonly used in determining the thickness of sedimentary basins. Depths are in kilometers

Field Procedure

MT Comprises two orthogonal electric dipoles to measure the two horizontal electric components and two magnetic sensors parallel to the electric dipoles to measure the corresponding magnetic components .



1. Two orthogonal grounded dipoles to measure electric components

2. Three orthogonal magnetic sensors to measure magnetic components.

Thus, at each location, five parameters are measured simultaneously as a function of frequency. By measuring the changes in magnetic (H) and electric (E) fields over a range of frequencies an apparent resistivity curve can be produced. The lower the frequency, the grater is the depth penetration.

Survey Design

EM data can be acquired in two configurations

1) Rectangular grid pattern
2) Along a traverse or profile .

EM equipment Operates in frequency domain. It allows measurement of both the .

1) in-phase (or real) component .
2) 90^0 out – of – phase (or quadrature) component.

Very Low Frequency (VLF) Method

VLF : uses navigation signal as Transmitter .
Measures tilt & phase

Main field is horizontal .

VLF detects electrical conductors by utilizing radio signal in the 15 to 30 KHZ range that are used for military communications.
VLF is useful for detecting long, straight electrical conductors
VLF compares the magnetic field of the primary signal (Transmitted) to that of the secondary signal (induced current flow with in the subsurface electrical conductor).

Advantages of VLF

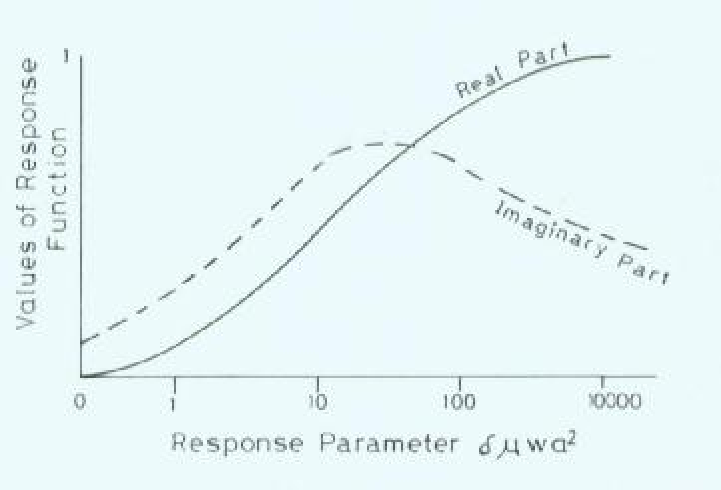
1) Very effective for locating zones of high electrical conductivity
2) fast
3) inexpensive
4) Requires one or two people .

Tilt Angle Method

Tilt angle systems have no reference link between Tx and Rx coils . Rx measures the total field irrespective of phase and the receiver coil tilted to direction of maximum or minimum magnetic field strength .

The response parameter of a conductor is defined are the product of conductivity – thickness (T) , permeability (μ) an angular frequency
$\omega = 2\pi f$ and the square of the target a^2 .

Poor conductors have response parameter < 1
Excellent conductor have response parameter greater than 1000



A Good conductor having a higher ratio A_R / A_i
A_R : Amplitude of Read (in – phase)
A_i : Amplitude of imaginary (out – of phase)

In the left side of the above figure and poor conductor having a lower ratio of A_R/ A_i .

Slingram System

- slingram is limited in the size of TX coil. This system has the Transmitter and Receiver connected by a cable and their separation kept constant as they are moved together along a traverse.

Magnetic field Through The receiver has two sources :

a) The primary field of The Transmitter .
b) The secondary field produced by The Target .

Turam system

More powerful system than Slingram. It uses a very large stationary Transmitter coil or wire laid out on the ground, and only The receiver is moved . TX 1-2 km long, loop over 10 km long. The receiver consists of two coils and kept a fixed distance between 10-50 m apart.

Ground Surveys of EM

A. Amplitude measurement

1- Long wire

- Receiver pick up horizontal component of field parallel to wire .
- Distortions of Normal field pattern are related to changes in subsurface conductivity.

B. Dip-Angle

Measures combined effect of primary and secondary fields at the receiver.

AFMAG : Dip-angle method that uses Naturally occurring ELF signals generated by Thunder storms.

Phase Component Methods

1) Work by comparing secondary & primary fields .
2) Compensator & Turam (long wire) .
3) Slingram Moving Trans / receiver

- Penetration ≈ ½ spacing of coil .
- Coil spacing critical .

- Over barren ground Null is at zero coil dip-Angle.
- Near conductor, dip angle $\neq 0$
- Dip – Angle is zero over Narrow conductor, and changes sign.

Dip-Angle method

1) easy , cheap

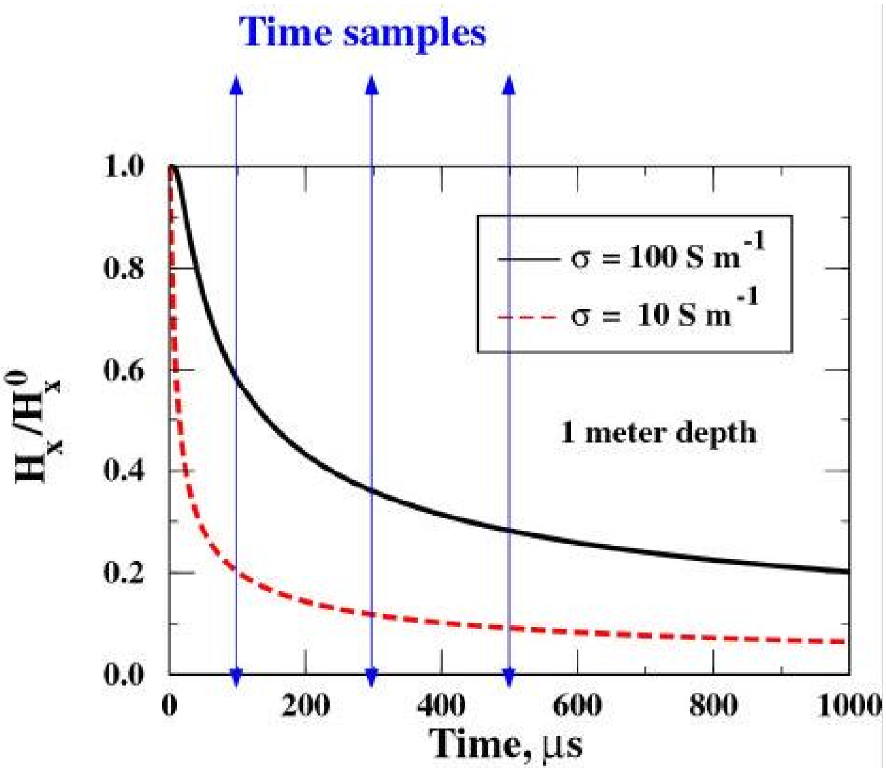
2) Quick
3) Sensitive to vertical
4) Difficult to distinguish between depth & conductivity

TDEM Method

A significant problem with many EM surveying techniques is that a small secondary field must be measured in the presence of a much larger primary field, with a consequent decrease in accuracy. This is circumvented to some extent in the FDEM method described about by measuring the out-of-phase component.

In a TDEM approach, the signal is not a continuous frequency but instead consists by a series of step-like pulses separated by periods where there is no signal generated, but the decay of the secondary field from the ground is measured. The induction

currents induced in a subsurface conductor diffuse outward when the inducing energy is suddenly switched off. The measurement of the field at a number of time steps is equivalent of measuring at several frequencies in an FDEM system. Usually two-coil systems are used and the results can be stacked to reduce noise. Modeling of the decay for layered systems, and more complicated conductivity geometry, can be carried out.



The figure above shows the behavior of the field for two different conductivities. If samples at different times were taken, then on could distinguish between the two conductivities. This is the principle of Time Domain Electromagnetic (TDEM) methods.

$\tau = \sigma \mu L^2 = \sigma \mu A$
where τ is a characteristic time constant and L and A correspond to a characteristic length scale and characteristic area, respectively.

The EM61 has a single time sample at $t \approx 0.5$ ms. Using a cylinder of radius 2 cm and a conductivity of steel of 10^7 S m^{-1}, then $\exp(-t/\tau) = 0.56$. where t is time constant.
On the other hand, assume a plastic drum of seawater of conductivity 10 S m^{-1} and radius 40 cm, then we obtain $\exp(-t/\tau) = 0$.

Airborne Electromagnetic Surveys

The general objective of **AEM** (Airborne ElectroMagnetic) surveys is to conduct a rapid and relatively low-cost search for metallic conductors, e.g. massive sulphides, located in bed-rock and often under a cover of overburden and/or fresh water. This method can be applied in most geological environments except where the country rock is highly conductive or where overburden is both thick and conductive. It is equally well suited and applied to general geologic mapping, as well as to a variety of engineering problems (e.g., fresh water exploration.) Semi-arid areas, particularly with internal drainage, are usually poor AEM environments.

Conductivities of geological materials range over seven orders of magnitude, with the strongest EM responses coming from massive sulphides, followed in decreasing order of intensity by graphite, unconsolidated sediments (clay, tills, and gravel/sand), and igneous and metamorphic rocks. Consolidated sedimentary rocks can range in conductivity from the level of graphite (e.g. shales) down to less than the most resistive igneous materials (e.g. dolomites and limestones). Fresh water is highly resistive. However, when contaminated by decay material, such lake bottom sediments, swamps, etc., it may display conductivity roughly equivalent to clay and salt water to graphite and sulphides.

Typically, graphite, pyrite and or pyrrhotite are responsible for the observed bedrock AEM responses. The following examples suggest possible target types and we have indicate the grade of the AEM response that can be expected from these targets.

- Massive volcano-sedimentary stratabound sulphide ores of Cu, Pb, Zn, (and precious metals), usually with pyrite and/or pyrrhotite. Fair to good AEM targets accounting for the majority of AEM surveys.
- Carbonate-hosted Pb-Zn, often with marcasite, pyrite, or pyrrhotite, and sometimes associated with graphitic horizons. Fair to poor AEM targets.
- Massive pyrrhotite-pentlandite bodies containing Ni and sometimes Cu and precious metals associated with noritic or other mafic/ultramafic intrusive rocks. Fair to good AEM targets.
- Vein deposits of Ag, often with Sb, Cu, Co, Ni, and pyrite in volcanic and sedimentary rocks. Generally poor AEM targets.
- Quartz veins containing Au with pyrite, sometimes also with Sb, Ag, Bi, etc., in volcanic or sedimentary (and possibly intrusive) rocks. Poor AEM targets.

Basic Principles of Airborne

Electromagnetic-induction prospecting methods, both airborne and (most) ground techniques, make use of man-made primary electromagnetic fields in, roughly, the following way: An alternating magnetic field is established by passing a current through a coil, (or along a long wire). The field is measured with a receiver consisting of a sensitive electronic amplifier and meter or potentiometer bridge. The frequency of the alternating current is chosen such that an insignificant eddy-current field is induced in the ground if it has an average electrical conductivity,

If the source and receiver are brought near a more conductive zone, stronger eddy currents may be caused to circulate within it and an appreciable secondary magnetic field will thereby be created. Close to the conductor, this secondary or anomalous field may be compared in magnitude to the primary or normal field (which prevails in the absence of conductors), in which case it can be detected by the receiver. The secondary field strength, Hs, is usually measured as a proportion of the primary field strength, Hp, at the receiver in percent or ppm (parts per million).

Anomaly = Hs / Hp.

Increasing the primary field strength increases the secondary field strength proportionally but the "anomaly" measured in ppm or percent remains the same.
prospecting for anomalous zones is carried out by systematically traversing the ground either with the receiver alone or with the source and receiver in combination, depending on the system in use. In the case of airborne systems, the receiver coils are usually in a towed bird and the transmitter may be a large coil encircling a fixed wing aircraft, e.g. INPUT systems, or one or more small coils in the same bird that houses the transmitting coils, e.g. most HEM (Helicopter EM) systems.
There are two different basic systems commonly used to generate and receive the electromagnetic field: transient or "time domain" systems like INPUT,GEOTEM and MEGATEM and a/c. "frequency domain" systems like most HEM systems.

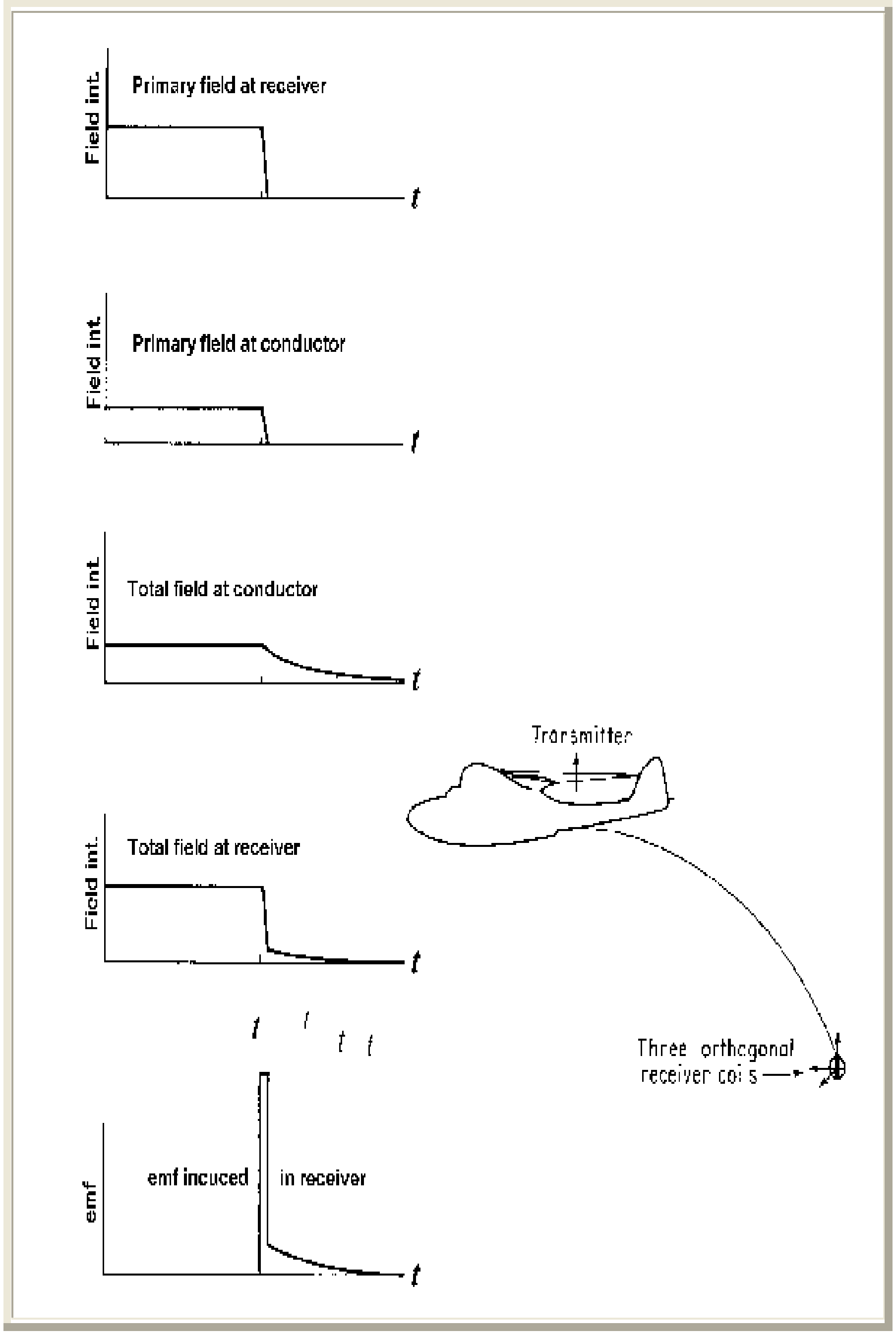
Transient Airborne Electromagnetics

Historically, the most commonly encountered system of this type was the INPUT system. The newer systems GEOTEM and MEGATEM (Fugro Airborne Surveys) function in a similar way to INPUT

In the INPUT system the transmitting coil, usually encircling a fixed wing aircraft, is energized by what is, essentially, a step current. In the absence of conductors, a sharp transient pulse proportional to the time derivative of the magnetic field is induced in the receiver. When a conductor is present, however, a sudden change in magnetic field intensity will induce in it a flow of current in the conductor which will tend to slow the decay of the field.

The receiver "listens" only while the transmitter is "quiet" so that problems arising out of relative motion between transmitter and receiver, because the receiver is towed in a bird behind the aircraft, are virtually eliminated. Moreover, if the entire decay of the secondary field could be observed, the response would be equivalent to AC measurements made over the whole of the frequency spectrum. It is important to note in this connection, however, that not the decay function itself but only its time derivative can be recorded if a coil is used as the detector. This means that the anomalous fields which decay very slowly are suppressed in amplitude more than the others, and since these are the very ones generally associated with good conductors, there would seem to be an inherent weakness in this system. Because it is difficult to precisely synchronize the instant when the transmitter becomes "quiet" with the instant that the receiver begins to "listen", it is nearly impossible to record the entire function. This is equivalent to being unable to record many of the lower frequencies in the a-c spectrum.

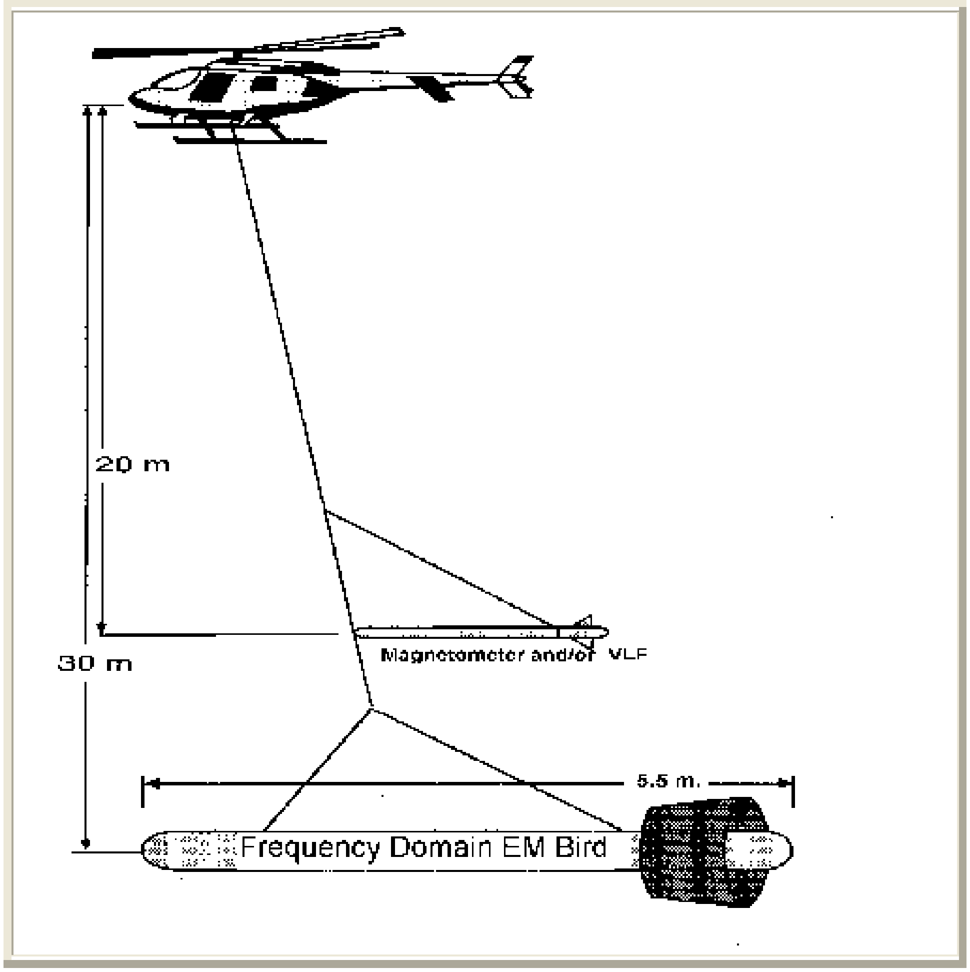
Typically, the time derivative of the decay function is measured using from six to twelve different time delays from the instant that transmitter stops transmitting before recording the signal received.



A sketch of the INPUT transient airborne EM system operation. The primary field is a step function and the receiver records the decay of the field after the transmitter stops transmitting. (Grant and West 1965)

Frequency Domain Airborne Electromagnetics

In the typical frequency domain helicopter EM system (HEM) both the transmitting coil set and the receiver coil set are housed in a rigid boom or "bird" that is towed beneath the helicopter. Commonly, this boom is from three to five meters long and contains from two to six coil pairs. Usually, half of the coils in each of the transmitter set and the receiver set are "co-axial", i.e. an axis normal to the plane of the coils passes through the centre of both coils. The second half of the coil sets are normally "co-planar", being equivalent to both the transmitting and receiving coil lying flat on the ground. Other coplanar orientations have been used occasionally.



The receiver measures the in-phase and out-of-phase, or quadrature, of the secondary field, expressed in ppm of the primary field. The two different coil orientations provide data that is useful in discriminating between dike like conductors that have considerable vertical extent and may be ore bodies, and horizontal sheet like conductors that are simply conductive overburden.

Factors Affecting Detectability

1. Signal-to-noise ratio:

In practice, because of "system noise" (Ns) and "geological noise" (Ng), the ability of a system to recognize and measure an anomaly is limited by the "signal-to-noise" ratio: **Signal-to-noise = Hs / (Ns + Ng)**
Because Hs and Ng are proportional to the primary field strength Hp, and Ns, in frequency-domain systems, usually contains elements proportional to Hp, there is little to be gained by increasing the primary field power. In time domain systems Ns is not greatly affected by Hp, so extra power does result in increased signal-to-noise. Attempts to increase the signal-to-noise are sometimes made by increasing the distance between the transmitter and receiver. This results in roughly the same Hs and Ng but often a lower system noise Ns.

2. Penetration

The penetration of an AEM system is its effective depth of exploration. Commonly, this is taken to include the elevation of the system above ground, as this is also affected by local environment and flying conditions.
In general, systems with large transmitter-receiver coil separation, usually referred to as Tx-Rx, have greater penetration than those with small separations. Penetration is closely related to signal-to-noise, as the system that produces a larger anomaly from a given conductor can, of course, look further into the ground.

3. Discrimination

The discrimination of an AEM system is the ability of the system to differentiate between conductors of different physical properties or geometric shapes. Discrimination, particularly between flat lying surficial conductors and steeply dipping conductors, is vitally important. Good discrimination can be achieved in HEM systems by using several frequencies and both co-axial and co-planar coil pairs.

4. Resolution

Resolution refers to the ability of an AEM system to recognize and separate the interfering effects of nearby conductors. A system that does this well also produces sharp anomalies over isolated or discrete conductors. Resolution generally increases with decreasing flight elevation and coil separation. Typically the HEM systems have better resolution than the fixed wing time domain systems.

Typical Electrical Properties of Earth Materials.

Rock, Mineral, etc.	Conductivity	Resistivity (ohm-

	(mohs/meter)	**meters)**
Bornite	330	3 x 10^{-3}
Chalcocite	10^{4}	10^{-4}
Chalcopyrite	250	4 x 10^{-3}
Galena	500	2 x 10^{-3}
Graphite	10^{3}	10^{-3}
Marcasite	20	5 x 10^{-2}
Magnetite	17 x 10^{-4} - 2 x 10^{4}	5 x 10^{-5} - 6 x 10^{-3}
Pyrite	3	0.3
Phrrhotite	10^{4}	10^{-4}
Sphalerite	10^{-2}	10^{2}
Igneous and Metamorphic Rocks	10^{-7} - 10^{-2}	100 - 10^{7}
Sediments	10^{-5} - 5 x 10^{-2}	20 - 10^{5}
Soils	10^{-3} - 0.5	2 - 10^{3}
Fresh Water	5 x 10^{-3} - 0.1	10 - 200
Saline Overburden	0.1 - 5	0.2 - 1
Salt Water	5 - 20	0.05 - 2
Sulphide Ores	10^{-2} - 10	0.1 - 100
Granite Beds and Slates	10^{-2} - 1	1 - 100
Altered Ultramafics	10^{-3} - 0.8	1.25 - 10^{3}
Water-filled faults/shears	10^{-3} - 1	1 - 10^{3}