A.A. 2021-2022

Corso di Laurea Magistrale in GEOSCIENZE

Metodi Elettromagnetici in Geofisica (6 CFU)
- MEMAG -

UD-3: LOW FREQUENCY EM

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We already sow that...

$$\nabla \times \nabla \times \boldsymbol{E} + \mu\sigma \frac{\partial \boldsymbol{E}}{\partial t} + \mu\varepsilon \frac{\partial^2 \boldsymbol{E}}{\partial t^2} = 0$$

A **B** **C**

We already pointed out the physical meaning of different terms in the ABC equation (as well as of its corresponding one related to the magnetic field).
When the fields are sinusoidal in time, it reduces into:

$$\nabla \times \nabla \times \mathbf{E} - i\omega\mu\sigma\mathbf{E} - \cancel{\omega^2 \varepsilon\mu\mathbf{E}} = 0$$

For LOW FREQUENCY ($f<10^5$Hz) ➔ $\omega^2\varepsilon\mu << \omega\mu\sigma$ so:

$$\nabla^2 \boldsymbol{E} \cong \mu\sigma \frac{\partial \boldsymbol{E}}{\partial t}$$

Conduction currents dominate ➔ INDUCTION REGIME

A **B**

Therefore, we exploit the possibility to INDUCE EM fields into the ground without needs to be in direct contact with the ground itself.

Low frequency EM methods: history and peculiarities

The use of electrodes fixed into the ground makes the RESISTIVITY METHODS high time demanding thus making practically impossible to investigate large areas with high spatial density. Moreover, when high resistive materials are at the surface, can be very difficult to inject electrical currents intro the subsurface (e.g. within ice or in dry desert sands).

The LOW frequency EM methods have been implemented at first for mineral exploration in the early '30s but have been widely applied starting since the '70s.

- No need of "electrodes"
- Higher spatial data density (in a shorter time)
- Highly cost effective

However:
- Less vertical resolution as compared to electrical (galvanic) techniques
- Higher sensitive to environmental noise (in general lower S/N)

The basic physics was already described but there are different categories of instrument implemented. We will focus on two of them (both active):

FREQUENCY DOMAIN EM

TIME DOMAIN EM

Low frequency EM methods: frequency range

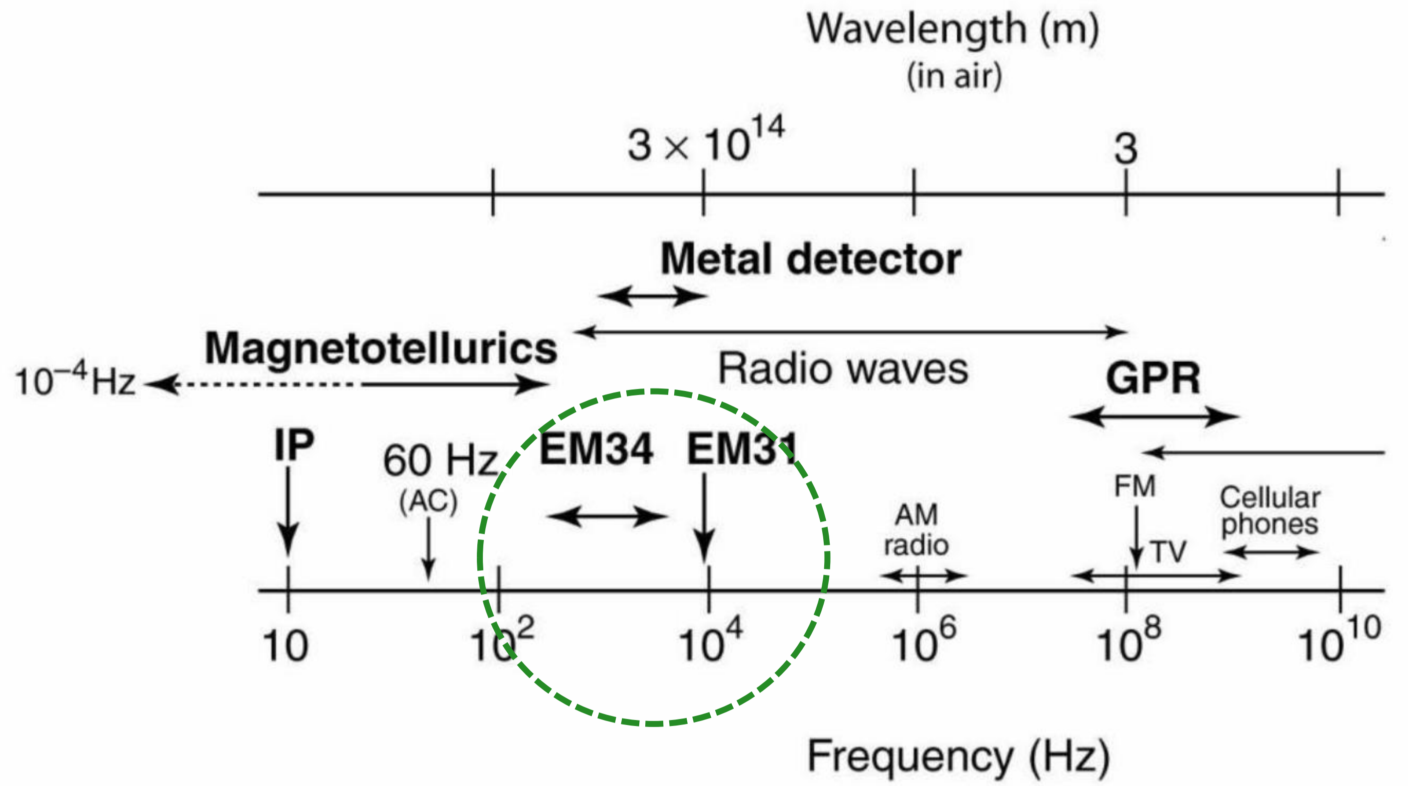


FIGURE 8.1 left

Introduction to Applied Geophysics

Low frequency EM methods: basic principles

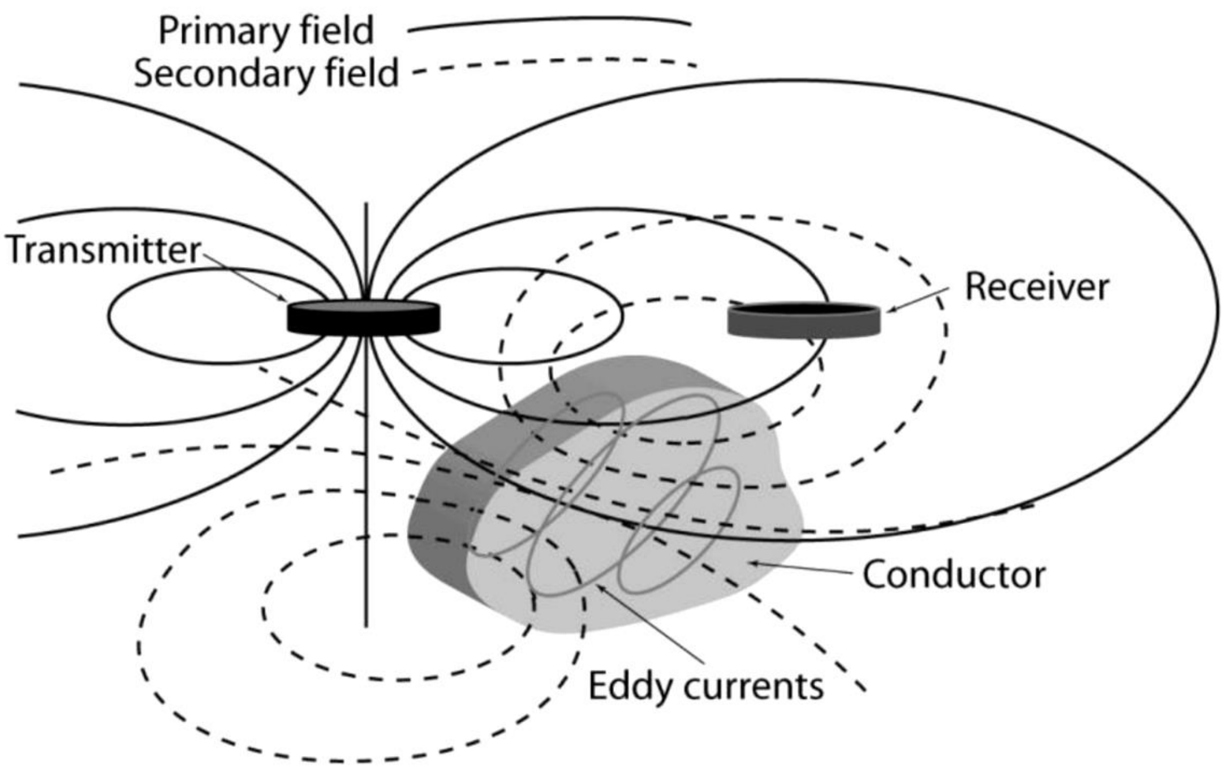


FIGURE 8.5g

Introduction to Applied Geophysics

The receiver measures the “combination” of primary and secondary fields, both producing an INDUCED e.m.f.

Low frequency EM methods: basic principles

The basic general principle is the following:

1) An electric current flows within a (source) coil
2) It generates a magnetic primary field (Ampere's law)
3) This in turn generates a corresponding electric field (Faraday's law)
4) The current changes due to encountered electric resistance (Ohm's law)
5) Eddy currents are so produced and a **secondary magnetic field** is recorded together with the primary one by a (receiving) coil
6) Primary field is separated (or canceled out) ➔ from the characteristics of the secondary field subsurface electromagnetic properties are inferred.

Low frequency EM methods: basic principles

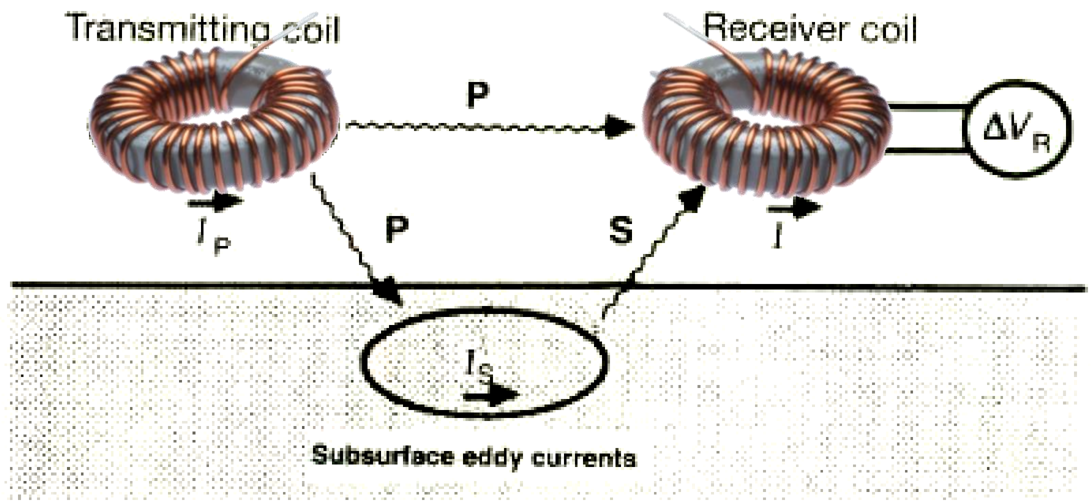
Interaction between EM field and the ground can be considered as an interaction between 3 separated components, namely:

1) A transmitting coil which induces a current into the ground

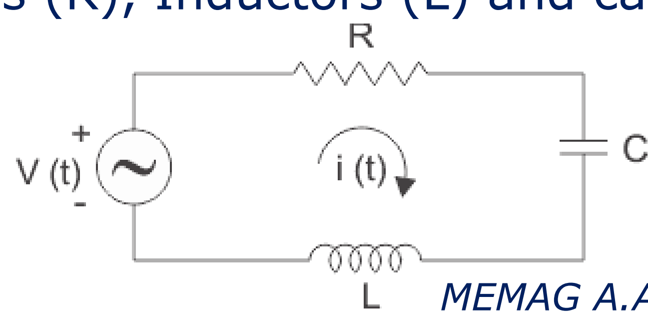
2) The ground acting as a "virtual coil"

3) A receiving coil

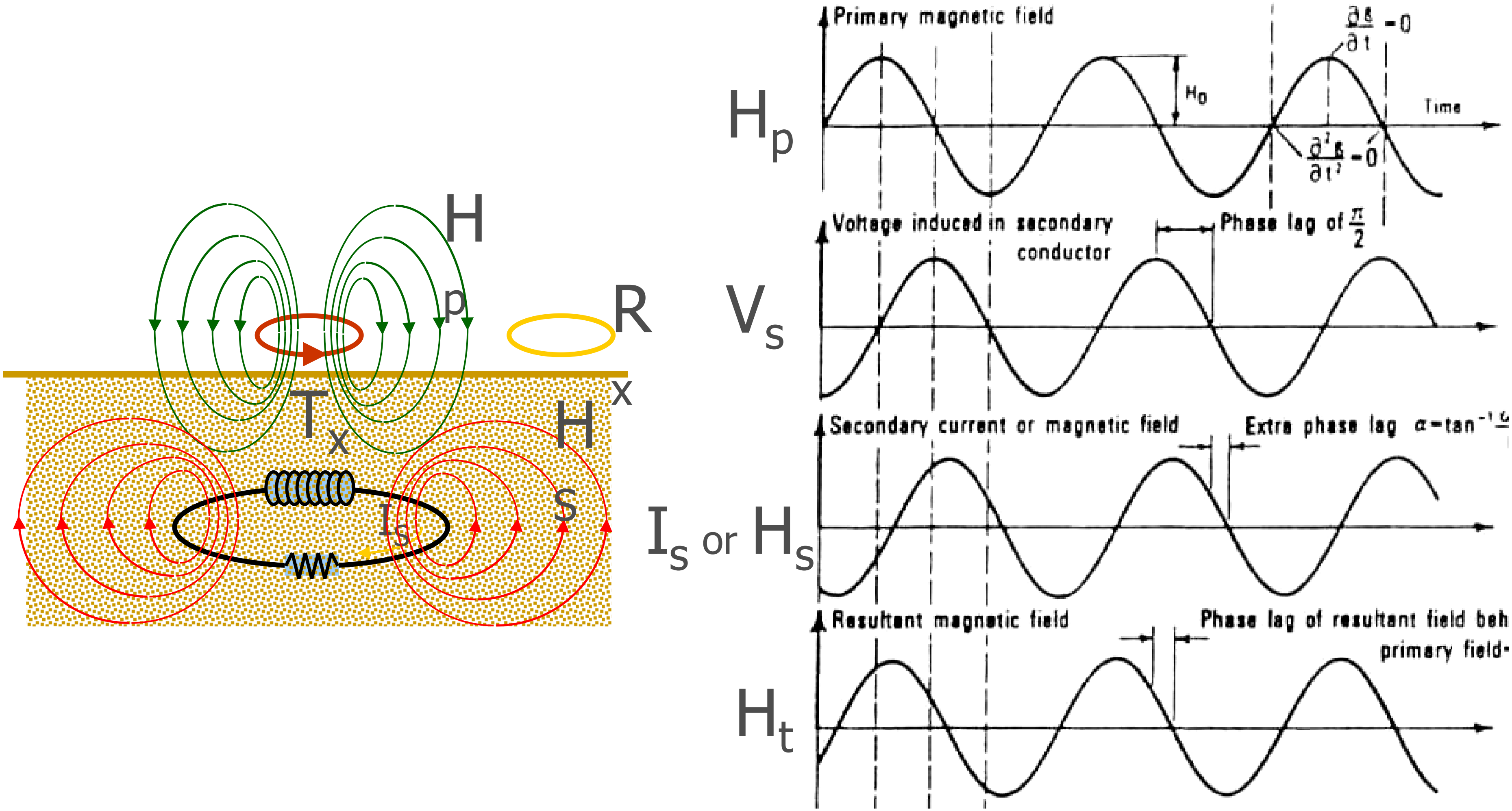
The measure of the intensity and characteristics of the induced field can give information about the subsurface ➔ GEOPHYSICAL PARAMETERS



The subsoil from the electrical point of viewcan be considered equivalent to an RLC circuit containing only Resistors (R), Inductors (L) and capacitors (C).



Low frequency EM methods: basic principles

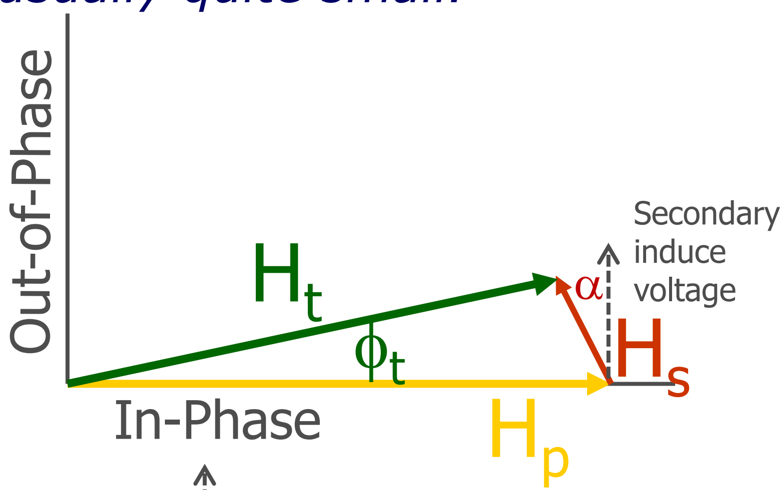


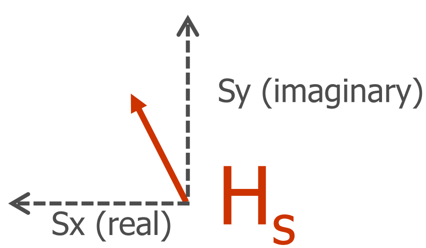
Instead to the "total components" we would like to measure only the components linked to the secondary induced effects, which give information about the ground.

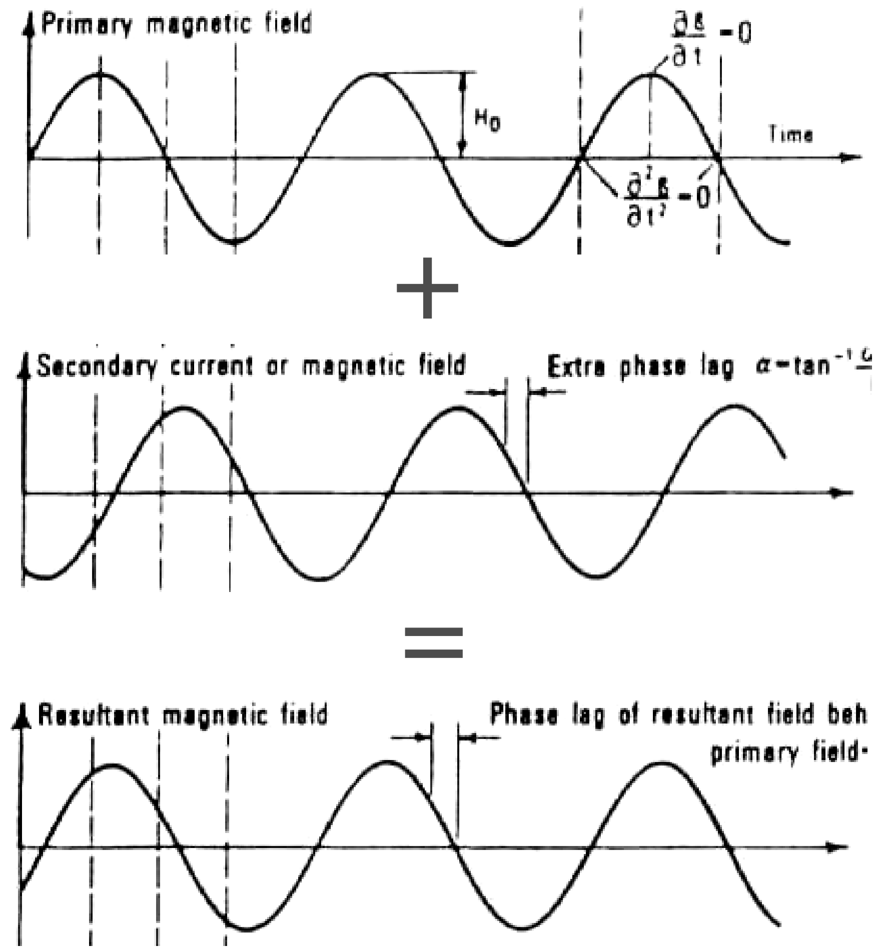
Low frequency EM methods: basic principles

For normal applications the strength of the primary field is several orders of magnitude higher than the induced one.

Moreover, the largest part of the phase change is due to the primary induction ($\pi/2$) while the one related to the induced currents is usually quite small.





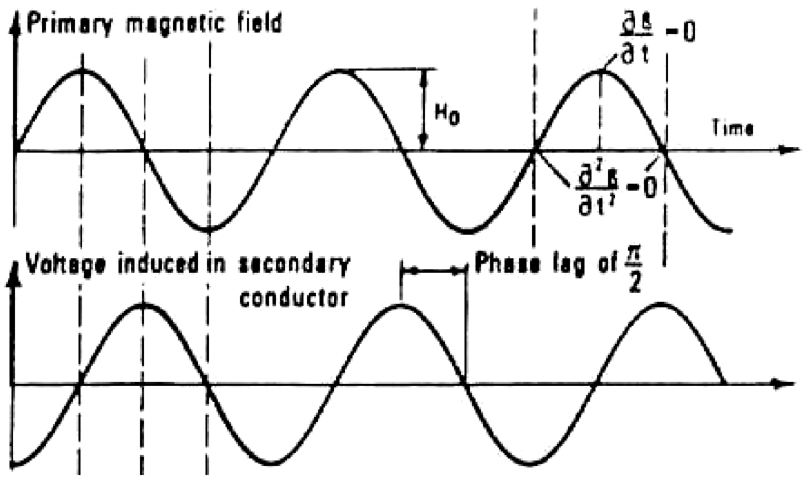


When H_p is known and by measuring H_t it is possible to calculate Hs and splitting it in real and imaginary components

Low frequency EM methods FDEM

In the FREQUENCY DOMAIN INSTRUMENTS (FDEM) the transmitted current varies sinusoidally with time at a fixed frequency.

The current measured at the receiving coil is the vector summation of the primary and secondary "eddy" currents (due to the variation of the induced EM field). The primary field produced by the transmitting coil propagates also through air: this latter component does not give any information about the subsurface.
The "out of phase" (i.e. Quadrature) component is proportional to the phase lag between transmitted and received currents angle ➔ it is proportional to σ (global) of the ground between the two coils.



They are also referred as "Continuous Wave" methods because the transmitting coil produces a continuously (sinusoidally) variable field while the measurements are taken.

Low frequency EM methods FDEM

The electric current induced into the ground for $V = V_0 sen\,\omega t$ is equal to:

$$I = \frac{V_0 sen\,(\omega t + \alpha)\omega t}{\sqrt{R^2 + (\omega L - 1/\omega C)^2}}$$

REAL — In-phase
IMAGINARY — Out-of-phase (Quadrature)

Therefore there is a phase lag between the applied (inducing) voltage and the resulting electric current:

$$\alpha = tan^{-1}\left(\frac{\omega L - 1/\omega C}{R}\right)$$

The phase angle describes the characteristics of the subsurface

Notice that while α is small for resistors (i.e. close to 0°)
It becomes larger for conductors (i.e. it approximates 90°)

➔ The method is suitable for the detection of conductors, while dielectrics cannot usually be distinguished!

Low frequency EM methods FDEM

The maximum exploration depth is a function of both the coils distance (10=m-101m), the frequency(ies) of the inductive field, of the coils geometry.

Strumento	Frequenza	Distanza tra le spire
EM31	9800 Hz	3.7 m
EM34-3	6400,1600,400	7.5,15,30 m
EM38	13200 Hz	1 m

Instruments with a fixed frequency and a fixed coil offset will measure just a single cumulative value.

GEOMETRIC VARIATION

By increasing the coil distance it is possible to increase the investigation depth by enlarging the portion reached by the induced currents

PARAMETRIC VARIATION

By decreasing the frequency of the inducing field it is possible to increase the investigation depth.

CMD Explorer

There are instruments with more than two coils that can be activated and which can operate with different frequencies ➔ several almost simultaneously measures can be collected reaching different investigation depths.

Low frequency EM methods FDEM

Different parameters can be actually measured:

1) Amplitude and phase of the induced field
2) In-phase and out-of-phase components
3) Electrical conductivity (only derived for coaxial and coplanar equipments with the distance between the coils is larger (at least 4-5 times) their diameters.

$$\sigma = \frac{1}{\rho} \cong \left(\frac{H_s}{H_P}\right)\frac{4}{\mu\omega r^2}$$

The investigation depth is an inverse function with the used frequency and the conductivity of the investigated media.

At the typical frequencies ($<10^5$Hz) attenuation effects are negligible, while signal losses occur by DIFFUSION.

The *Skin depth (δ)* is defines as *the depth at which the amplitude of a plane EM radiation has decrease to 1/e (≅37%) relative to its initial amplitude A_0*:

$$A_z = A_0 e^{-1} \qquad\qquad \delta = \sqrt{\frac{2}{\mu\omega\sigma}} \cong \frac{503}{\sqrt{f\sigma}}$$

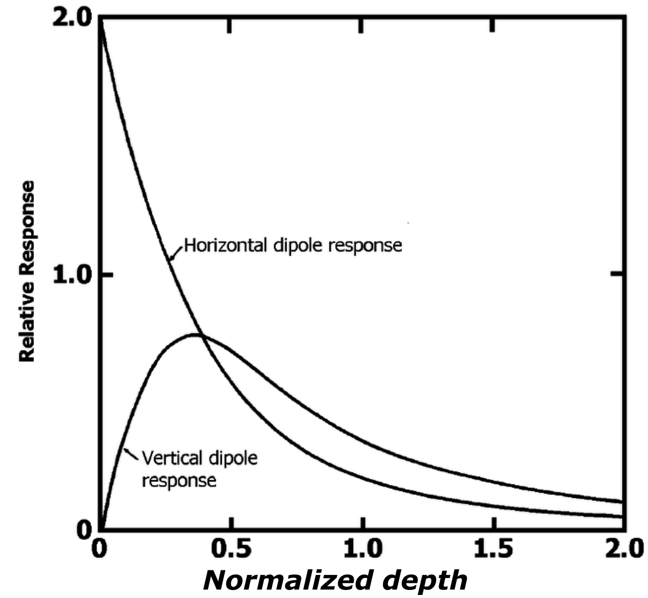
An approximated and realistic value for the investigation depth is equal to about $\delta/5$.

Low frequency EM methods FDEM

The investigation depth can also be modified by changing the orientation of the coils.

1) *Horizontal coils produce vertical magnetic dipole (**VMD**)*
2) *Vertical coils produce horizontal magnetic dipole (**HMD**)*

Reynolds, 1997



It is possible to calculate the contributions of all the materials within a depth z ➔ Cumulative Response Function R(z), different for the two configurations

In a 2-layer model:

$\sigma_a = \sigma_1(1-R)$ *being* $R \Rightarrow z = d/s$ *(d= actual depth; s= inter-coil separation*

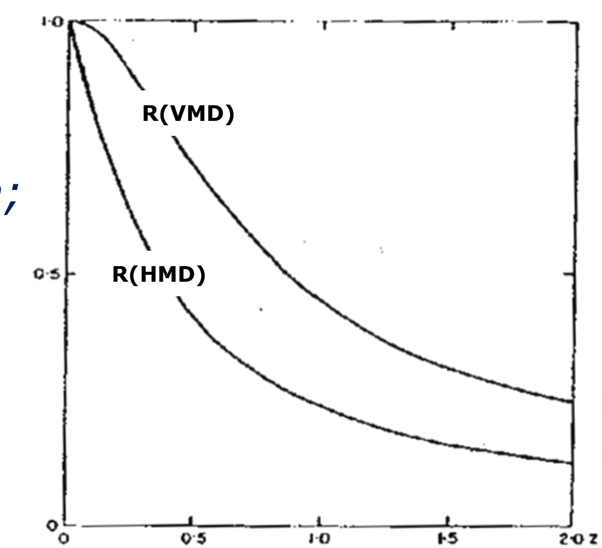
$\sigma_a = \sigma_2 R$

The total contribution to the apparent conductivity is:

$$\sigma_a = \sigma_1(1-R) + \sigma_2 R$$

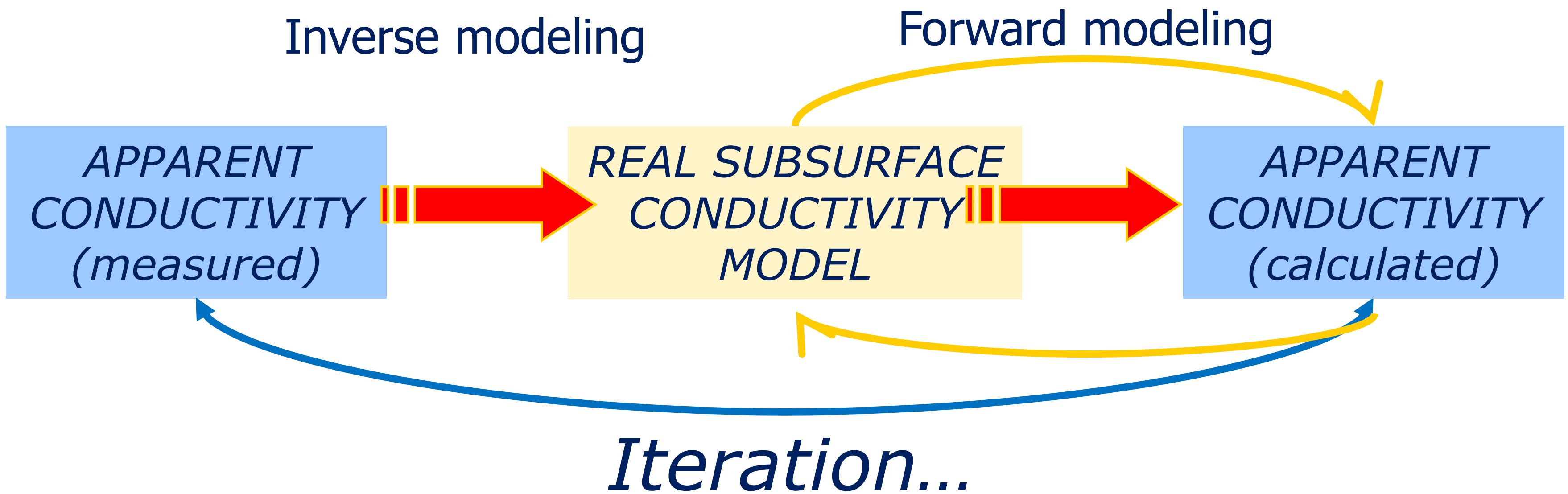
In a 3-layer model:

$$\sigma_a = \sigma_1(1-R_1) + \sigma_2(R_1 - R_2) + \sigma_3 R_2$$



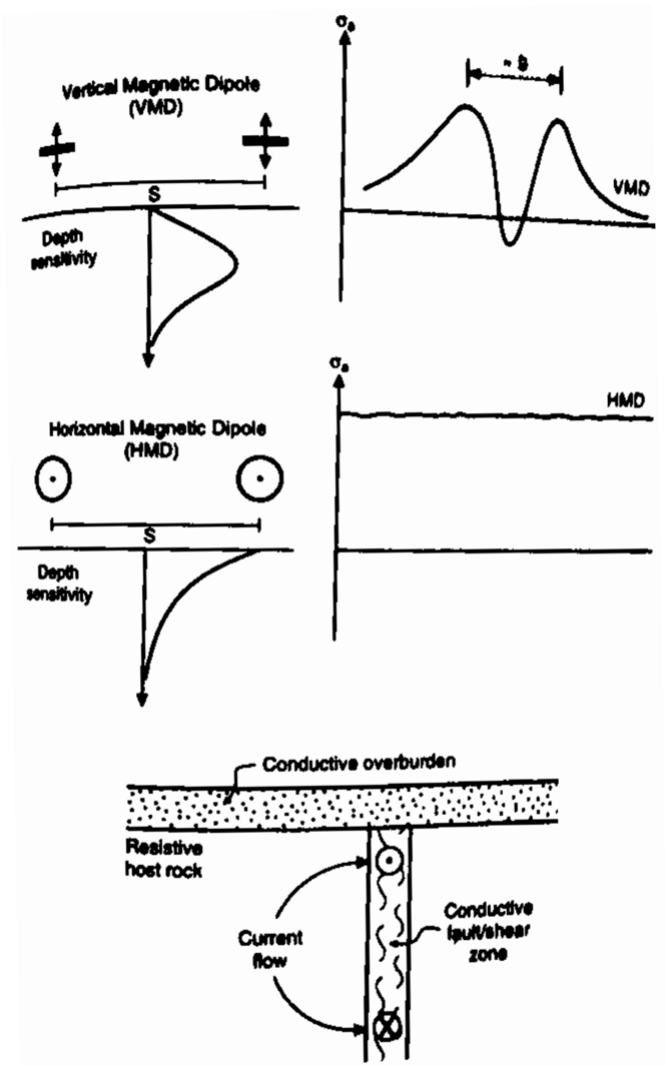
Low frequency EM methods FDEM

The previous analytical process can be generalized and iterated in order to solve the typical inverse problem:
from the cumulative apparent conductivity derive the local real conductivity distribution.



https://em.geosci.xyz/content/geophysical_surveys/airborne_fdem/interpretation.html

Low frequency EM methods FDEM



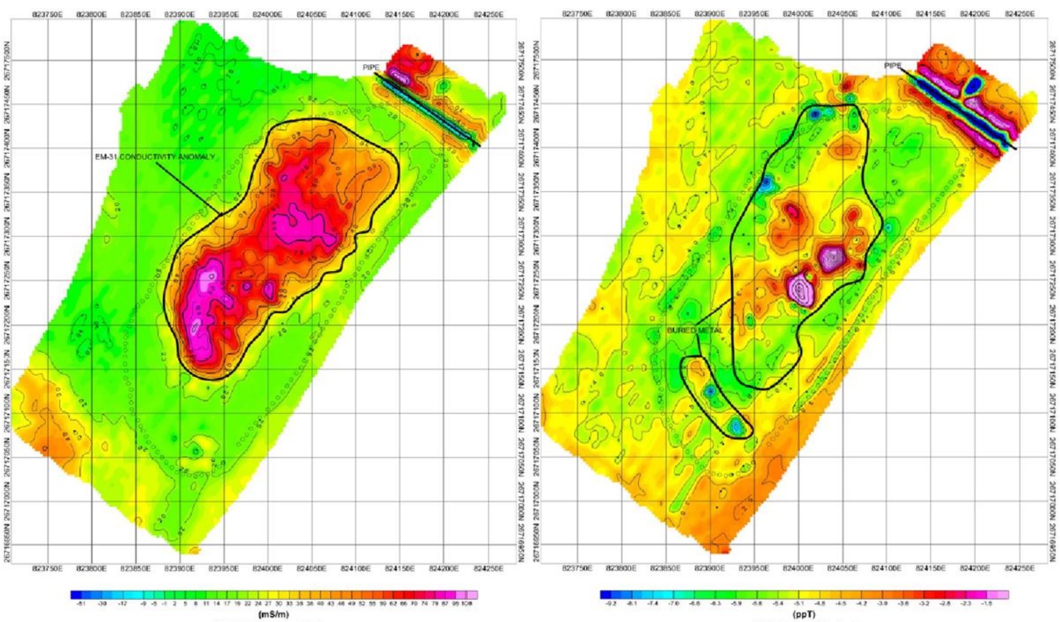
Reynolds, 1997

When two separated coils are used, a single target produces a complex shape of the anomaly, with two positive and one negative peak in between.
The separation between the two positive peaks is (when properly sampled) similar to the coils separation ➔ the target is at the midpoint.

The shape of the anomaly varies depending upon which dipole orientation is used!

Low frequency EM methods FDEM: Pros and Cons

1) No need to be in contact with the ground (induction) ➔ time and cost effective
2) Fast sampling rate due to the rapid induction mechanism (10^0ms-10^1ms)
3) Can be tailored to different surveys by adapting the offset between the coils, the applied frequency(ies) and the coils orientation (VMD or HMD)
4) Very effective for conductive structure but low sensitivity for dielectrics
5) Not very precise as far as the shape of the anomaly and its link with the shape of the target ➔ data difficult to be inverted
6) Complementary to ERT and IP technique
7) Only shallow investigations are possible (max 10^1m)
8) Overall quite low vertical and lateral resolution

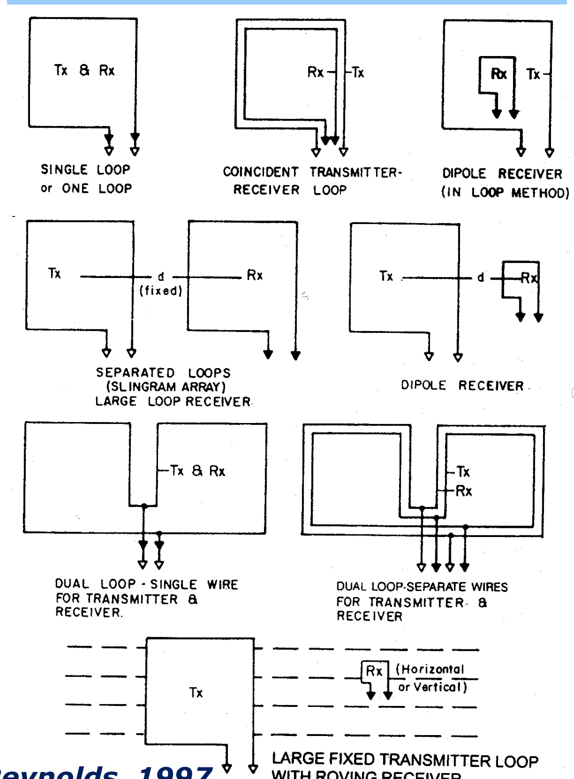


Frequency-domain EM color-contour maps of conductivity (left) and in-phase component (right). This survey was conducted over an abandoned landfill to map the extent of the clay liner beneath, which is revealed by the red area on the conductivity map, and to locate metallic fill concentrations. A large metallic pipe is evident in the upper right corner of the map. (Zonge international).

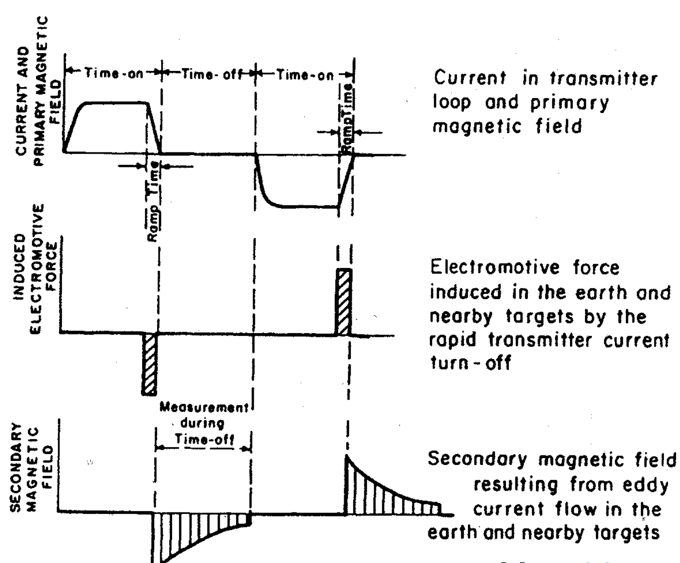
Low frequency EM methods TDEM

In the TIME DOMANI INSTRUMENTS (TDEM) the primary field is applied and STOPPED (the techniques is in fact a.k.a. Pulse Transient). After that the secondary (induced) field is measured at specific time intervals. The decay of the eddy currents with time is related to the physical properties of the ground.
One or more loops can be used with different possible geometrical and operative schemes.

TDEM configurations



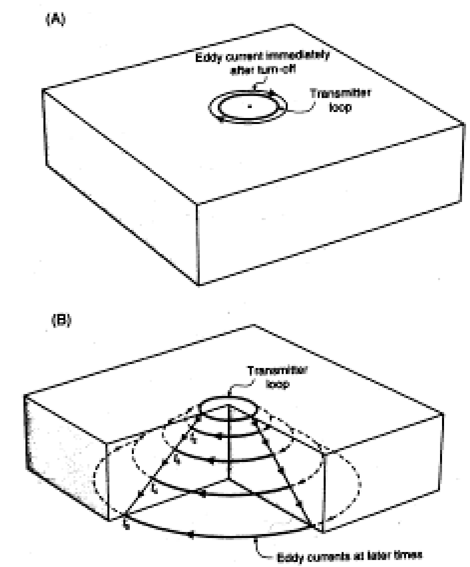
Reynolds, 1997



Reynolds, 1997

Physical basis

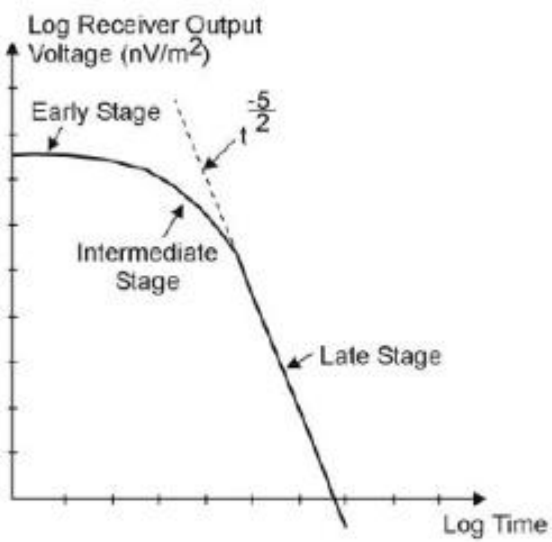
Typical time length equals to 10-50ms



Reynolds, 1997

For increasing measuring times it is possible to reach deeper levels

Low frequency EM methods TDEM



Output voltage $$e(t) = \frac{k_1 M \sigma^{3/2}}{t^{5/2}},$$

$e(t)$= output voltage from a single-turn receiver coil of area 1 m^2
k_1 = a constant
M = magnetic moment: product of Tx current and area (a-m^2)
σ = terrain conductivity (siemens/m = S/m = 1/Ω m)
t = time (s)

$$\rho_a(t) = \frac{1}{\sigma_a(t)} = \frac{k_2 M^{2/3}}{e(t)^{2/3} t^{5/3}}$$

From the measured voltage decay curve with time it is possible to calculate the (apparent) resistivity as a function of time when the geometrical parameters of the system are known.
Later times ➔ larger investigation depths
The approach is similar to the Induce Polarization (IP) technique.

The following physical quantities can be used:

- *Voltage (t)*
- *Voltage at specific times*
- ***Resistivity values***

As for FDEM, also in this case data inversion is possible but not straightforward.

Low frequency EM methods TDEM

The investigation depth depends by the time interval after stopping the inducing field ➔ from a few metres (10^{-2}ms) down to several hundreds metres (s). Moreover, larger transmitting loops (and higher inducing fields) can reach larger depths (with lower resolution!) as well as larger distances between T and R can further increase the investigation depth.

Approximately, the maximum effective investigation depth is about 2-3 times the dimensions of the transmitting circuit.

In a uniform conducting medium, the transient electric field achieves a maximum at the *diffusion depth (d)*, such as:

$$d = \sqrt{\frac{2t}{\mu\sigma}}$$

In a conducting half-space, the downward velocity is given by: $v = \sqrt{2(\pi\sigma\mu t)}$

In TDEM measures there are 3 main sources of errors, namely:

1) Geometric errors (T and R positions and topography)
2) Static cultural noise (e.g. due to pipes, cables, metal fences)
3) Dynamic cultural noise (AC power lines, VLF transmitters (10-25 KHz)

Stacking of repeated measurements can increase S/N


Questions?