ERTH2020

Introduction to Geophysics

The Electromagnetic (EM) Method

‘Active EM’
Overview

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Review DC/ IP

**DC Resistivity**
Direct Electrical Connection
Injected DC current via electrodes
Electrical potential

**IP Chargeability**
Electrical potential decay
Resistivity
Chargeability
Electromagnetic Induction

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Electromagnetic Induction

Ampere’s Law (1826)
\[ \nabla \times \mathbf{H} = \mathbf{J} + \partial_t \mathbf{D} \]

Faraday’s Law (1831)
\[ \nabla \times \mathbf{E} = -\partial_t \mathbf{B} \]

(magneto) quasi-static approximation, i.e. separation of electrical charges occur sufficiently slowly that the system can be taken to be in equilibrium at all times

- **J** electric current density (A/m²)
- **H** magnetic field intensity (A/m)
- **B** magnetic induction (Wb/m² or T)
- **E** magnetic field intensity (V/m)

E.g. [http://farside.ph.utexas.edu/teaching/302l/lectures/node70.html](http://farside.ph.utexas.edu/teaching/302l/lectures/node70.html)
[http://farside.ph.utexas.edu/teaching/302l/lectures/node85.html](http://farside.ph.utexas.edu/teaching/302l/lectures/node85.html)
Terminology

Type of EM measurement

- FDEM – Frequency Domain EM
- TDEM – Time Domain EM
- TEM – Transient EM

System responses

- B-field, magnetic field, step response
- dB/dt, voltage, emf, impulse response

Tx

- Transmitter

Rx

- Receiver
EM methods

Ground-EM

Airborne-EM

Downhole-EM

Sea-EM
EM methods

- **Frequency Domain EM (FDEM)**
  - The ground is energised by passing an alternating current (AC) of a certain frequency through an ungrounded loop on or above the earth.
  - The primary magnetic field of the loop induced in the subsurface will induce eddy currents in all conductors present in the earth.
  - The secondary EM fields due to these induced currents, together with the primary EM field, are recorded at various points.
  - Separation of primary and secondary field is difficult as the primary field is several magnitudes larger.

- **Time Domain EM (TDEM or TEM)**
  - A strong DC current is passed through an ungrounded loop which is abruptly interrupted causing eddy currents in the subsurface.
  - The induced eddy currents create secondary magnetic fields which are measured with suitable receivers at various points.
  - Primary and secondary field are well separated in TEM.
FDEM employs one or several frequencies for energising the subsurface – each frequency corresponds to a certain depth (sounding & profiling techniques).

TDEM employs a broadband spectrum covering a wide range of depths, which depends on Tx-power, Tx-size, ground conductivity and measurement times.
Data acquisition

Transmitter Zonge GGT-30

SmartEM-V Receiver

Transmitter wire

Transmitter Zonge GGT-30
data acquisition

Loop Sensor (dB/dt)

SQUID sensor (B)
Effective measured fields

- **Loop or coil receivers:**
  
  \[ \text{dB(t)/dt in fractions of Volts (e.g. micro- or nanovolts)} \]

  - normalised with Tx-current and Tx-area \( \rightarrow \frac{nV}{A \cdot m^2} \)
  
  - (but sometimes normalised only with Tx-current)
  
  - (sometimes also in terms of magnetic field \( \text{dH/dt in Ampere/metre-sec} \))

- **Magnetometers:**
  
  \[ \text{B(t) in fractions of Teslas (e.g. nano- or picotesla)} \]

  - normalised with Tx-current \( \rightarrow \frac{pT}{A} \)
  
  - (sometimes also in terms of magnetic field \( H \) in Ampere/metre)
data acquisition

Measured components

- **Z – Vertical**  “horizontal receiver”
- **X – Inline**  “vertical receiver” (X-orthogonal)
- **Y – Crossline**  “vertical receiver” (Y-orthogonal)
- **(ρ – Horizontal)**  (calculated from X and Y)
Most commonly, ground TEM data acquisition employs either the moving-loop or fixed-loop survey geometry:

- **Moving-loop**
  - transmitter and receiver are moved simultaneously along a survey line.
  - a single TEM measurement is made for each transmitter setup.
  - loop sizes typically restricted to 100-200 m due to logistical difficulties.
  - moving-loop surveys are generally used for reconnaissance.
Most commonly, ground TEM data acquisition employs either the **moving-loop** or **fixed-loop** survey geometry:

- **Fixed-loop**
  - a large transmitter loop is laid out and remains in position during the TEM survey.
  - measurements are made along a survey line at a series of receiver positions.
  - Loop sizes vary from several hundreds of meters to up a few kilometres and are positioned for maximum magnetic field coupling with prospective targets.
  - Typically, rectangular transmitter loops are employed, with the long side oriented parallel to the expected strike of the target conductors.
data acquisition

(a) SINGLE LOOP or ONE LOOP

(b) COINCIDENT TRANSMITTER-RECEIVER LOOP

(c) DIPOLE RECEIVER (IN LOOP METHOD)

(d) SEPARATED LOOPS (SLINGRAM ARRAY)

(e) LARGE LOOP RECEIVER

DUAL LOOP - SINGLE WIRE FOR TRANSMITTER & RECEIVER.

DUAL LOOP - SEPARATE WIRES FOR TRANSMITTER & RECEIVER.
EM sounding

- Because the depth of penetration of the EM fields depends on frequency (or time), it is possible to carry out a depth sounding by keeping the transmitter and receiver positions fixed and by making measurements at a range of delay times.

- Sounding is logistically easier using EM methods than using DC resistivity techniques, where increased depth of penetration can only be achieved by increasing the electrode separation.

- As with DC resistivity sounding, EM sounding can be performed by keeping the frequency (or time) fixed, and increasing the separation between the transmitter and receiver.
EM profiling

• EM profiling may be carried out in two ways:
  – The transmitter may remain fixed, and the receiver coil moved along the survey line (Fixed-loop geometry)
  – The transmitter and receiver coils may be moved along the survey line together, with the distance between them remaining constant (Moving loop geometry)

• Profiling is usually carried out in order to detect local zones of anomalously high conductivity (e.g., massive sulfides) - this is the most common application of the TEM method

• As was the case for DC resistivity profiling, the shape of the anomaly over a given target is strongly dependent on the transmitter-receiver geometry used
TEM Exploration Principle

- An insulated transmitter loop (Tx-loop) carries a DC current which sets up a primary magnetic field according to Ampere’s law.
- The ground is then energised by means of a sharp turn-off of the steady-state current flowing in the Tx-loop.
- The rapid change in Tx primary field will induce an electric field in the subsurface according to Faraday’s law.
- In a conductive earth, these electric fields generate currents as specified by Ohm’s law.
- These currents successively generate a secondary magnetic field as described by Ampère’s law.
- The transient secondary EM fields are recorded at a series of measurement times at designated recording stations.
- Recordings are obtained via coil receivers which measure the rate of change of the magnetic flux density cutting the coil ($\partial_t \mathbf{B}$), or via magnetometers which measure the magnetic flux directly ($\mathbf{B}$).
Induction in a confined subsurface conductor

Square Tx-Waveform

Note: The induced eddy-currents will be in such a direction as to oppose the motion or change causing it (Lenz’s law)
Induction in a confined conductor

- Stages of time-domain EM induction

(a) EARLY TIME  (b) INTERMEDIATE TIME  (c) LATE TIME

Nabighian and Macnae, 1991

- At early time, the initial surface current distribution is independent of the conductivity of the body and depends only on size and shape of the conductor.
- At the later stages, the rate of change of the induced currents and of their accompanying secondary magnetic field is dependent on the conductivity, size and shape of the conductor.
Response of a confined conductor

dB/dt
• Poor conductors have a large initial dB/dt response but the field decays rapidly
• Good conductors initially show smaller dB/dt values but the field decays slower

B
• The initial amplitude of the magnetic field is independent of the conductivity
• The decay rate is dependent on conductivity and on size also
Response of a confined conductor

dB/dt measurements are less sensitive to conductive structure at depth than B measurements

advantage

dB/dt (Voltage)

Poor Conductor

Good Conductor

disadvantage

B-Field

Conductivity Increases

time
Current diffusion in a Half-Space

a) Early time
   – Immediately after current shut-off in the Tx-loop, the induced current is confined to the surface underneath the transmitter.
   – The induced currents are distributed in such a manner as to maintain the magnetic field everywhere at the value that existed before turn-off.
   – At early times the induced current system in the subsurface primarily reflects the conductivity of the top layers.

b) Intermediate time
   – The initial current distribution starts to diffusing into the earth.
   – As the current system diffuses and decays, it appears to move outward and down.
   – Recordings of the secondary EM fields will therefore give information about the conductivity as a function of depth.

c) Late time
   – As time passes by, the currents in the host propagate away and resistance in the subsurface weakens the induced currents.
   – Eventually the current density dissipates due to the Ohmic losses.
Current diffusion in a Half-Space

- Contour plots of current density at increasing times
- Current diffuses in an outward and downward expanding pattern.
- The diffusing current pattern in a half-space can be described as a “smoke-ring” moving downward and outward from the Tx-loop.

Current diffusion in a Half-Space

- The transient EM field of a conducting half space can be represented by a simple current filament of the same shape as the transmitter loop, moving downward and outward with a decreasing velocity and diminishing amplitude ("smoke ring").

- The “smoke ring” current filament is a mathematical abstraction which replicates the magnetic field on the surface.

- When the “smoke ring” passes below the observation point, the vertical magnetic field changes sign near the time that the current maximum passes beneath the observation point.

- The zero-crossover of the vertical component migrates outward with time and are dependent on delay time, host conductivity and receiver position.
Current diffusion in a Half-Space

(Contours of the secondary magnetic field)

More conductive:
- Later cross-over
- Further distance

Less conductive:
- Earlier cross-over
- Closer distance
TEM decay profiles

- Decay curves for the vertical component at a point 100 m from a small transmitter loop on a 100 Ohm-m homogeneous earth.

Decay curves at a receiver are plotted on a log-log scale. Negative portions of the decay curves are plotted as if positive but appropriately marked. The zero cross-over manifests as a jump in a log-log-plot.
TEM decay profiles

- **Early time:** the induced current system beneath the Tx-loop prevents the magnetic field from shutting down immediately (no ‘decay’ is observed).

- The decay curves then change sign when the current maximum passes beneath the receiver station. The time derivative changes sign at a slightly later time.

- **Late times:** the decays show up as linear relations on the log-log plot and the late time asymptotes decay with a power law of -3/2 \( (h_z) \) and -5/2 \( (dh_z/dt) \)
Current diffusion in a Half-Space

- Increases with increasing $t$
- Decreases with increasing $\sigma$
- Also depends on system geometry and on noise level

Diffusion depth

$$\delta_{TD} = \sqrt{\frac{2t}{\sigma \mu}}$$

$t$ = ‘delay’ time
$\sigma$ = conductivity
$\mu$ = magnetic permeability
TEM anomaly profiles

**Fixed-Loop 100 Ohm-m Half-Space**

- Z-Component
- 42 Delay Times (0.1ms - 700ms)
- TX
- Channel 1
- Channel 2
- Channel 3
- Channel 11
- "Smoke-Ring" passes receivers

**Moving-Loop 100 Ohm-m Half-Space**

- TX
- 100m
- Receiver station (metres)
- Bz(t) Response (pT/A)
TEM anomaly profiles

- Plot of $B(t)$ or $dB/dt$ decays against receiver stations (stacked or constant delay time profile).

  - Fixed-Loop host-rock responses are characterized by bell shaped anomalies with zero crossovers in the vertical component. The anomalies become steadily wider with time due to the migrating “smoke ring”.

  - Moving In-Loop (Central-Loop) host-rock responses are ‘flat’ with decreasing magnitude as time increases and are always positive (non-polarizable, non-magnetic earth).
TEM anomaly profiles

• Moving In-Loop profile over a conductive vertical plate.

\[ \sigma_p \cdot t_p = 10 \, S \]

\[ \sigma_h = 0.01 \, S/m \]
\[ (\rho_h = 100 \, \Omega \cdot m) \]

• “Anomalies” show up when there are conductive (or resistive) inhomogeneities in the subsurface

• The anomaly shape depends on the geometry and size of the target

• The anomaly magnitude depends on the conductivity of the target

• Moving In-loop anomalies are relative easy to identify
TEM anomaly profiles  (Abra Pb-Ag-Cu-Au deposit, WA)

Contours of ML responses

Moving Loop (Line 8600E)

FIGURE 4
Contours of observed SIROTEM Ch. 8 (4.2 msec delay) TEM response (contour interval 2 \( \mu \)V/A) using 200 m single loop, moving source mode. Surface projection of matching plate model is indicated.
TEM anomaly profiles

- Effect of conductive overburden
  - induced currents will flow on the surface of the overburden shielding the conducting target initially
  - at later times the target is visible for a short period before the currents are completely decayed
Fixed-Loop profile over a conductive vertical plate.

- Fixed-loop profiles are more complicated
- Migrating cross-overs due to smoke-ring
- Localised cross-overs due to plate-interaction
TEM anomaly profiles

41 channel delay times (0.1-700 msec)

\[ \sigma_h = 0.01 \, \text{S/m} \]

\[ (\rho_h = 100 \, \Omega \cdot \text{m}) \]

\[ \sigma_p \cdot t_p = 10 \, \text{S} \]
TEM anomaly profiles

Fixed-Loop data, Gamsberg zinc deposit, South Africa
Data interpretation

- The measured **TEM response** of a conductive target depends on a wide range of factors, including
  - Survey type (e.g. Fixed loop, Moving loop, Slingram, etc.)
  - Positions of Tx and Rx relative to target
  - Size of Tx loop and Rx coil
  - Measured component
  - Target size, shape, dip, and depth of burial
  - Conductivity of the target
  - Exact Tx waveform, and Rx measurement times
Data interpretation

• **Data inspection**
  – determine anomalies, noise level and incorrect data
  – pre-process data, e.g. filtering of 50 Hz power line noise
  – stripping – estimate of host rock response is subtracted

• **Preliminary 1D interpretation**
  – e.g. Conductivity-Depth-Imaging (CDI)
    transformation into cross-section of apparent conductivity vs. apparent depth
  – apparent conductivity bears resemblance to apparent resistivity but *it is not the same!* Apparent conductivity, \( \sigma_a \), has units of \( S/m \) (Siemens per metre)
  – apparent conductivity is a convenient data transformation and generally does not reflect the true conductivity distribution of the subsurface

• **1D Layered earth inversion**
  – Inversion using a 1D layered half-space

• **3D modelling**
  – Trial & Error forward modelling using thin sheet models

• **(2D/3D inversions)**
Data interpretation

*Conductivity-Depth-Imaging*

- At each delay time an apparent conductivity is calculated (e.g. via asymptotic “late-time” formula, or via a simple least-squares inversion)
- Apparent conductivity is defined as the conductivity of a homogeneous half space which produces the same response as the actual measurement over an inhomogeneous earth.
- (e.g.) Apparent depth at each delay time is the depth of the current maximum ($E_{\text{max}}$) in a half-space with conductivity corresponding to the apparent conductivity at that time.
Data interpretation

Conductivity-Depth-Imaging

decay for 2-layered earth.

decays for each app. cond.

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Data interpretation (CDI)

- CDI from Airborne EM data over the Lisheen sphalerite-galena mine, Ireland.
- Estimated depth from the CDI is ~200 m, which agrees with drilling.
- Conductivity of the mineral assemblage is believed to be mainly from the association of marcasite and pyrite with sphalerite and galena.

(Nabighian and Asten, 2002, Geophysics, V67, No.3, pp.964)
Data interpretation (CDI)

(Nabighian and Asten, 2002, Geophysics, V67, No.3, pp.964)
Approximate 3D modelling with Thin Sheet Model

- Prediction of the likely TEM response of even simple targets is difficult without the assistance of complicated modelling software
- A model widely-used for interpretation of TEM profiling data acquired for massive sulphide exploration is the thin sheet, or plate model
- The thin sheet is useful for modelling the TEM response of vein or stratabound massive sulphide mineralisation
- Thin sheet models are characterised by their depth, dip, strike and dip extents, and conductance (conductivity - thickness product)
- For targets in a more conductive host, the host-response need to be stripped before thin-sheet modelling can proceed
Data interpretation

- Approximate 3D modelling with Thin Sheet Model
  - loop circuits or current filaments residing in the plane of the plate
  - thin sheet models are free-space models, host is not considered
  - approximate responses for 3D models
  - widely used in exploration industry (“MAXWELL” Plate modelling)

Geophysical model is dipping plate with conductance $S = \sigma \times t$
($= \text{conductivity} \times \text{thickness}$)
Data interpretation

• The following slides show the response of some thin-sheet models for both moving in-loop and fixed-loop transmitter-receiver geometries

• In each case the parameters of the thin-sheet target are
  – Depth to top = 50 m
  – Strike extent = 400 m
  – Dip extent = 200 m
  – Conductance = 10 Siemens

• The TEM receiver in each case is SMARTEM - delay times are noted on the first figure

• Note the effect of Tx-Rx configuration and target dip on the shape of the profile
• 100 m moving in-loop response of vertical target

Data interpretation

Early time
channel 1 = 0.1 ms

Later time
channel 14 = 1.6 ms

Primary field for ML over plate

Cross section view - plate strikes into/out of page

Vertical component

Top of plate

Depth (m)

\( \frac{\partial B_z}{\partial t} (\mu V/A) \)
Data interpretation

- 100 m moving in-loop response of target dipping at 45 degrees

**Vertical component**

\[
\frac{\partial B_z}{\partial t} \text{ (\(\mu\text{V/A}\))}
\]

**Depth (m)**

**Early time**

channel 1 = 0.1 ms

**Later time**

channel 14 = 1.6 ms

**Top of plate**

*Cross section view - plate strikes into/out of page*
Data interpretation

- Fixed-loop response of vertical target - vertical component

Early time channel 1 = 0.1 ms

Top of plate

Edge of Tx loop

Primary B

Note sign change in response!
interpretation of tem data

- **Fixed-loop response of vertical target – horizontal component**

Horizontal component

$\frac{\partial B_x}{\partial t} (\mu V/A)$

Depth (m)

Top of plate

Later time channel 14 = 1.6 ms

Peak in response directly over target
References

Introductory level:


Advanced level:
