Curtin University

Lecture Notes GEOP3003 Semester 2, 2015

Electromagnetics & Radiometrics for Exploration

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LECTURE 00

PREAMBLE S2 2015

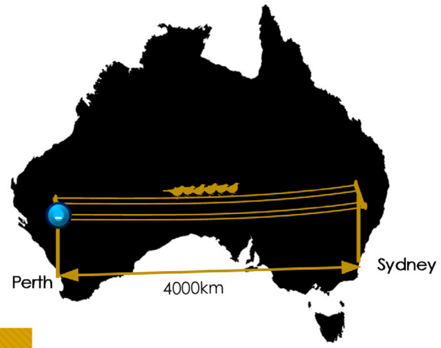
- Lecture and lab schedule
- What you should take away from this unit
- Assessments
- What is expected from the labs

Electrons versus electromagnetic waves

Scenario: Speed of an Electron

You have decided to string up a 4000km power pole from Perth to Sydney and transmitted a DC current through that wire.

Approximately how long would it take an individual electron to travel from Perth to Sydney?



Note: The speed of an electromagnetic wave in a wire is ~1.8x10^8 m/s

Speed Comparison in a Copper Wire

Electrons move sloooowww

- Drift Velocity (Electron Velocity)

  ~0.00028 m/s **(REALLY SLOW)**

  96 days to travel from Perth to Sydney

- Electromagnetic field velocity

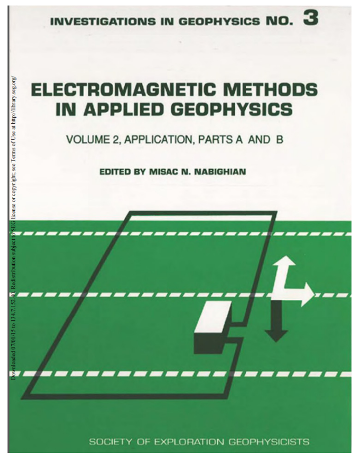
  ~180,000,000 m/s **(REALLY FAST)**

  ~0.022 s to travel from Perth to Sydney

Extra Reading

READ THIS!

- **Nabighian M.N. (1998) - Electromagnetic Methods in Applied Geophysics – Applications Part A and Part B: Editor, Vol 2, SEG IG No. 3 (FREE ONLINE @ Curtin)**
- **Nabighian M.N.(1987) Electromagnetic Methods in Applied Geophysics – Theory: Editor, Vol 1, SEG IG No. 3 (FREE ONLINE @ Curtin)**
- Parasnis, D.S. (1996) Principles of Applied Geophysics: 5th Ed., Chapman & Hall (easy to read if you can get your hands on)
- Telford, W.M., Geldart, D.P., and Sheriff, R.E. (1990) Applied Geophysics: Vol. 2, Cambridge University Press. (For the more adventurous)
- Grant, S., and West, G.F. (1965) Introduction Theory in Applied Geophysics: McGraw- Hill.
- Keller, G., and Frischnecht, F. (1966) Electrical Methods in Geophysical Prospecting: Pergamon



Program calendar

Program Calendar – Semester 2 2015

Week	Begin Date	Lecture/ Seminar	Pre-readings	Tutorial/Other	Assessment Due
Orientation	**27 July**	Orientation Week			
1.	**3 August**	Fundamentals of EM for Targeting I (AP/MC)		Assignment 1: FEM modelling (AP) (LVC)	**18 August**
2.	**10 August**	Fundamentals of EM for Targeting II (MC)		Assignment 1: FEM modelling (AP) (LVC)	**18 August**
3.	**17 August**	Frequency Domain Response (AP)		Assignment 2: Vortex modelling (AP) (LVC)	**1 September**
4.	**24 August**	Time Domain Systems and Impulse Response (AP)		Assignment 2: Vortex modelling (AP) (LVC)	**1 September**
5.	**31 August**	Tuition Free Week			
6.	**7 September**	Profiling with TEM (AP)		Assignment 3: Field Data Collection (AP) (ARC)	**22 September**
7.	**14 September**	Response and Modelling of discrete target (AP) GP3009 2nd Group		Assignment 4: Layered Earth Modelling and Fitting of Plates to TEM (AP) (LVC)	**29 September**
8.	**21 September**	Response and Modelling of discrete target (AP) GP3009 1st Group		Assignment 4: Layered Earth Modelling and Fitting of Plates to TEM (AP) (LVC)	**29 September**
9.	**28 September**	Tuition Free Week			
10.	**5 October**	Decay Curves and Sounding for TEM (AP)		Magnetotelluric Field Demonstration (AP) (ARC)	**Not Assessed**
11.	**12 October**	Magnetotelluric Methods and VLF (AP)		Assignment 5: Magnetotelluric Modelling (AP) (LVC) (DT)	**27 October**
12.	**19 October**	Noise, Anomalous Responses and Improving Signal (AK)		Assignment 5: Magnetotelluric Modelling (AP) (LVC) (DT)	**27 October**
13.	**26 October**	High Frequency EM (RFMT and Radar) (TBA)		Assignment 6: Ground Penetrating Radar (AP) (LVC)	**10 November**
14.	**2 November**	Radiometrics (MC)		Assignment 6: Ground Penetrating Radar (AP) (LVC)	**10 November**
15.	**9 November**	Study Week			
16.	**16 November**	Examinations			
17	**23 November**	Examinations			

AP – Andrew Pethick
MC – Michael Carson
AK – Anton Kepic
LVC –Van Anh Cuong Le
DT – Duy Thong Kieu

What you should understand

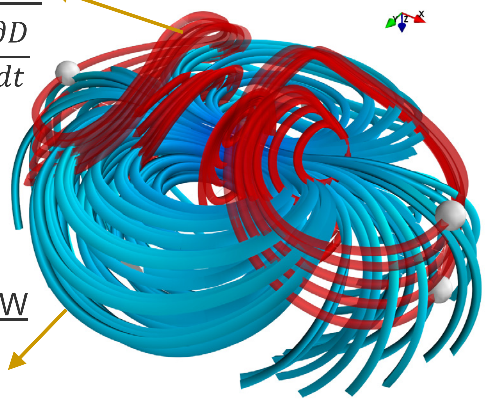
Fundamentally, what are electromagnetic fields?

AMPERE'S LAW

$$\nabla \times H = J + \frac{\partial D}{dt}$$

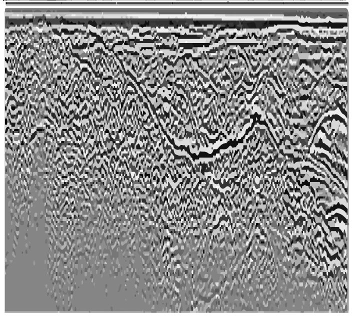
FARADAY'S LAW

$$\nabla \times E = -\frac{\partial B}{dt}$$



What you should understand

EM is useful for ALL depths of investigations

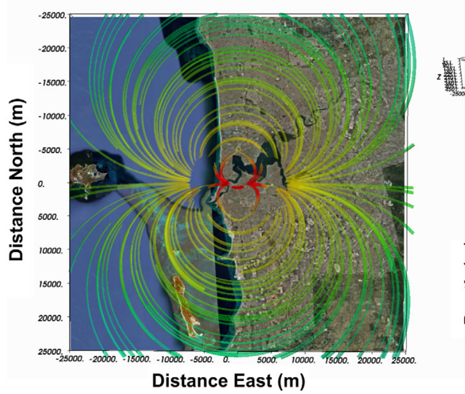


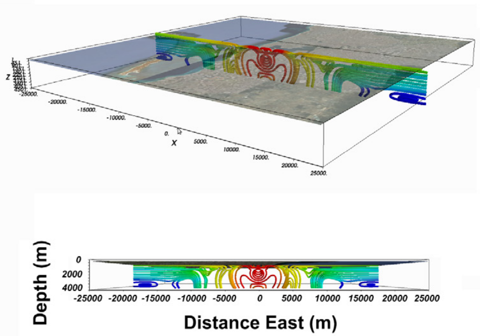
EM allows you to detect subsurface electrical properties

from a few metres under the earth….

What you should understand

Keep scale in perspective!





…to kilometres under the earth…

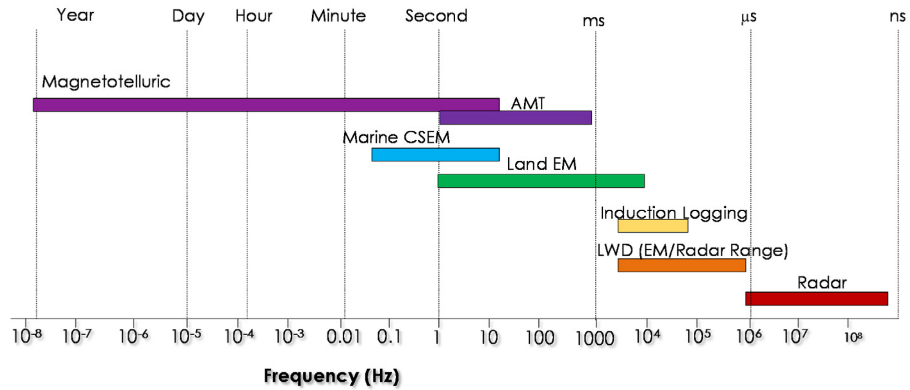
What you should understand

What equipment is available and fundamentally what is transmitted

PICK THE RIGHT TOOL FOR THE JOB

What you should understand

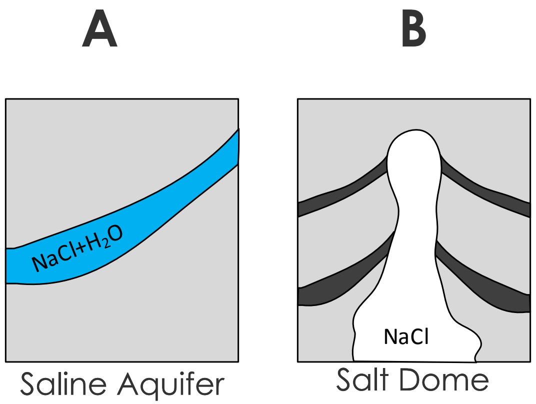
Geophysical EM methods span many decades of the EM Spectrum



What you should understand

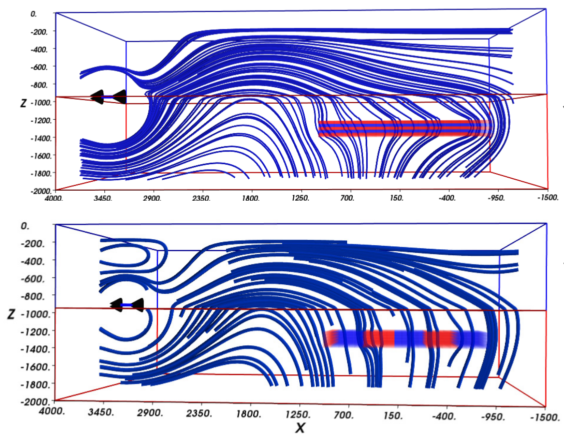
Electrical Rock properties and what does it mean for exploration?

Which is more conductive?



What you should understand

How do electromagnetic fields interact with the earth?

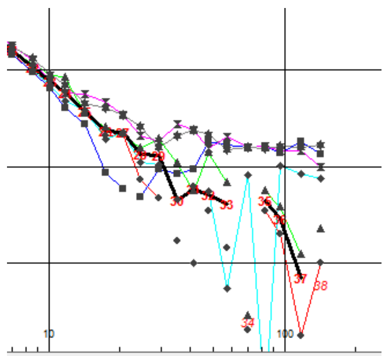


Same amount of resistive and conductive material.

VERY DIFFERENT RESPONSE!

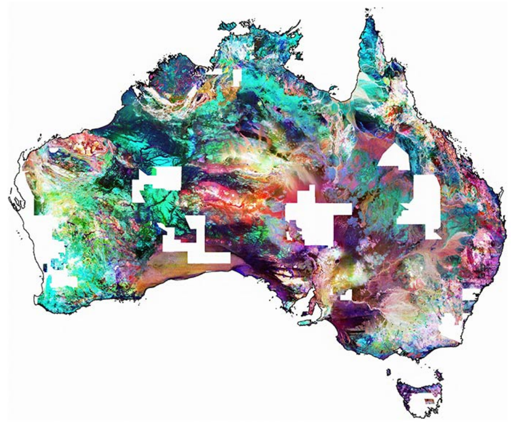
How to get the best out of your data

What is noise? Identifying it? How to reduce its impact?



Radiometrics

What is it? Basic processing and interpretation.

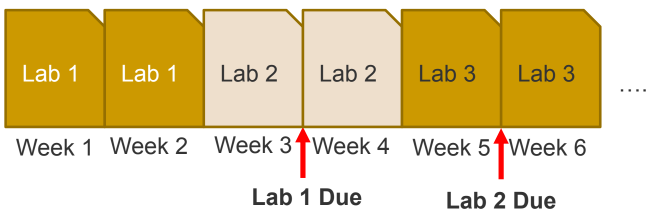


Ternary image of the Radiometric Map of Australia
http://www.ga.gov.au/scientific-topics/disciplines/geophysics/radiometrics

Labs

REQUIREMENTS

- Each lab requires 2 weeks
- You have 1 week after the lab to submit the report



Labs

REQUIREMENTS

- How to earn 50%
  - Show up
  - Do lab
  - Write report with figures and one sentence explanations
  - Captions must be 100% correct
  - **NO PLAGARISM!**

TURNITIN WILL BE USED

- How to earn >50%
  - Show up
  - Complete lab with good, clear figures and diagrams
  - Do a proper write up; aim, background, method **(do not get carried away with the method),** discussion and conclusion
  - Reference with 15th Ed. - The Chicago Manual of Style

LECTURE 01

Fundamentals of EM for Targeting I — S2 2015

- Electric and Magnetic Field Definitions
- Maxwell's Equations
- Wave Equation

Electric Field Defined

Coulomb's Law

- The Electric Field or (E-Field) is the force a charged particle would experience at a location X – charge is the source of E-field
- That is, the force per unit charge ($N \bullet C^{-1}$)
- Use volts per metre ($V \bullet m^{-1}$)
- The electric field surrounding a single charged particle only and in free space is defined by Coulombs law

$$E = \frac{q}{4\pi\varepsilon_0 R^2} \quad (1)$$

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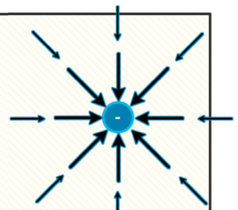
E-Field Defined :

Computing The Field (Source code if you are inclined)

ElectricField.py

```
import numpy as np
import numpy as np
permitivityOfFreeSpace = 8.854*1E-12;
e = permitivityOfFreeSpace;

def efield(xsource,ysource, xreceiver, yreceiver, charge):
    rx = (xreceiver - xsource);    #compute x distance
    ry = (yreceiver- ysource);     #compute y distance
    r = np.sqrt(np.power(rx,2)+np.power(ry,2)); #compute total distance
    vector = np.array([rx/r,ry/r]); #force vector in direction towards source
    et = charge/(4*np.pi*e*np.power(r,2)); #compute the total electric field
    efield = np.multiply(vector,et); #efield vector in direction 'vector'
    return efield;
```



$$E = \frac{q}{4\pi\varepsilon_0 R^2} \quad (1)$$

THIS IS ELECTROSTATICS

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Electric Field Defined : Computing The Field

2D vector field surrounding an electron (Source code if you are inclined)

RunEH.py

1. Create a grid of electric field 'receivers'
2. Compute the response at each receiver

```
import ElectricField
import numpy as np

#### Charge of a single electron
echarge = -1.6021765*1E-19;

#### Create a 2D Grid of Receivers
xs = np.linspace(-1,1,21);
ys = np.linspace(-1,1,21);
c = np.array([np.linspace(i,j,N) for i,j in zip(xs,ys)])

#### Define a source location
sourcex1 = 0; #source x position
sourcey1 = 0; #source y position

#### Loop over all receivers and compute efield vector
for i in range(0,len(xs)) :
    for j in range(0,len(ys)) :
        ef = efield(sourcex1,sourcey1,xs[i],ys[j],echarge);
```

1. (Create a 2D Grid of Receivers)
2. (ef = efield(...))

THIS IS ELECTROSTATICS

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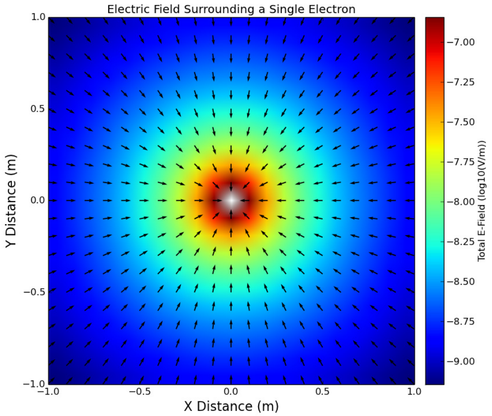
Electric Field Defined : Computing The Field

2D vector field surrounding an electron

Resulting vector field surrounding the electron

Note that the amplitudes are plotted on a log scale.



THIS IS ELECTROSTATICS

Electric Field Defined : Computing The Field

Computing a rudimentary electric bipole

RunEH.py

```
.
.
.
#### Define a source location
#### THIS TIME ADD A SECOND SOURCE
sourcex1 = 0;
sourcey1 = -0.5;
sourcex2 = 0;
sourcey2 = 0.5;

#### Loop over all receivers and compute efield vector
for i in range(0,len(xs)) :
    for j in range(0,len(ys)) :
        efp = efield(sourcex1,sourcey1,xs[i],ys[j],echarge);  #-ve charge
        efn = efield(sourcex2,sourcey2,xs[i],ys[j],-echarge); #+ve charge
        et = efp + efn; #the total is the summation from both charges
```

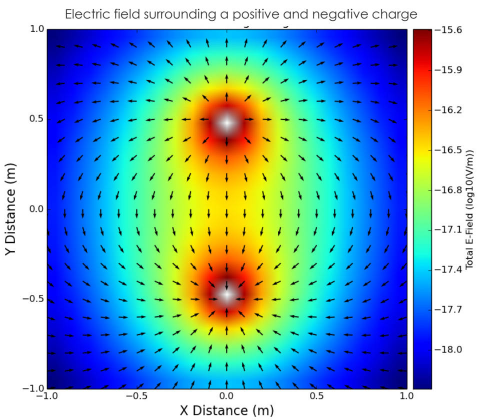
THIS IS ELECTROSTATICS

Electric Field Defined : Computing The Field

2D vector field surrounding a rudimentary electric dipole

If a positive and negative charge were held in place by an infinitely resistive material, this would be the resulting electric field.

Which is + and which is - ?

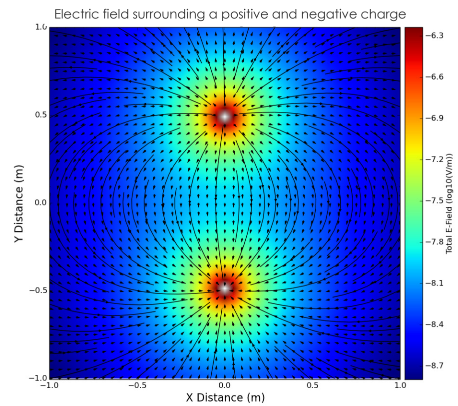


THIS IS ELECTROSTATICS

Electric Field Defined : Computing The Field

2D vector field surrounding a rudimentary electric bipole

- If you place a charged ion in this area, it will follow the path of the field lines
- streamlines are used to visualize field lines



THIS IS ELECTROSTATICS

Magnetic Field Defined

What is a Magnetic Field?

- The Magnetic Field or (H-Field) is the force a moving charged particle would experience at a location X given velocity v – current is the source of H-field (*but* see Ampere's law later…)
- That is, the force per meter per Ampere ($N \bullet m^{-1} \bullet A^{-1}$)
- Use Ampere's per metre ($A \bullet m^{-1}$)
- The magnetic field that surrounds a current carrying wire is given by: $\boldsymbol{H} = \frac{I}{2\pi R}$ (2)

THIS IS MAGNETOSTATICS

H-Field Defined : Computing The Field

Source Code if you are Inclined

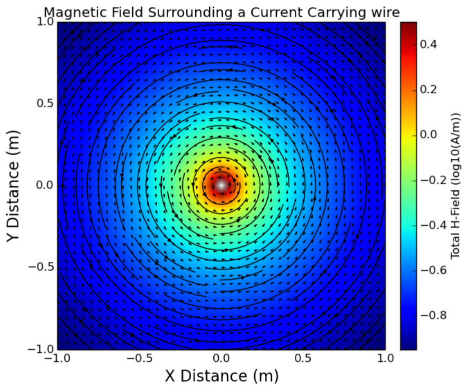
MagneticField.py

```
def hfield(xsource,ysource, xreceiver, yreceiver, current):
    #current travelling in vector direction v<0,0,1> out of the page)
    rx = (xreceiver - xsource);                      #compute x distance
    ry = (yreceiver- ysource);                       #compute y distance
    r = np.sqrt(np.power(rx,2)+np.power(ry,2)); #compute total distance
    #vector in direction perpendicular to current flow (unit vector)
    vector = np.array([ry/r,-rx/r]);
(2) ht = current/(2*np.pi*r);                        #Compute total H-Field
    hfield = np.multiply(vector,ht);                 #Create H-Field Vector
    return hfield;
```

THIS IS MAGNETOSTATICS

H-Field Defined : Computing The Field

- The resulting magnetic field is a vector field



THIS IS MAGNETOSTATICS

Maxwell's Equations

The Four Equations

GAUSS' LAW

$$\nabla \cdot \mathbf{D} = \rho_v \quad (3)$$

GAUSS' MAGNETISM LAW

$$\nabla \cdot \mathbf{B} = 0 \quad (4)$$

FARADAY'S LAW

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (5)$$

AMPERE'S LAW

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \quad (6)$$

Maxwell's Equations

Breaking it Down: Gradient Operator (Del)

∇ Gradient Operator

Represents the standard derivative

$$\nabla = \left(\frac{\partial}{\partial x}\boldsymbol{i}, \frac{\partial}{\partial y}\boldsymbol{j}, \frac{\partial}{\partial z}\boldsymbol{k}\right)$$

$$\nabla = \begin{bmatrix} \partial/\partial x \\ \partial/\partial y \\ \partial/\partial z \end{bmatrix}$$

$$\nabla f(x,y,z) = \frac{\partial f}{\partial x}\, i + \frac{\partial f}{\partial y}\, \mathrm{j} + \frac{\partial f}{\partial z}\, k$$

Maxwell's Equations

Breaking it Down: Divergence

If $\mathbf{A} = \begin{bmatrix} A_x \\ A_y \\ A_z \end{bmatrix}$ and $\nabla = \begin{bmatrix} \partial/\partial x \\ \partial/\partial y \\ \partial/\partial z \end{bmatrix}$

The dot product between the 3D vector $\mathbf{A}$ at point **P(x,y,z)** (i.e., $\nabla \cdot \mathbf{A}$) is considered to be:

$$\nabla \cdot \mathbf{A}(x,y,z) = \frac{\partial A_x}{\partial x} + \frac{\partial A_y}{\partial y} + \frac{\partial A_z}{\partial z}$$

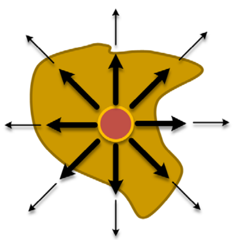
Maxwell's Equations

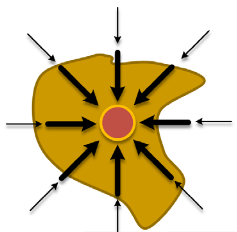
Breaking it Down: Divergence

$\nabla \cdot$ Divergence at point (x,y,z) measures the flow out of the point.

Consider an surface surrounding a point.
Sum up all of the vectors flowing through that surface.

If positive : Point is a source   If Negative: Point is a Sink

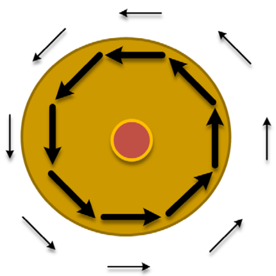


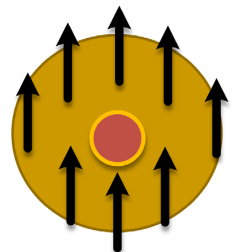


Maxwell's Equations

Breaking it Down: Zero Divergence

$\nabla \cdot \mathbf{V} = 0$ Cases when there is **zero divergence**





Maxwell's Equations

Breaking it Down: Curl

$\nabla \times$ Curl

The Curl Operator measures the rotation of a vector field

Maxwell's Equations

Breaking it Down: Curl

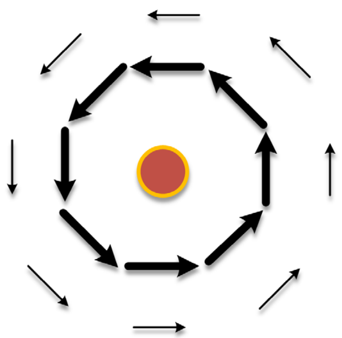
If $\mathbf{A} = \begin{bmatrix} A_x \\ A_y \\ A_z \end{bmatrix}$ and $\boldsymbol{\nabla} = \begin{bmatrix} \partial/\partial x \\ \partial/\partial y \\ \partial/\partial z \end{bmatrix}$

The cross product of **∇** and **A** would be:

$$\nabla \times \mathbf{A} = \begin{vmatrix} i & j & k \\ \dfrac{\partial}{\partial x} & \dfrac{\partial}{\partial y} & \dfrac{\partial}{\partial z} \\ A_x & A_y & A_z \end{vmatrix} = \begin{bmatrix} \left({}^{\partial A_z}/_{\partial y} - {}^{\partial A_y}/_{\partial z} \right) \\ \left({}^{\partial A_x}/_{\partial z} - {}^{\partial A_z}/_{\partial x} \right) \\ \left({}^{\partial A_y}/_{\partial x} - {}^{\partial A_x}/_{\partial y} \right) \end{bmatrix} \begin{matrix} \text{spin in Y-Z Plane} \\ \text{spin in X-Z Plane} \\ \text{spin in X-Y Plane} \end{matrix}$$

Maxwell's Equations

Breaking it Down: Curl



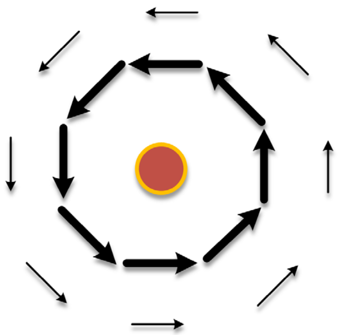
Note
An analogy of a water wheel is often used:

Think of a vector field as flowing water and the rotation speed at which a **water wheel** placed in that water is the **curl**.

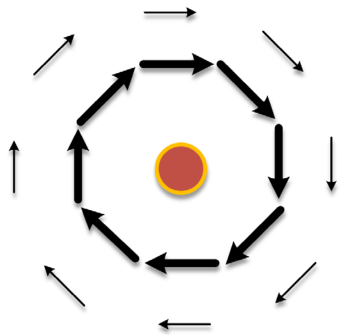
Maxwell's Equations

Breaking it Down: Curl

Spin counter-clockwise, curl is positive



Spins clockwise, curl is negative

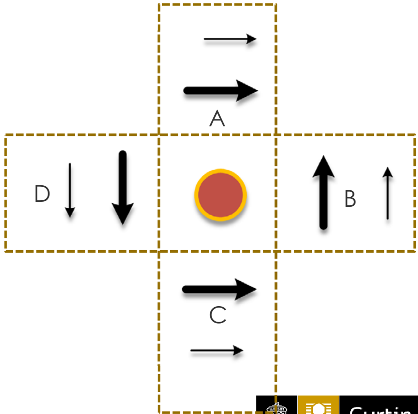


Maxwell's Equations

Breaking it Down: Curl

Parallel Vectors
A and **C** cancel out rotation, net resulting curl is zero

Perpendicular Vectors
B and **D** contribute to rotation, Net resulting curl is positive



Maxwell's Equations

Medium dependent equations aka Constitutive relations

$$\mathbf{J} = \sigma\mathbf{E} \quad (7)$$

$$\mathbf{B} = \mu\mathbf{H} \quad (8)$$

$$\mathbf{D} = \varepsilon\mathbf{E} \quad (9)$$

σ, μ and ε determine the Earth's reponse to inputs **E** and **H**

Maxwell's Equations

Medium dependent equations: Physical Constants

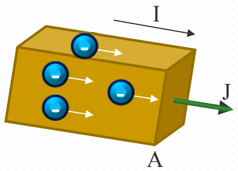
$$\mathbf{J} = \sigma\mathbf{E} \quad (7)$$

*Electrons in the presence of an electric field (**E**) will flow.*

*The amount of electrons that will flow in a given area (**J**) is determined by the material's properties (σ).*

In essence it is a Vectorised version of Ohm's Law

$V = IR \leftrightarrow E = J\left(\frac{1}{\sigma}\right)$

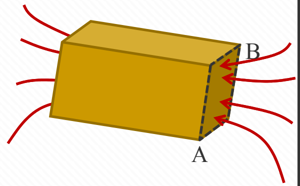
Current Density	Electrical Conductivity
$\mathbf{J}$	σ
Current per unit cross sectional area	Measure of how easily current can flow through a medium
SI units A/m²	SI units S/m
	*Air* $\sim 5 \times 10^{-15}$ *Sea Water* ~ 3 *Fresh Water* < 0.05

Maxwell's Equations

Medium dependent equations: Physical Constants

$$\mathbf{B} = \mu\mathbf{H} \quad (8)$$

*In many ways the magnetic flux density (**B**) and magnetic field intensity(**H**) are similar but are related by the magnetic permeability. **B** depends on the material whereas **H** does not.*

Magnetic Flux Density	Magnetic Permeability
$\mathbf{B}$	μ
Measure of the strength of the magnetic field	Measure of how easily a magnetic field can pass through a medium
B has SI units T or Wb/m² **H** has SI units A/m	$\mu_0 = 4\pi \times 10^{-7} H/m$ SI units H/m (or N/A²)
	*Relative* $\mu_r = \frac{\mu}{\mu_0}$ *Air* 1.0 *Water* 0.999992

Maxwell's Equations

Medium dependent equations: Physical Constants

$$\mathbf{D} = \varepsilon \mathbf{E} \quad (9)$$

*In many ways the electric displacement field (**D**) and electric field (**E**) are similar but the displacement field is not medium dependent*

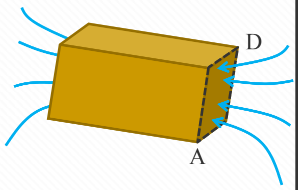
Refer to Coulombs law

$$E = \frac{q}{4\pi\varepsilon R^2}$$

$$D = \varepsilon E = \varepsilon \frac{q}{4\pi\varepsilon R^2}$$

D gives rise to a displacement current

Displacement Field	Electrical Permittivity
$\mathbf{D}$	ε
Density of transported charges in a second over a given area.	Measure of how easily a material stores charge when an electric field is applied
SI units C/m²	$\varepsilon_0 = 8.854187 \times 10^{-12} F/m$
	SI units F/m



$$Relative \ \varepsilon_r = \frac{\varepsilon}{\varepsilon_0}$$

Air	1.0
Water	80
Granite	5 – 20

Maxwell's Equations

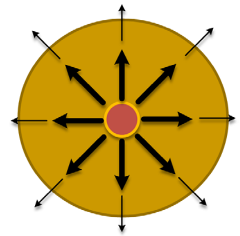
Breaking it Down: Gauss's Law

GAUSS'S LAW

$$\nabla \cdot \mathbf{D} = \rho_v \quad (3)$$

Gauss' Law dictates electric field behaviour around electric charges

If an electric charge exists, an E-field must exist
If no electric charges exists, the E-fields is zero



Note: electric charge density ρ_v denotes the number of electric charges in a given volume (C/m³)

Maxwell's Equations

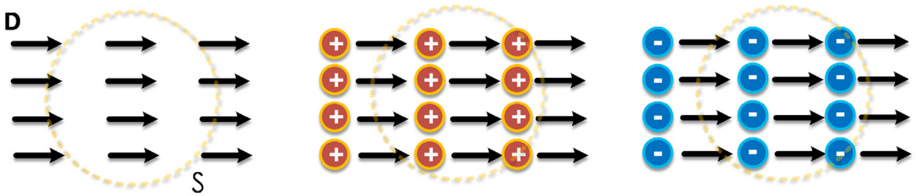
Breaking it Down: Gauss's Law, What is possible and Impossible

GAUSS'S LAW

$$\nabla \cdot \mathbf{D} = \rho_v \quad (3)$$

Case 1: No Charge, No Divergence

No Charges | **Positive Charges** | **Negative Charges**



Agrees
No electric charges but divergence is zero

Violates
Positive charges exist but divergence is zero

Violates
Negative charges exist but divergence is zero

Maxwell's Equations

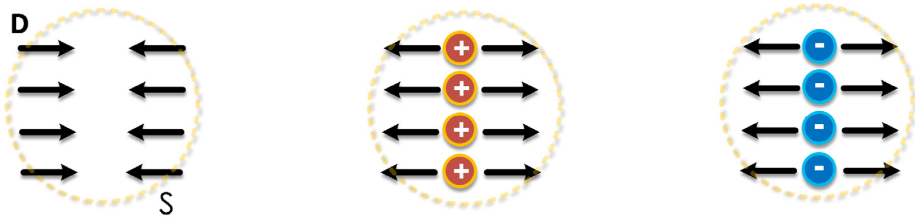
Breaking it Down: Gauss's Law, What is possible and Impossible

GAUSS'S LAW

$$\nabla \cdot \mathbf{D} = \rho_v \quad (3)$$

Case 1: No Charge, No Divergence

No Charges | **Positive Charges** | **Negative Charges**



Violates
Divergence is non-zero, but no charges exist

Agrees
Positive charges exist and divergence is positive

Violates
Negative charges exist but divergence is positive

Maxwell's Equations

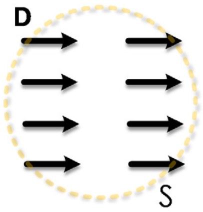
Breaking it Down: Gauss's Law, What is possible and Impossible

GAUSS'S LAW

$$\nabla \cdot \mathbf{D} = \rho_v \quad (3)$$

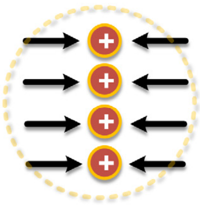
Case 1: No Charge, No Divergence

No Charges



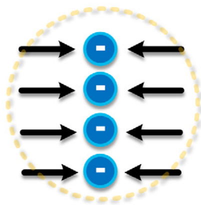
Violates
Divergence is non-zero, but no charges exist

Positive Charges



Agrees
Positive charges exist but divergence is negative

Negative Charges



Violates
Negative charges exist and divergence is negative

Maxwell's Equations

Breaking it Down: Gauss's Law

GAUSS' MAGNETISM LAW

$$\nabla \cdot \mathbf{B} = 0 \quad (4)$$

Gauss' Law Magnetic Monopoles do not exist (i.e., single magnetic charges do not exist)

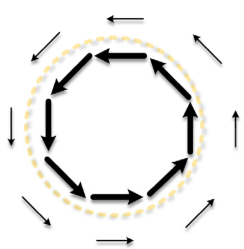
Divergence of the magnetic flux density is always zero

Maxwell's Equations

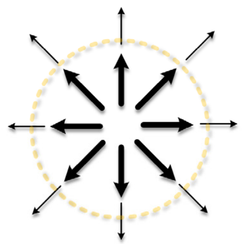
Breaking it Down: Gauss's Law

GAUSS' MAGNETISM LAW

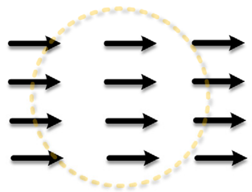
$$\nabla \cdot \mathbf{B} = 0 \quad (4)$$



Agrees
Divergence is zero as flow is circular



Violates
Divergence is non-zero Represents magnetic point source



Agrees
Divergence is zero as flow is parallel

Maxwell's Equations

Breaking it Down: Ampere's Law

AMPERE'S LAW

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \quad (5)$$

*Flowing current (**J**) within a medium creates a circulating magnetic field (**H**)*

Also, A time varying electric field generates a circulating magnetic field

Maxwell's Equations

Breaking it Down: Faraday's Law

FARADAY'S LAW

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (6)$$

Known as Faraday's Law of Induction
A time varying magnetic field creates a circulating E-Field
A time varying circulating E-Field generates a time varying B-field

Deriving The Wave Equation

Fundamental equations to EM wave propagation

Start off with Maxwell's equations

$$\nabla \cdot D = \rho_v \quad (3)$$
$$\nabla \cdot B = 0 \quad (4)$$
$$\nabla \times E = -\frac{\partial B}{dt} \quad (5)$$
$$\nabla \times H = J + \frac{\partial D}{dt} \quad (6)$$

First two equations not required as these are conditions rather that EM field behaviour

Deriving The Wave Equation

Fundamental equations to EM wave propagation

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \quad (3)$$
$$\nabla \times \boldsymbol{H} = \boldsymbol{J} + \frac{\partial \boldsymbol{D}}{\partial t} \quad (4)$$

Step 1: Rewrite equations in time harmonic form

$$\nabla \times \boldsymbol{E} = -i\omega \boldsymbol{B} \quad (10)$$
$$\nabla \times \boldsymbol{H} = \boldsymbol{J} + i\omega \boldsymbol{D} \quad (11)$$

Deriving The Wave Equation

Fundamental equations to EM wave propagation

$$\nabla \times \boldsymbol{E} = -i\omega \boldsymbol{B} \quad (10)$$
$$\nabla \times \boldsymbol{H} = \boldsymbol{J} + i\omega \boldsymbol{D} \quad (11)$$

Step 2: Substitute the medium dependent parameters

$$\boldsymbol{J} = \sigma \boldsymbol{E} \quad (7)$$
$$\boldsymbol{B} = \mu \boldsymbol{H} \quad (8)$$
$$\boldsymbol{D} = \varepsilon \boldsymbol{E} \quad (9)$$

$$\nabla \times \boldsymbol{E} = -i\omega\mu \boldsymbol{H} \quad (12)$$
$$\nabla \times \boldsymbol{H} = \sigma \boldsymbol{E} + i\omega\varepsilon \boldsymbol{E} \quad (13)$$

Deriving The Wave Equation

Fundamental equations to EM wave propagation

$$\nabla \times \boldsymbol{E} = -i\omega\mu\boldsymbol{H} \qquad (12)$$
$$\nabla \times \boldsymbol{H} = \sigma\boldsymbol{E} + i\omega\varepsilon\boldsymbol{E} \qquad (13)$$

Step 3: Take the Curl of both sides

NOTE: That vector identity $\nabla \times \nabla \times \boldsymbol{H} = \nabla(\nabla \cdot \boldsymbol{H}) - \nabla^2\boldsymbol{H}$

$$\nabla \times \nabla \times \boldsymbol{E} = -\nabla^2\boldsymbol{E} = -i\omega\mu(\nabla \times \boldsymbol{H}) \qquad (14)$$
$$\nabla \times \nabla \times \boldsymbol{H} = -\nabla^2\boldsymbol{H} = \sigma(\nabla \times \boldsymbol{E}) + i\omega\varepsilon(\nabla \times \boldsymbol{E}) \qquad (15)$$

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Deriving The Wave Equation

Fundamental equations to EM wave propagation

$$-\nabla^2\boldsymbol{E} = -i\omega\mu(\nabla \times \boldsymbol{H}) \qquad (14)$$
$$-\nabla^2\boldsymbol{H} = \sigma(\nabla \times \boldsymbol{E}) + i\omega\varepsilon(\nabla \times \boldsymbol{E}) \qquad (15)$$

Step 4: Substitute Ampere's and Faraday's Laws

$$\nabla \times \boldsymbol{E} = -i\omega\mu\boldsymbol{H} \qquad (10)$$
$$\nabla \times \boldsymbol{H} = \sigma\boldsymbol{E} + i\omega\varepsilon\boldsymbol{E} \qquad (11)$$

$$-\nabla^2\boldsymbol{E} = -i\omega\mu(\sigma\boldsymbol{E} + i\omega\varepsilon\boldsymbol{E}) \qquad (16)$$
$$-\nabla^2\boldsymbol{H} = \sigma(-i\omega\mu\boldsymbol{H}) + i\omega\varepsilon(-i\omega\mu\boldsymbol{H}) \qquad (17)$$

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Deriving The Wave Equation

Fundamental equations to EM wave propagation

$$-\nabla^2\boldsymbol{E} = -i\omega\mu(\sigma\boldsymbol{E} + i\omega\varepsilon\boldsymbol{E}) \qquad (16)$$
$$-\nabla^2\boldsymbol{H} = \sigma(-i\omega\mu\boldsymbol{H}) + i\omega\varepsilon(-i\omega\mu\boldsymbol{H}) \qquad (17)$$

Step 5: Rearrange to equal zero

$$\nabla^2\boldsymbol{E} + (-i\omega\mu\sigma + \omega^2\mu\varepsilon)\,\boldsymbol{E} = 0 \qquad (18)$$
$$\nabla^2\boldsymbol{H} + (-i\omega\mu\sigma + \omega^2\mu\varepsilon)\mathbf{H} = 0 \qquad (19)$$

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Deriving The Wave Equation

Fundamental equation to EM wave propagation

<u>FINAL SOLUTION TO THE WAVE EQUATION</u>

$$\nabla^2\boldsymbol{E} + (-i\omega\mu\sigma + \omega^2\mu\varepsilon)\,\boldsymbol{E} = 0 \qquad (18)$$
$$\nabla^2\boldsymbol{H} + (-i\omega\mu\sigma + \omega^2\mu\varepsilon)\mathbf{H} = 0 \qquad (19)$$

let the wavenumber $k^2 = -i\omega\mu\sigma + \omega^2\mu\varepsilon \qquad (20)$

$$\boldsymbol{\nabla^2 E} + \boldsymbol{k^2 E} = \mathbf{0} \qquad (21)$$
$$\boldsymbol{\nabla^2 H} + \boldsymbol{k^2}\mathbf{H} = \mathbf{0} \qquad (22)$$

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Deriving The Wave Equation

Fundamental equations to EM wave propagation

So why is the solution to the wave equation so important

$$k^2 = -i\omega\mu\sigma + \omega^2\mu\varepsilon \qquad (20)$$
$$\nabla^2 \boldsymbol{E} + k^2\boldsymbol{E} = \mathbf{0} \qquad (21)$$
$$\nabla^2 \boldsymbol{H} + k^2\mathbf{H} = \mathbf{0} \qquad (22)$$

At frequencies below 100kHz $\omega^2\mu\varepsilon \ll \omega\mu\sigma$ the equation is predominantly dominated by the **diffusive component**

The influential earth property is **conductivity**

$$\nabla^2 \boldsymbol{E} - i\omega\mu\sigma\boldsymbol{E} = \mathbf{0}$$
$$\nabla^2 \boldsymbol{H} - i\omega\mu\sigma\mathbf{H} = \mathbf{0}$$

(TEM,FDEM,MT,CSAMT…)

Deriving The Wave Equation

Fundamental equations to EM wave propagation

So why is the solution to the wave equation so important

$$k^2 = -i\omega\mu\sigma + \omega^2\mu\varepsilon \qquad (20)$$
$$\nabla^2 \boldsymbol{E} + k^2\boldsymbol{E} = \mathbf{0} \qquad (21)$$
$$\nabla^2 \boldsymbol{H} + k^2\mathbf{H} = \mathbf{0} \qquad (22)$$

At frequencies above100kHz $\omega^2\mu\varepsilon \gg \omega\mu\sigma$ the equation is predominantly dominated by the **reflective component**

The influential earth property is **electrical permittivity**

$$\nabla^2 \boldsymbol{E} + \omega^2\mu\varepsilon\boldsymbol{E} = \mathbf{0}$$
$$\nabla^2 \boldsymbol{H} + \omega^2\mu\varepsilon\boldsymbol{E} = \mathbf{0}$$

(VHF, Radar…)

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LECTURE 02

Fundamentals of EM for Targeting II — S2 2015

- Maxwell's Equations (Recap)
- Resistivity versus Conductivity
- Archie's Law
- Rock Electrical Resistivity
- Driving current through the ground

Maxwell's Equations

Questions should know the answers to

- What is an magnetic field (include units)?
- What is an electric field (include units)?
- Differentiate electro-static, magneto-static and electromagnetics?

- Define current (include units)
- What is current density (include units)?
- What are displacement currents (include units)?

- What is magnetic flux? (include units)
- What is magnetic field intensity? (include units and symbol)
- What is electric field intensity? (include units and symbol)

Maxwell's Equations

The Four Equations

GAUSS'S LAW

$$\nabla \cdot D = \rho_v \quad (3)$$

GAUSS' MAGNETISM LAW

$$\nabla \cdot B = 0 \quad (4)$$

FARADAY'S LAW

$$\nabla \times E = -\frac{\partial B}{dt} \quad (5)$$

AMPERE'S LAW

$$\nabla \times H = J + \frac{\partial D}{dt} \quad (6)$$

$$J = \sigma E \quad (7)$$

$$B = \mu H \quad (8)$$

$$D = \varepsilon E \quad (9)$$

Maxwell's Equations

The Wave Equation

$$k^2 = -i\omega\mu\sigma + \omega^2\mu\varepsilon \quad (20)$$

$$\nabla^2 E + k^2 E = 0 \quad (21)$$

$$\nabla^2 H + k^2 H = 0 \quad (22)$$

What is conductivity and resistivity

Textbook definition

Conductivity

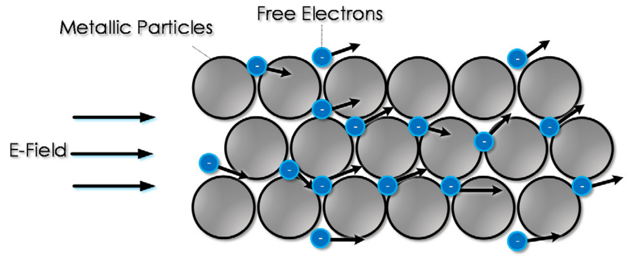
"The ability of a material to conduct electrical current. In isotropic material, the reciprocal of resistivity"

- Sheriff's Encyclopaedic Dictionary of Applied Geophysics, fourth edition

Types of Conduction

Metallic Conduction

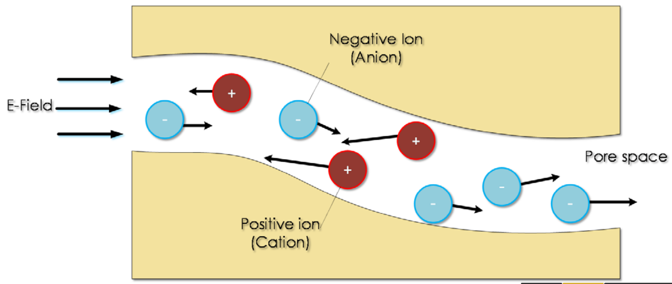
- Metals consist of a rigid lattice of atoms, the electrons in the outer shell can freely dissociate
- In the presence of an electric field it is the movement of electrons and not the atoms themselves that creates the current (i.e., see drift velocity)
- There is no chemical change due to the movement of electrons
- There is no net change in mass of the material due to the movement of electrons



Types of Conduction

Ionic Conduction

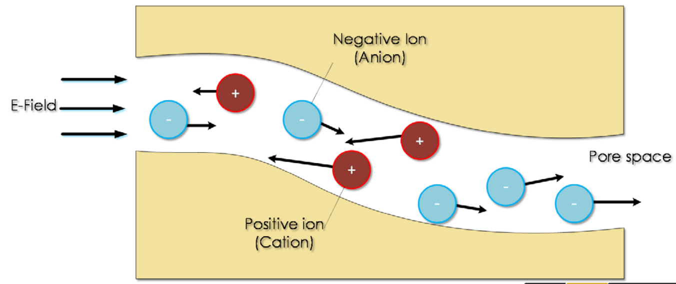
- Ionic conduction in pore fluid is a major form of conduction you will encounter in the earth
- It is caused by the flow of ions rather than free electron flow
- These ions are particles that move in the fluid in the presence of an electric field
- There is a change in water chemistry due to the movement of ionic conduction



Types of Conduction

Ionic Conduction

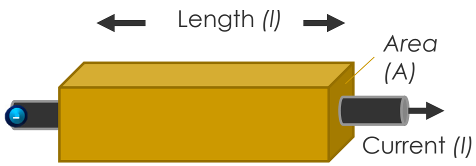
- Positive ions include:
  - Sodium (Na+), Potassium (K+), Magnesium (Mg2+), Calcium (Ca2+)
- Negative ions include;
  - Chloride (CL-), Sulfate (SO42-), Bicarbonate (HCO3-)



Electrical Resistivity

Electrical resistivity of rocks?

- Diffusive electromagnetic methods detect variations in electrical resistivity
- Consider the scenario of passing a current through a rock sample

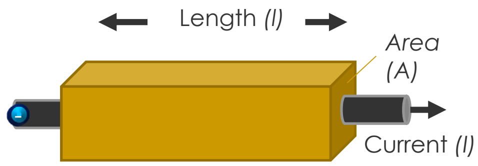


Electrical Resistivity

The rock resistivity

$$\rho = R\frac{A}{l}$$

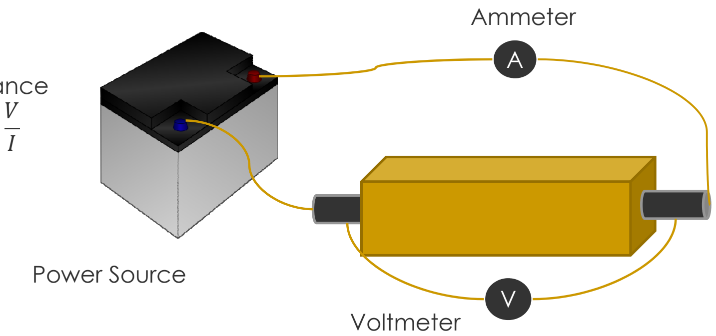
ρ - *Electrical Resistivity* ($\Omega \cdot m$)
R - *Electrical Resistance* (Ω)
A - *Cross sectional Area* (m^2)
l - *Sample Length* (m)



Electrical Resistivity

Practically measuring **RESISTANCE**

Resistance
$R = \frac{V}{I}$

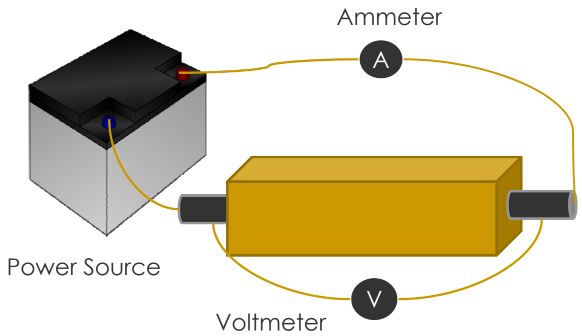


Electrical Resistivity:

Practically measuring **RESISTANCE**

Of course rocks can be very heterogeneous the resistance measured is the average over each rock grain and fluid properties

Note: electrical resistivity is a **tensor.**
That is, rock is electrically anisotropic.



Electrical Resistivity
Electrical Conductivity

Compute the inverse!

Electrical Conductivity is purely the inverse of resistivity

$$\rho = \sigma^{-1}$$

ρ - *Electrical Resistivity* (Ω•m)
σ - *Electrical Conductivity* (S/m)

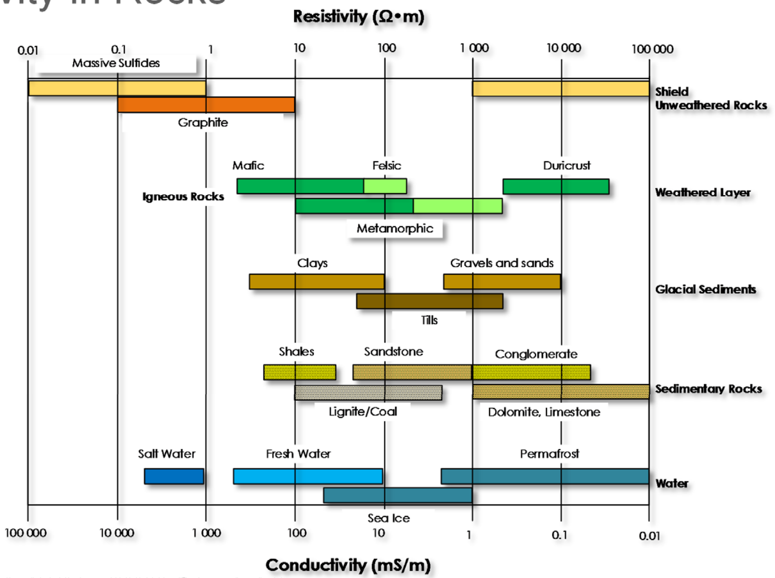
Electrical Resistivity: Theoretical

Relationship between electric field and resistivity

- When you have a resistor within an open environment, you have to view resistivity slightly differently:
  - An electric field inside a rock will cause electrical current to flow through it.
  - The resistivity is the ratio of the electric field and current density

$$\rho = \frac{E}{J}$$

Resistivity in Rocks

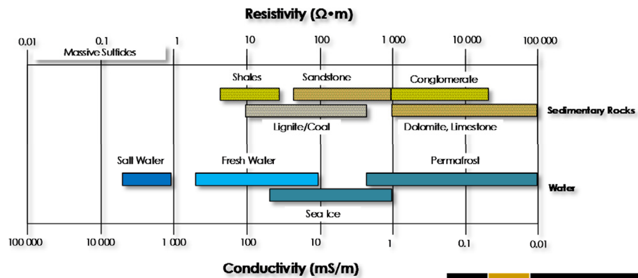


Reproduced from Zonge, Kenneth L., L. J. Hughes, and M. N. Nabighian, "Electromagnetic methods in applied geophysics." *Electromagnetic methods in applied geophysics* (1991).

Resistivity of Sedimentary Rocks

Electrical Conductivity in the Earth

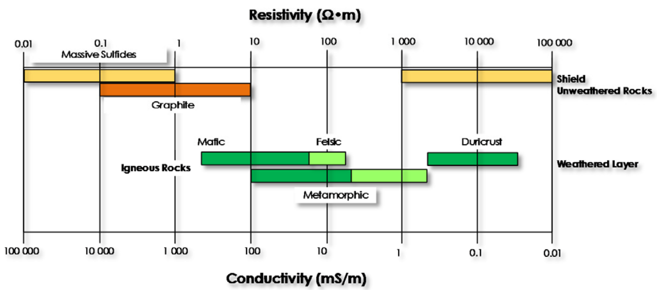
- In sedimentary environments the earth is composed mainly of unconsolidated sands.
- These sands are silicate rich and natural insulators
- Quartz for example has a resistivity of
  $\sim 1 \times 10^{17} \Omega \cdot m$
- The most conductive component of a sedimentary formation is typically the fluid that resides in that rock.



Resistivity of Hard Rock

Electrical Conductivity in the Earth

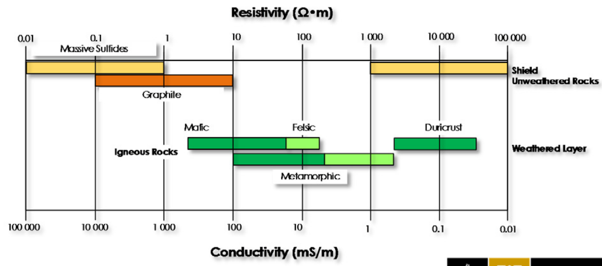
- In hard rock environments massive sulphides are the most conductive features
- Graphitic shale packages may mislead geophysicists as they are also conductive



Resistivity of Hard Rock

Electrical Conductivity in the Earth

- In massive sulphides, conduction is due to metallic conduction. Compared to basaltic and granitic rock, massive sulphides are extremely conductive compared to the host.
  - Aluminium $(\sim 2.8 \times 10^{-8} \Omega \cdot m)$ See http://appliedgeophysics.berkeley.edu/dc/EM44.pdf
  - Copper $(\sim 1.7 \times 10^{-8} \Omega \cdot m)$
  - Iron$(\sim 10 \times 10^{-8} \Omega \cdot m)$

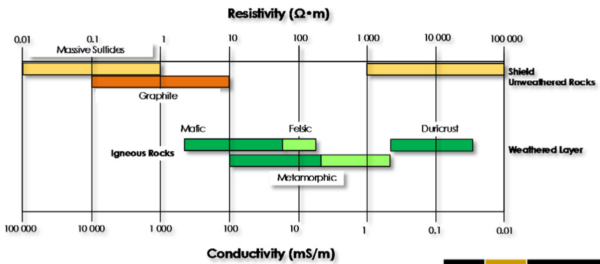


Resistivity of Hard Rock

Electrical Conductivity in the Earth

- Other ore minerals include
  - Chalcopyrite ($CuFeS_2$) : $1.2 \times 10^{-5} \Omega \cdot m$
  - Pyrite (FeS_2) : $3.0 \times 10^{-5} \Omega \cdot m$
  - Galena(PbS) : $3.0 \times 10^{-5} \Omega \cdot m$
  - Hematite (Fe_2O_3) : $3.5 \times 10^{-3} \Omega \cdot m$
  - Magnetite(Fe_3O_4) : $5.0 \times 10^{-4} \Omega \cdot m$

See http://appliedgeophysics.berkeley.edu/dc/EM44.pdf



Resistivity of Sedimentary Rocks

Archie's Law in Context

Gus Archie wanted to determine a relationship between permeability and electrical resistivity.

He did not find any relationship, nor has anyone since found any relationship between permeability and electrical resistivity.

Instead he found a relationship between electrical resistivity and:

- **Pore fluid (R_w)**
- **Porosity (ϕ)** (Within the scope of the course)
- Fluid Saturation (S_w)
- Cementation (m)
- Tortuosity (a)

So in 1942 Archie's law was founded $$R_t = aR_w\phi^{-m}S_w^{-n}$$

Archie's Law

"It is no exaggeration to say that the entire logging industry is based on 'Archie's Law'." – Parasnis, D.S., 1997

$$F = \frac{R_0}{R_w} = \frac{a}{\phi^m} \qquad S_w^n = \frac{R_0}{R_t}$$

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Factors Influencing Formation Resistivity

Physical characteristics of sedimentary formations influencing electrical conductivity

A sedimentary formation's resistivity is generally influenced more by the fluid properties than the rock matrix.

- water chemistry (solute type and concentration)
- formation temperature
- Porosity (ϕ)
- degree of saturation (S_w)
- the nature and degree of cementation (m)
- sediment consolidation and compaction (a)

$$S_w^n = \frac{R_0}{R_t}$$

$$F = \frac{R_0}{R_w} = \frac{a}{\phi^m}$$

- clay type
- clay content
- and clay/cement/silt/sand/gravel distribution within the formation.

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Resistivity of Sedimentary Rocks

Archie's Law

Archie's Law links electrical conductivity of sedimentary rock to its porosity and fluid saturation (i.e., how much of it pore space filled with fluid)

$$F = \frac{R_0}{R_w} = \frac{a}{\phi^m} \qquad S_w^n = \frac{R_0}{R_t}$$

F –Formation Factor
R_0 –Resistivitiy of formation when 100%
S_w –saturated with formation water (Ω•m)
R_w –Resistvitity of formation water (Ω•m)
R_t –True resistivity of formation (Ω•m)
a –Proportionality constant
ϕ –Porosity (%)
m –Cementation factor (1.3-3)
S_w –Water Saturation (%)

Example constants and cementation factors

Description of Rock	a	m
Weakly cemented detrital rocks, such as sand, sandstone, and some limestones, with a porosity range from 25 to 45% usually tertiary in age	0.88	1.37
Moderately well cemented sedimentary rocks, including sandstones and limestones, with a porosity range from 18 to 35%	0.62	1.72
Well cemented sedimentary rocks with a porosity range from 5% to 25%	0.62	1.95
Highly porous volcanic rocks, such as tuff, aa, and pahoehoe, with a porosity in the range of 20% to 80%	3.5	1.44
Rocks with less than 4% porosity, including dense igneous rocks and metamorphosed sedimentary rocks	1.4	1.58

Archie's Law example description table modified from Sheriff, R. (2002). Encyclopedic Dictionary of Applied Geophysics. Society of Exploration Geophysicists.

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Resistivity of Sedimentary Rocks

Archie's Law in Context

Pore Fluid Resistivity (R_w)

In most scenario's ions in the pore fluids control the resistivity of a porous rock formation.

The fluid's resistivity is controlled by several factors including:

- **Total dissolved salts (TDS)**
- Temperature

$$R_t = aR_w\phi^{-m}S_w^{-n}$$

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Resistivity of Sedimentary Rocks

Archie's Law in Context

Pore Fluid Resistivity (R_w)

Total dissolved salts (TDS)

The more ions dissolved in the pore fluid, the more ions that can move in the presence of an electric field.

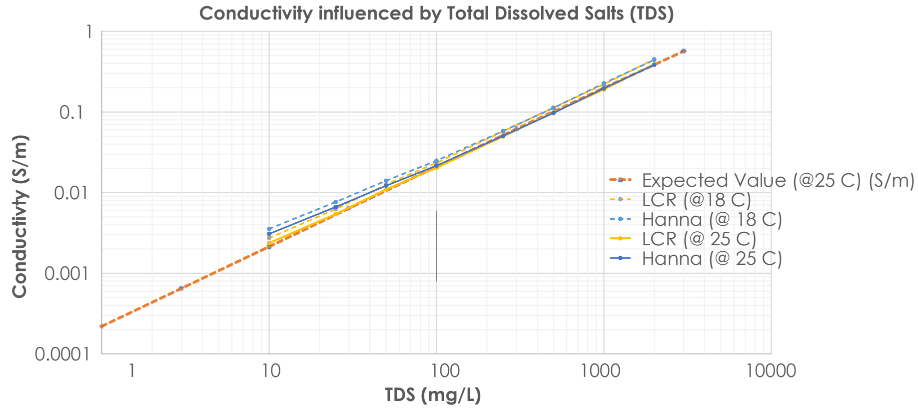
As TDS increases, conductivity increases.

For example:
Rainwater is <100 mg/L (~100 Ω•m)
Tap water 250-400 mg/L (~50 Ω•m)
'Undrinkable water' 1000-2000+ mg/L (~10 Ω•m)
Sea water 30,000 mg/L (~0.3 Ω•m)

$$R_t = aR_w\phi^{-m}S_w^{-n}$$

Factors Influencing Fluid Conductivity

More Total Dissolved Salts (TDS), more ions, more conductive.



Fresh Water 0-1,000 mg/L
Brackish Water 1,000 – 10,000 mg/L
Seawater >35,000 mg/L

Resistivity of Sedimentary Rocks

Archie's Law in Context

Pore Fluid Resistivity (R_w)

In ionic conduction (not metallic conduction):

As temperature increases, conductivity increases.

Ion mobility in solution increases with temperature. An approximate formula can be established linking resistivity as a function of temperature. In seawater it is :

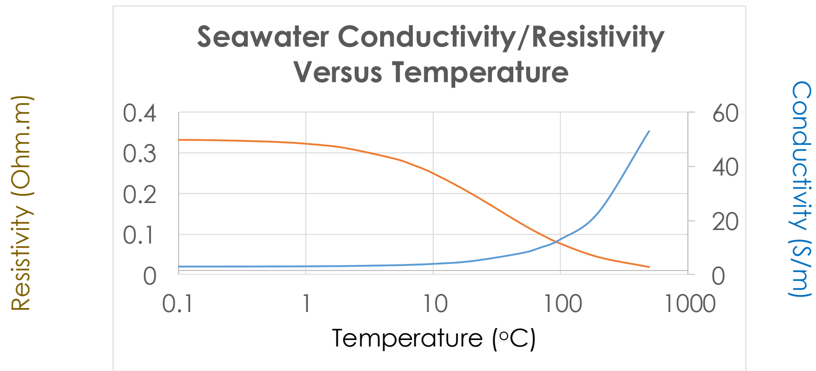
$$\sigma = 3 + \frac{T}{10} \text{ S/m}$$

T is temperature

$$R_t = aR_w\phi^{-m}S_w^{-n}$$

Factors Influencing Fluid Conductivity

The more greater the temperature, the more conductive the fluid

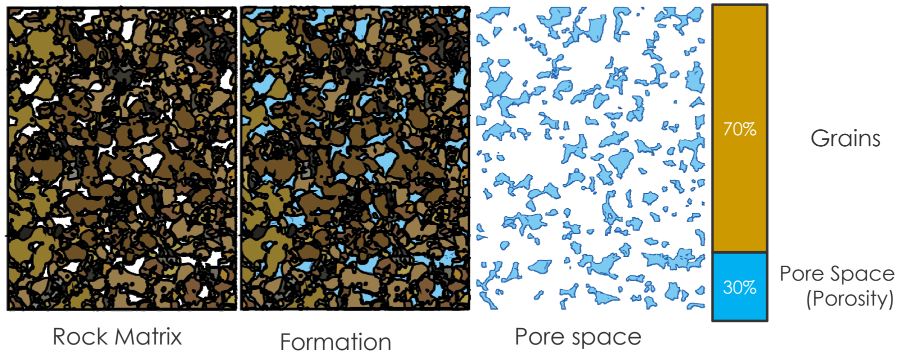


Resistivity of Sedimentary Rocks

Archie's Law

Porosity (ϕ)

Consider a sedimentary rock, it consists of a rock matrix and pore fluids within that rock matrix. The porosity is the percentage of the total formation that could be filled with fluid. With increase porosity increases possible pore fluid capacity



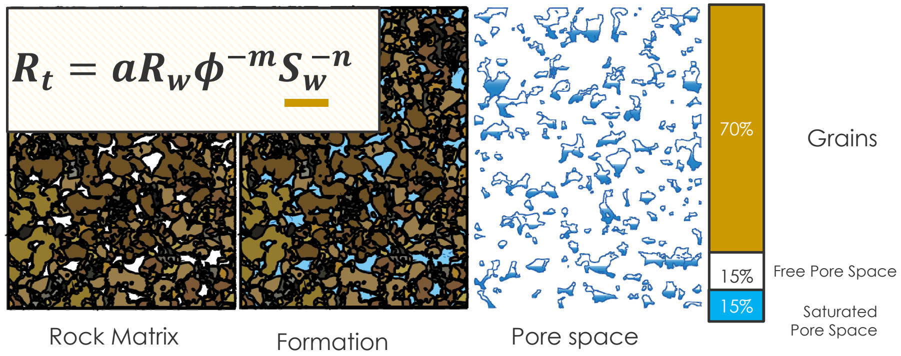
Resistivity of Sedimentary Rocks

Archie's Law

Saturation (S_w)

The saturation is the fraction of the available pore space in the formation that is filled with fluid:
If $S_w = 100\%$ all pore spaces are filled with fluid
Note: Not all pore spaces are filled with fluid

$$R_t = aR_w\phi^{-m}S_w^{-n}$$



Resistivity of Sedimentary Rocks

Archie's Law Effect of Clay

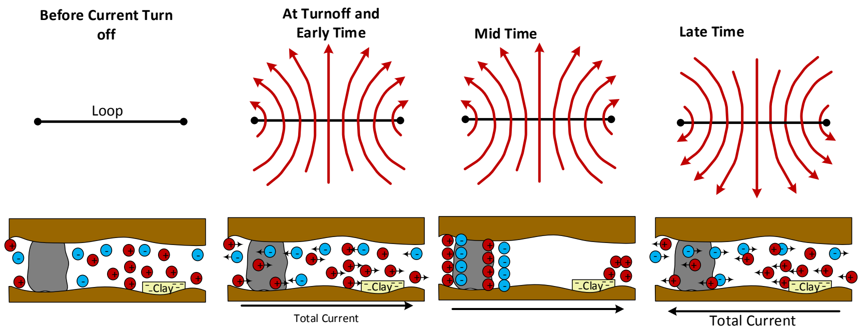
- The presence of clay complicates Archie's law
- Clay causes resistivity to be frequency dependent
- With increasing clay content, bulk resistivity decreases

According to Berkley, 2015,

"The effect on the bulk resistivity was first noticed in studies of rocks containing clay where it was found that the Archie equation obtained with low resistivity pore fluids consistently overestimated the bulk resistivity predicted when high resistivity pore fluids were substituted. The effect is due to the fact that clay minerals have an electrically 'active' surface layer"

See http://appliedgeophysics.berkeley.edu/dc/EM44.pdf

- Induced polarization (IP) are caused by ionic movement in fluid filled pore spaces when metallic and clay minerals are present.



Rock Properties

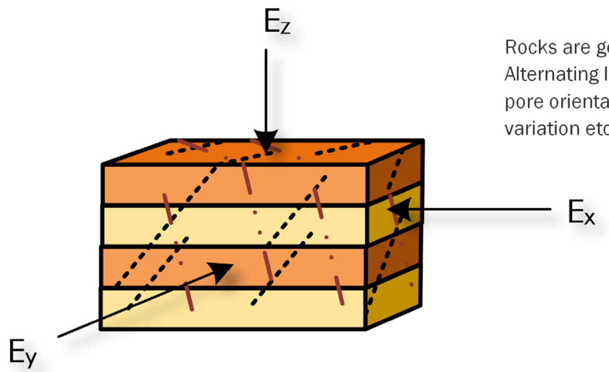
Driving current in multiple directions

Conductivity is a tensor and represents the degree to which the rock conducts electricity for a given electric field.

$$J = \sigma E$$

$$\sigma = \begin{matrix} \\ x \\ y \\ z \end{matrix} \begin{matrix} x & y & z \\ \left[\begin{matrix} \sigma_{xx} & & \\ & \sigma_{yy} & \\ & & \sigma_{zz} \end{matrix}\right] \end{matrix}$$

Rocks are generally anisotropic. Alternating layers, fractures, grain and pore orientation, fluid conductivity variation etc..

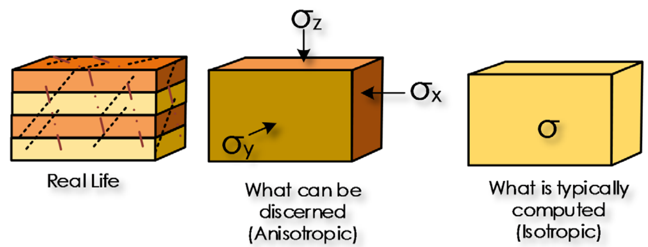


Rock Properties

Driving current in multiple directions

Low frequency electromagnetics is diffusive and as a result it detects bulk volumes of rock.

Packages of thin layers may appear as a single anisotropic or isotropic unit.



$$\sigma = \begin{bmatrix} \sigma_{xx} & \sigma_{yx} & \sigma_{zx} \\ \sigma_{xy} & \sigma_{yy} & \sigma_{zy} \\ \sigma_{xz} & \sigma_{yz} & \sigma_{zz} \end{bmatrix}$$

Full tensor, for each grain, fracture, layer etc…

$$\begin{bmatrix} \sigma_h & & \\ & \sigma_h & \\ & & \sigma_v \end{bmatrix}$$

Only horizontal (σ_h) and vertical (σ_v) conductivity

$$\begin{bmatrix} \sigma & & \\ & \sigma & \\ & & \sigma \end{bmatrix}$$

Constant conductivity

Anisotropy

Computation

Resistivity and Conductivity are both tensors. However different forward and inverse codes may simplify the full conductivity/resistivity tensor.

Complex/computationally expensive

$$\begin{matrix} x & y & z \\ \left[\begin{matrix} \rho_{xx} & \rho_{xy} & \rho_{xz} \\ \rho_{yx} & \rho_{yy} & \rho_{yz} \\ \rho_{zx} & \rho_{zy} & \rho_{zz} \end{matrix}\right] \end{matrix}$$

Full Resistivity Tensor

$$\rho = \begin{matrix} \\ x \\ y \\ z \end{matrix} \begin{matrix} x & y & z \\ \left[\begin{matrix} \rho_h & & \\ & \rho_h & \\ & & \rho_v \end{matrix}\right] \end{matrix}$$

2D Anisotropic Resistivity Tensor (Horizontal and vertical only)

$$\rho = \begin{matrix} \\ x \\ y \\ z \end{matrix} \begin{matrix} x & y & z \\ \left[\begin{matrix} \rho & & \\ & \rho & \\ & & \rho \end{matrix}\right] \end{matrix}$$

Isotropic Resistivity Tensor (Horizontal and vertical only)

'simple'/computationally inexpensive

Increasing Complexity\Computation

Rock Properties

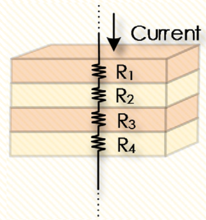
Layers as a circuit

Remember the connection between Ohm's Law ($V = IR$) and current density ($J = \sigma E$):

$$V = IR \leftrightarrow E = J\left(\frac{1}{\sigma}\right)$$

The earth can also be thought as a circuit of connected resistors. The total resistance of the 'earth circuit' depends on which direction current is driven.

Vertical Resistivity

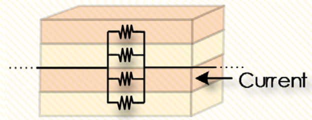


Resistors in series

$$R_T = R_1 + R_2 + R_3 + R_4 \ldots$$

Sensitive to highest resistance

Horizontal Resistivity



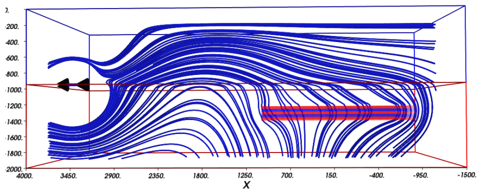
Resistors in parallel

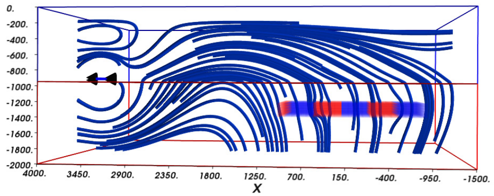
$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} \ldots$$

Sensitive to lowest resistance

Anisotropy

Driving current through the earth





These are electric field lines and represent the direction of current flow.

Both images have the same volume of resistive and conductive material

(**TOP**) Note that current is driven vertically through the body when it is layered avoids the package of interbedded rock.

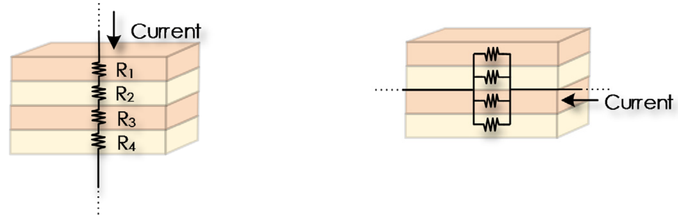
(**BOTTOM**) Note that the current 'avoids' the resistive (red) material and preferentially is driven between the conductive (blue) blocks.

- Resistive Material
- Conductive Material

Driving Current Through the Earth

Remember!

The electrical property of earth detected from an EM survey is determined by the direction of current flow through the earth.



Driving Current Through the Earth

First Some Definitions

Dipole

1. *A pair of equal charges or poles of opposite signs that ideally are infinitesimally close together.*
2. *In resistivity and IP surveying, a pair of nearby current electrodes that approximates a dipole field from a distance, or a voltage-detecting electrode pair. Where the electrode separation is large, it is sometimes called a bipole.*
3. *In electromagnetic surveying, an electric- or magnetic-field transmitting or receiving antenna which is small enough to be represented mathematically as a dipole. The near fields (electric and magnetic) from a magnetic and electric dipole (respectively) vary as the inverse cube of the distance.*

- **Sheriff's Encyclopaedic Dictionary of Applied Geophysics, fourth edition**

Question

Bipole or Dipole

Bipole

"A dipole electrode arrangement in which the electrodes of the dipole are an appreciable distance apart when compared to source-receiver separation."

- **Sheriff's Encyclopaedic Dictionary of Applied Geophysics, fourth edition**

Driving Current Through the Earth

First Some Definitions

	Electric	Magnetic
Bipole		
Dipole		

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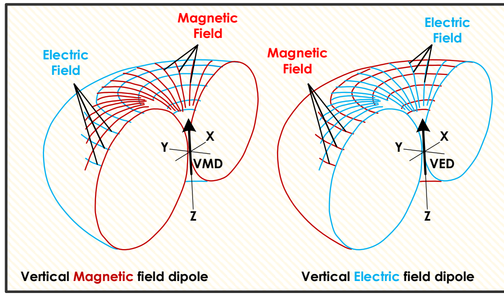
Driving Current Through the Earth

Types of sources

The transmitter type and orientation determines how current travels in the subsurface

There are three main types of electromagnetic sources :
- Electric field
- Magnetic field
- Electromagnetic plane wave



Current is driven along the electric field lines

For VMD, current is horizontal
For VED, current is vertical
For plane wave, current is horizontal

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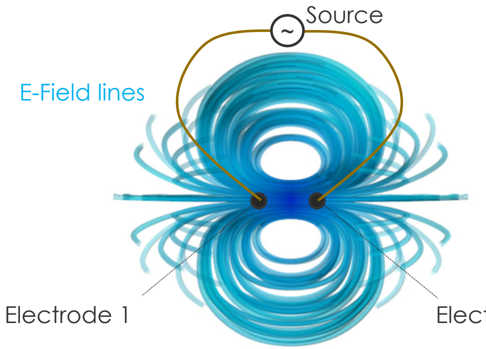
Driving Current Through the Earth

What is an electric field source?

An **electric bipole** source consists of two electrodes connected to a waveform generator.



In a horizontally layered earth, a horizontally placed electric bipole will drive current will be driven vertically through the earth

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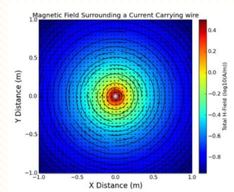
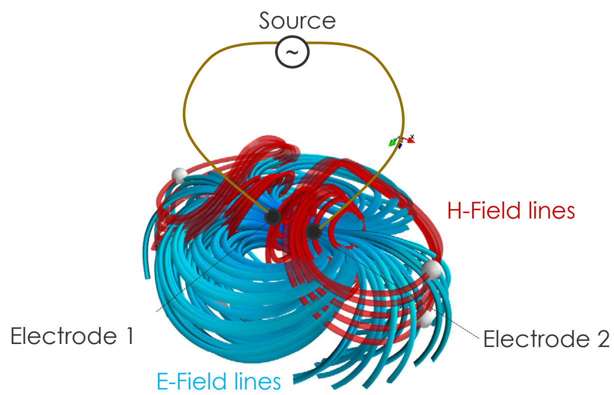
Driving Current Through the Earth

Electric field sources

Note the circulating magnetic field. Just like the circulating magnetic field around a wire, but time varying





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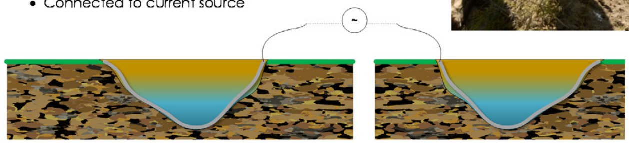
Driving Current Through the Earth

Examples of electric field sources

Ground based CSEM using an electric bipole transmitter

Two Electrode pits
- Lined with aluminium foil
- Filled with saline water
- Connected to current source



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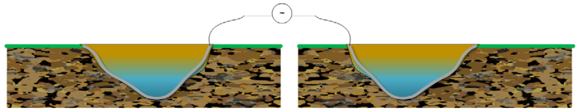
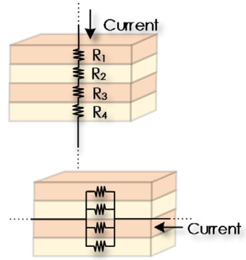
Question

Using this electric bipole transmitter:

1. What direction is current driven into the Earth?
2. What component of the conductivity tensor are we sensitive to?
2. Is this system sensitive to 'conductive' or 'resistive' layers?





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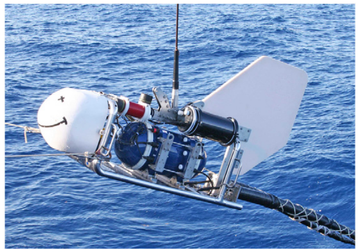
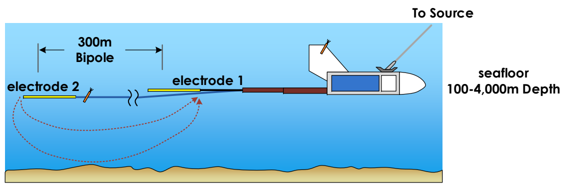
Driving Current Through the Earth

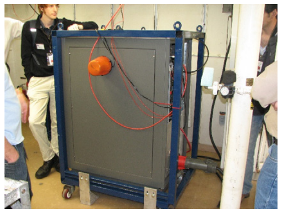
Examples of electric field sources



Marine based CSEM using an electric bipole transmitter

Transmitter "fish" (From Key, K. (2009). Scripps undersea electromagnetic source instrument. http://marineemlab.ucsd.edu/instruments/suesi.html.)





1000A Source

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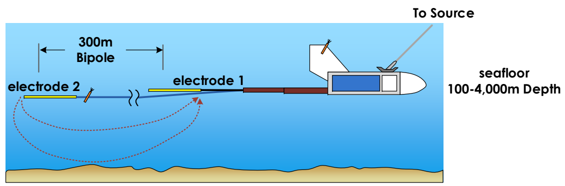
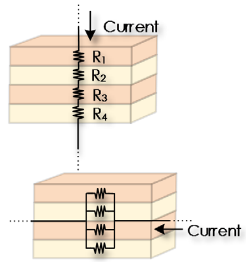
Question

Using this electric bipole transmitter:

1. What direction is current driven into the Earth?
2. What component of the conductivity tensor are we sensitive to?
2. Is this system sensitive to 'conductive' or 'resistive' layers?





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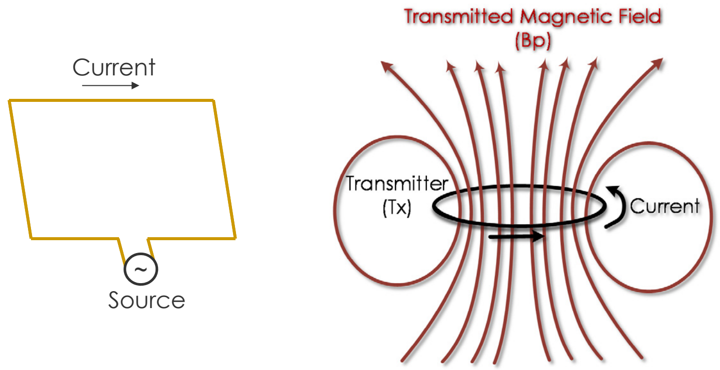
Driving Current Through the Earth

What is a magnetic field source?

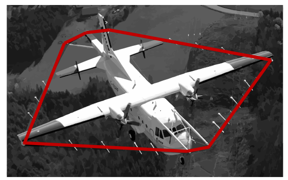
An **magnetic loop** source consists of a loop circuit connected to a waveform generator.

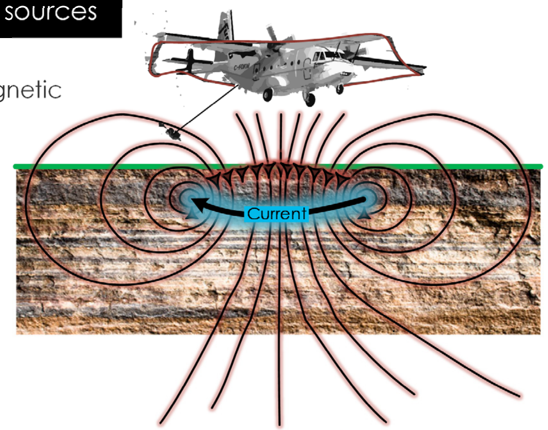


Driving Current Through the Earth

Examples of magnetic field sources

Airborne EM, Tempest magnetic field loop source

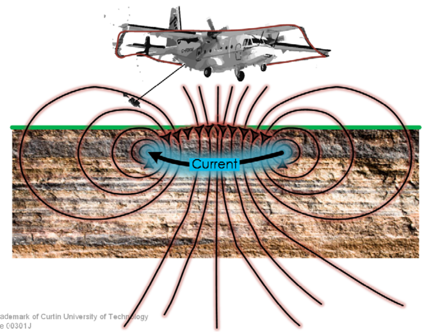


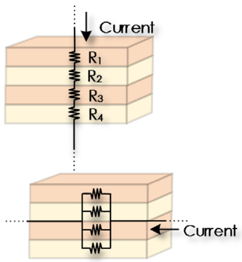


Question

Using this horizontal magnetic loop transmitter:

1. What direction is current driven into the Earth?
2. What component of the conductivity tensor are we sensitive to?
2. Is this system sensitive to 'conductive' or 'resistive' layers?





Driving current through the earth

Transmission and detection of electric and magnetic fields

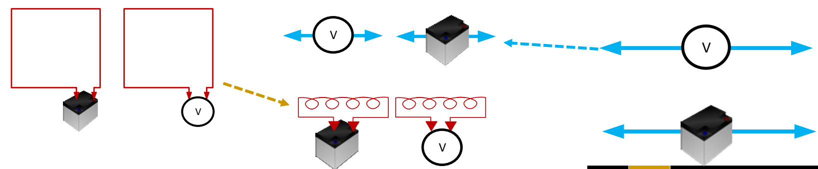
Physically Transmitters and Receivers are the same
(Except one transmits and one receives)

Magnetic Field → Loop (Vertex Positions)

Magnetic Field → Dipole ← Electric Field

Dipole: Dimensionless (only orientation)

Electric Field → Bipole (Vertex Positions)



LECTURE 03

Frequency Domain Electromagnetics S2 2015

- Eddy Current
- Earth as a RL Circuit
- FDEM Complex Response
- Relationship between Time Domain and Frequency Domain
- Attenuation, Skin Depth and Diffusion Depth
- Applications of FDEM

Lecture 02 - Recap

Questions should know the answers to

- What is conductivity
- What is it's relationship to resistivity
- How do you measure rock conductivity in the lab
- What are the two main types of conduction
- Rank the following from most conductive to least conductive
  - Clay
  - Salt Water
  - Sandstone saturated with fresh water
  - Granite
  - Massive Sulphide Ore
- List the main types of electric and magnetic field transmitters?
- In a horizontally layered earth what direction does current flow due to a horizontal magnetic field loop transmitter?

Frequency domain EM

What is Frequency Domain EM

Frequency domain
Energizes the earth with a few discrete frequencies

The response is analyzed in frequency domain
(Amplitude, phase, in-phase, quadrature versus frequency)

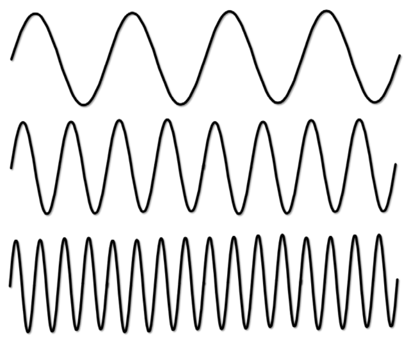
Time domain EM
Energizes the earth with a wide, continuous range frequencies

The response is analyzed in time
(Amplitude versus time)

Frequency domain EM

What is Frequency Domain EM

Frequency domain EM (FDEM)
Transmits a time varying, typical monochromatic (Single frequency) frequency



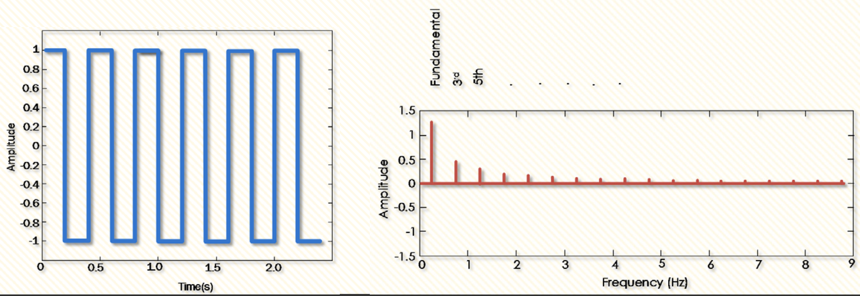
**Did you know that?
Electromagnetic field forward and inverse solutions are typically computed in the frequency domain. Not the time domain.**

Frequency domain EM

What is Frequency Domain EM

FDEM surveys transmit a time varying electric or magnetic field. The waveform is typically constructed to emphasize several key frequencies.

Consider this example of a 0.25Hz 100% duty cycle waveform. The waveform distributes its energies on odd harmonics of the base frequency (i.e., 0.25,0.75,1.25,1.75…)



What is an Eddy Current

Eddy Current

"A circulating electrical current induced in a conductive body by a time-varying magnetic field. Lenz's law states that the direction of eddy current flow is such as to produce a secondary magnetic field that opposes the primary field. The secondary field has a quadrature component that depends on the ratio of the resistance to the reactance of the eddy-current path. In electromagnetic prospecting, eddy currents should be distinguished from naturally occurring currents or those of natural electrochemical origin. "

- **Sheriff's Encyclopaedic Dictionary of Applied Geophysics, fourth edition**

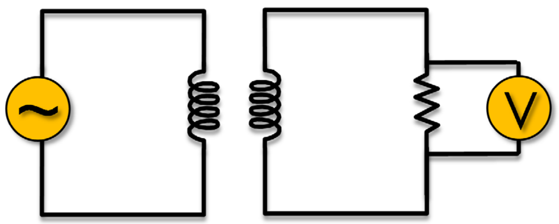
Frequency domain EM

Mutual Inductance

Mutual inductance:

When a transmitted magnetic field via a coil induces a voltage in an adjacent coils.

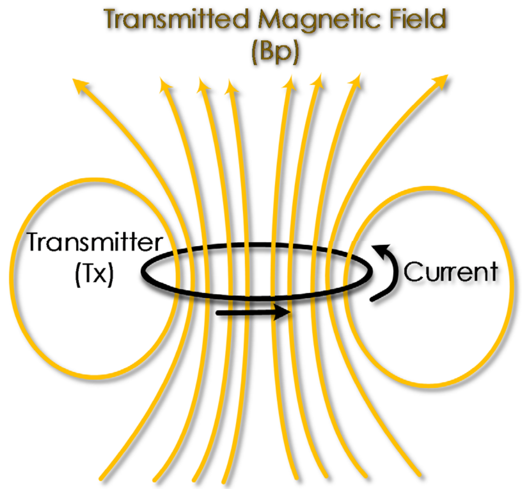
Think transformers.



Frequency domain EM

What is Frequency Domain EM

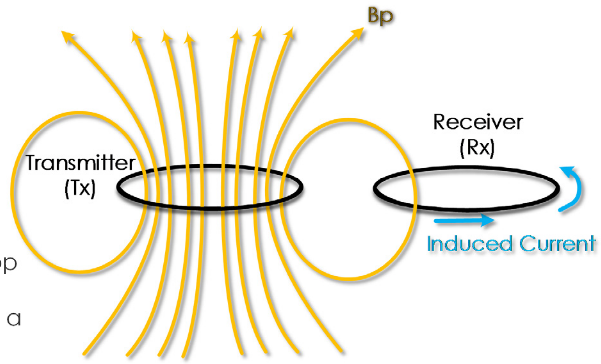
The primary transmitted field
A loop of wire that has flowing current will induce a magnetic field.



Frequency domain EM

What is Frequency Domain EM

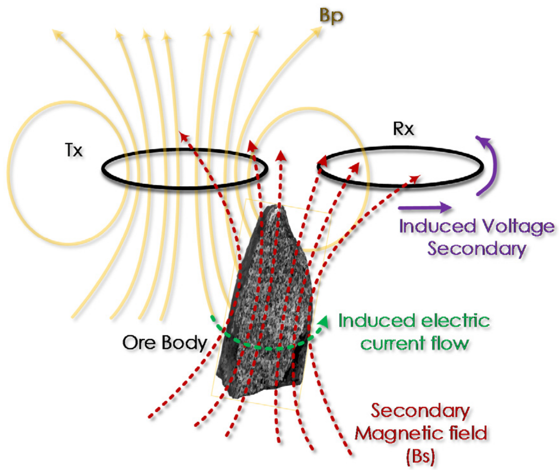
The received field
This induced primary magnetic field can be detected in a second loop receiver (Rx). The field Primary H-field will induce a current in the Rx Loop.



Frequency domain EM

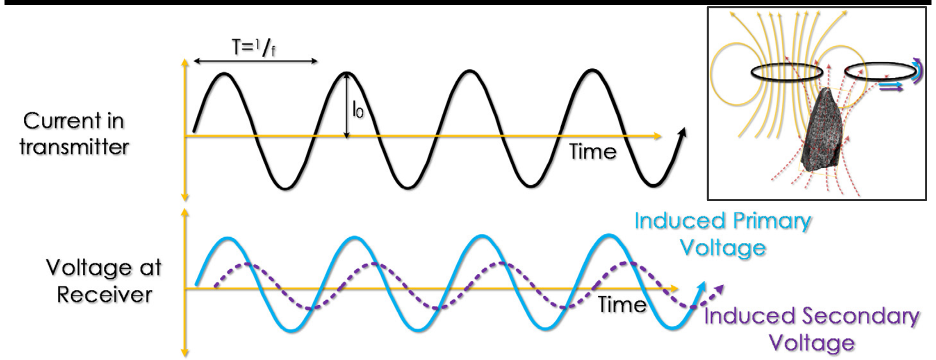
The secondary field
The primary magnetic field will induce eddy currents to flow in a conductive ore body. The current will induce a secondary (Bs) magnetic field.

This secondary magnetic field is also detected at the receiver.



Frequency domain EM

What is Frequency Domain EM



The receiver loop will detect voltages induced from both the **primary** and **secondary** magnetic fields.

The induced **secondary** recorded voltage will be lower than the induced **primary** voltage and at with phase (ϕ) offset.

Frequency domain EM

Real and Imaginary Components

- A sinusoidal wave has multiple representations including:

  Standard Representation

  $y = A_0 \sin(2\pi f t + \phi)$

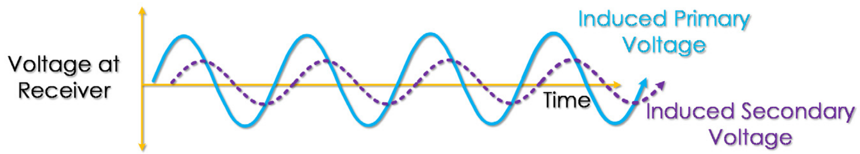
  Complex Representation

  $z = a + bi$

- These representations are interchangeable

  $A_0 = \sqrt{a^2 + b^2}$

  $\phi = atan2(b, a)$

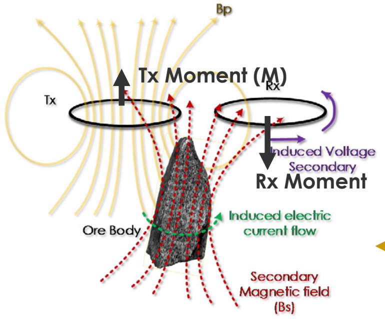


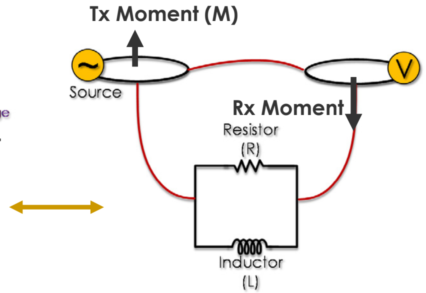
Frequency domain EM

Mathematical Representation of Mutual Coupling

System as a RL Circuit

We can conceptualise the earth as mutual conduction or magnetic flux linked circuits. In this case a LR circuit.





Frequency domain EM

Mathematical Representation of Mutual Coupling

System as a RL Circuit

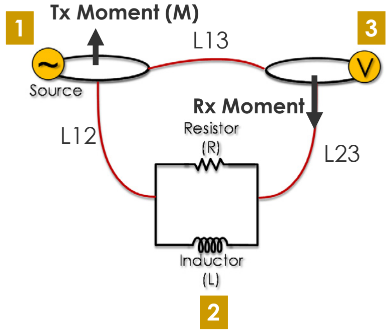
We consider **L** to be a mutual induction term and links each circuit.

The alternating primary magnetic field there creates are **"Primary Field Linkages".**

- L13 - Primary Flux
- L12 - Inducing Flux

The eddy currents induced in the body generates a secondary magnetic field. This creates **"Secondary Field Linkages"**

- L23



Frequency domain EM

Mathematical Representation of Mutual Coupling

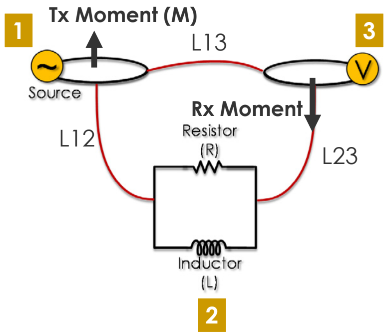
System as a RL Circuit

L13 is the mutual inductance link between transmitter and the receiver. It incorporates all information about TX-RX geometry and

L12 is the mutual inductance link between the transmitter and earth body. It is the excitation force.

L22 is the targets own self inductance

L23 is the secondary field linkage



Frequency domain EM

Mathematical Representation of Mutual Coupling

System as a RL Circuit

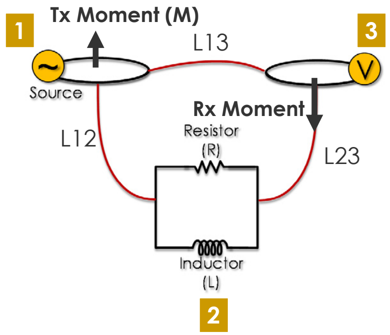
L13
The primary magnetic flux generated at the receiver can be computed using the equation:

$$B_p = \frac{\mu M}{4\pi r^2}$$

Where,

$M = AI$

$\mu = 1.26 \times 10^{-6}$
$r =$ Distance from transmitter (m)
$A =$ Transmitter Loop Area (m^2)
$I =$ Transmission Current (A)



Frequency domain EM

Mathematical Representation of Mutual Coupling

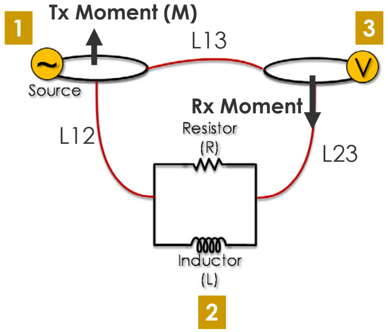
System as a RL Circuit

Mutual Inductance

The voltage of the system also is proportional to the inductance and the change in current with time.

The higher the change, the larger the induced voltage

$$e = -L\frac{dI}{dt} \quad \text{(Differential Form)}$$
$$e = -i\omega LI \quad \text{(Frequency Form)}$$



Frequency domain EM

Mathematical Representation of Mutual Coupling

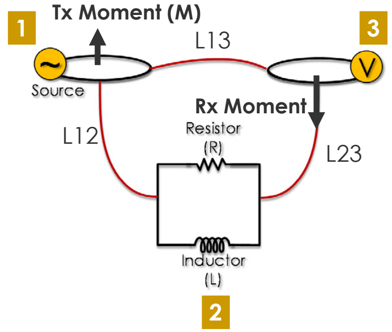
System as a RL Circuit

Coupling between the transmitter and receiver (L13)
The magnetic flux from the primary loop cuts across the receiver loop. The voltage induced follows

$$e_p = -i\omega L_{13} I_1$$

I_1 - Transmitted Primary Voltage

$$e = -L\frac{dI}{dt} \quad \text{(Differential Form)}$$
$$e = -i\omega LI \quad \text{(Frequency Form)}$$



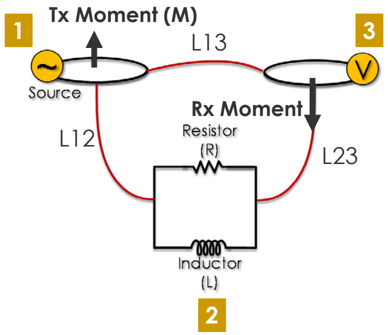
Frequency domain EM

Mathematical Representation of Mutual Coupling

System as a RL Circuit

Coupling between the induced EMF and receiver (L23)
The secondary magnetic flux induced from the circuit cuts across the receiver loop. The voltage induced follows

$$e_s = -i\omega L_{23} I_2$$



Frequency domain EM

Mathematical Representation of Mutual Coupling

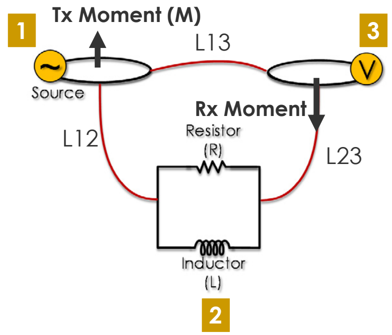
System as a RL Circuit

$$e_s = -i\omega L_{23} I_2$$

The Induced eddy current in "body" (I_2)is computed from:

$$I_2 = \frac{-\omega L_{12} I_1}{R_{22} + i\omega L_{22}}$$

Note that the induced eddy currents are proportional to the transmitted current. **Double the current, double the response.**



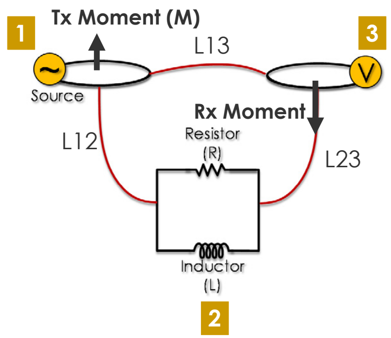
Frequency domain EM

Mathematical Representation of Mutual Coupling

System as a RL Circuit

The ratio of secondary to primary voltage at the receiver

$$\frac{e_s}{e_p} = -\left(\frac{L_{12}L_{23}}{L_{22}L_{13}}\right)\left(\frac{i\omega\tau}{1+i\omega\tau}\right)$$



Frequency domain EM

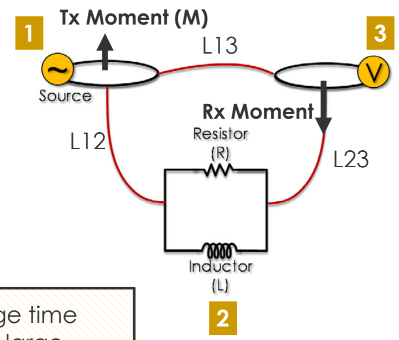
Mathematical Representation of Mutual Coupling

System as a RL Circuit

What is τ?

τ is the <u>time constant</u> gives you an idea of earth properties. It is dependent upon the circuits shape, size and conductivity.

$$\tau = \frac{L}{R}$$

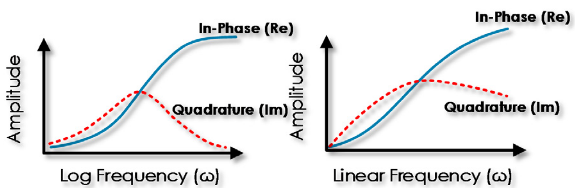


In a survey you discover a target with a large time constant, you can conclude that it is either large, conductive or better yet both large and conductive.

Frequency domain EM

Mathematical Representation of Mutual Coupling

So how do you display Frequency Domain results?



The results are typically plotted on a linear-log plot of amplitude versus frequency of both the real and imaginary components.

Note:
These phrases are interchangeable

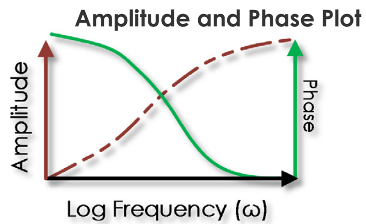
<u>Real Component</u>
Re
In-Phase component

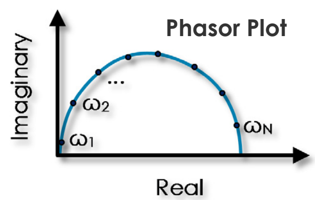
<u>Imaginary Component</u>
Im
Imag
Quadrature
Out-of-phase component

Frequency domain EM

Mathematical Representation of Mutual Coupling

So how do you display Frequency Domain results?





Remember that amplitude and phase can be converted from Re an Im

$$A_0 = \sqrt{re^2 + im^2}$$
$$\phi = atan2(im, re)$$

(Note: Display FD information is not limited to these representations.)

Frequency domain EM

Side Note: Why use atan2 and not atan

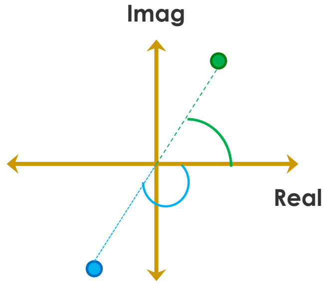
So, why do you use **atan2** instead of **atan** to compute phase calculations?

$$A_0 = \sqrt{re^2 + im^2}$$
$$\phi = atan2(im, re)$$

atan takes in a single value re/im, while atan2 takes both arguments and handles negatives.

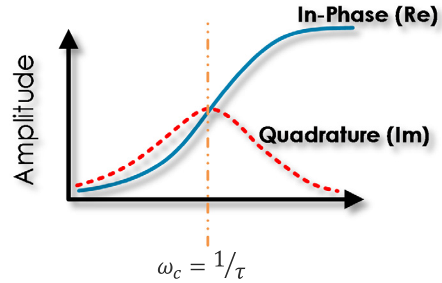
real =	1
imag =	2
atan2(imag/real) =	1.107148718
atan(imag/real) =	1.107148718

real =	-1
imag =	-2
atan2(imag/real) =	-2.034443936
atan(imag/real) =	1.107148718



Frequency domain EM

Mathematical Representation of Mutual Coupling

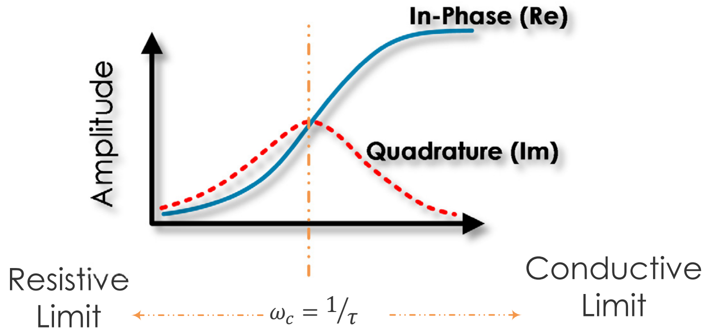


On a log-log plot the in-phase and quadrature response smoothly transitions between the low and high frequency limits. The transition centres upon the characteristic frequency.

ω_c the characteristic frequency is dependent upon the circuit's shape, size and conductivity.

Frequency domain EM

Mathematical Representation of Mutual Coupling

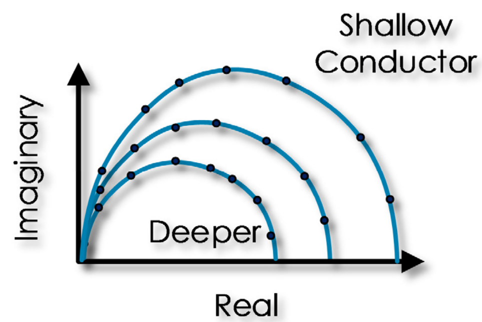


The **Low-frequency limit** is termed the **resistive limit**. This occurs when the induced current $\left(I \propto \frac{dB}{dt} \propto \omega\right)$ from the resulting magnetic flux is so weak that the magnetic flux in target loop is near zero.

The **High-frequency limit** is termed the **inductive limit**. This is where the amplitude of the induced flux converges on that of the primary magnetic flux.

Frequency domain EM

Mathematical Representation of Mutual Coupling



See how different geo-electrical factors influence the frequency domain response in lab 1

Attenuation with distance

EM Wave attenuation

- Electromagnetic waves do not attenuate in free space. For low frequencies consider it as infinitely resistive.
- In the earth, and at low frequencies, the conductivity of the earth influences the rate of energy loss.
- EM Energy is merely the conversion between other forms of energy
  - Heat
  - EM to Sound (electro-seismic)
  - Sound to EM (seismo-electric)
  - Mechanical

ELECTROMANGETIC WAVES DO NOT WANT TO EXIST

Attenuation with distance

EM Wave attenuation

Remember the solution to the wave equation?

$$\mathbf{k^2 = -i\omega\mu\sigma + \omega^2\mu\varepsilon}$$
$$\mathbf{\nabla^2 E + k^2 E = 0}$$
$$\mathbf{\nabla^2 H + k^2 H = 0}$$

$\boldsymbol{\varepsilon_0 = 8.854187 \times 10^{-12} F/m}$ $\boldsymbol{\mu_0 = 4\pi \times 10^{-7} H/m}$

In Air

$\varepsilon_{air} = 1.00054 \times \varepsilon_0$
$\mu_{air} = \mu_0$
$\sigma_{air} \approx 10^{-12} S/m$

if $f = 1000Hz$
$k^2 = -i \times 7.90 \times 10^{-15} + 4.4 \times 10^{-10}$

In Granite

$\varepsilon_{granite} = 10 \times \varepsilon_0$
$\mu_{granite} = \mu_0$
$\sigma_{granite} \approx 10^{-4} S/m$

if $f = 1000Hz$
$k^2 = -i \times 7.90 \times 10^{-7} + 4.4 \times 10^{-9}$

The imaginary component becomes significant in more conductive material

Attenuation with distance

EM Wave attenuation

Remember the solution to the wave equation?

$$\mathbf{k^2 = -i\omega\mu\sigma + \omega^2\mu\varepsilon}$$
$$\mathbf{\nabla^2 E + k^2 E = 0}$$
$$\mathbf{\nabla^2 H + k^2 H = 0}$$

$\boldsymbol{\varepsilon_0 = 8.854187 \times 10^{-12} F/m}$ $\boldsymbol{\mu_0 = 4\pi \times 10^{-7} H/m}$

In air and poorly conducting rocks $k \approx 0$

$$\nabla^2 E = 0$$
$$\nabla^2 H = 0$$

In conductive environments k becomes significant (and at low frequencies)

$$\nabla^2 E = i\omega\mu\sigma E$$
$$\nabla^2 H = i\omega\mu\sigma H$$

Attenuation with distance

EM Wave attenuation

$$\nabla^2 E = i\omega\mu\sigma E$$
$$\nabla^2 H = i\omega\mu\sigma H$$

(travelling along z axis with xy polarization plane)

The solution for the above wave equations for a plane polarized wave takes the form:

$$H = H_y(z,t) = H_0 e^{i\omega t + mz}$$

$$\text{Where } m^2 = i\omega\mu\sigma = -(1+i)\sqrt{\left(\frac{\omega\mu\sigma}{2}\right)}$$

Taking the real component we get

$$H_y = H_0 e^{-\sqrt{\frac{\omega\sigma\mu}{2}}z}$$

Skin Depth

1/e

$$H_y = H_0 e^{-\sqrt{\frac{\omega\sigma\mu}{2}}z}$$

$$E_y = E_0 e^{-\sqrt{\frac{\omega\sigma\mu}{2}}z}$$

Rearranging equation for Hy will enable us to determine the depth at which the in-phase component of the electromagnetic field will drop to 1/e

$$\delta = \sqrt{\frac{2}{\sigma\mu\omega}} = 503\sqrt{\frac{\rho}{f}}\ \text{m}$$

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Skin Depth

1/e

Skin Depth

The effective depth of penetration of electromagnetic energy in a conducting medium when displacement currents can be neglected. The depth at which the amplitude of a plane wave has been attenuated to 1/e (or 37 percent).

$$\delta = \sqrt{\frac{2}{\sigma\mu\omega}} = 503\sqrt{\frac{\rho}{f}}\ \text{m}$$

σ – Conductivity (S/m)
ρ – Resistivity (Ω•m)
f – Frequency (Hz)

- Sheriff's Encyclopaedic Dictionary of Applied Geophysics, fourth edition

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Skin Depth

1/e

$$\delta = \sqrt{\frac{2}{\sigma\mu\omega}} = 503\sqrt{\frac{\rho}{f}}\ \text{m}$$

↑Frequency leads to ↓penetration depth
↑Waveform period leads to ↑penetration depth

↑Earth Conductivity leads to ↓penetration depth
↑Earth Resistivity leads to ↑penetration depth

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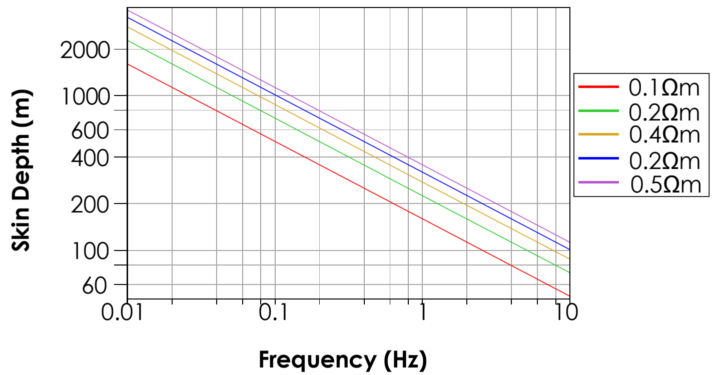
Skin Depth

Computed skin depths

Skin Depth for Various Resistivity Mediums versus Frequency



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Examples of FDEM Systems

DIGHEM V Helicopter Borne FDEM System

Credit: Romios Gold Resources Inc , 2015
Image reproduced from http://www.romios.com/s/TrekPhotos.asp?ReportID=326921

Examples of FDEM Systems

EM-38 (20,000Hz)

Credit: Agrosal, 2015
Image reproduced from http://agrosal.ivia.es/imagenes/b_sonda_vertical.jpg

LECTURE 04

Time Domain EM and the Impulse Response S2 2015

- Time Domain Principles
- Time Domain Surveys
- Eddy Currents and Secondary Magnetic Fields
- Smoke Rings
- Applications in Time Domain EM

MOCK TEST

MOCK TEST

1. What is an electric field (1 sentence)
2. What is an magnetic field? (1 sentence)
3. Write down Maxwell's four (4) equations
   (**Ampere's Law, Gauss's Law, Faraday's Law, Gauss's Magnetism Law)**
4. What are the constitutive/medium dependent parameters
5. What is conductivity and what is its relationship to resistivity.
   (Use the phrase "*current density*" in your answer)
6. List several factors which influences the resistivity of a sedimentary rock? (e.g., clay content)
7. Which of the following scenarios will result in the greatest skin depth?
   - 1 Ω•m earth given a transmission frequency of 1Hz
   - 100 Ω•m earth given a transmission frequency of 1Hz
   - 1 Ω•m earth given a transmission frequency of 100Hz
   - 100 Ω•m earth given a transmission frequency of 100Hz

Recap of Last Week

Frequency Domain EM

What is an eddy current?
What is mutual inductance?
What is amplitude and phase in relation to real and imaginary?
What are the characteristic curves for FDEM?
How do EM Fields attenuate?
What is the skin depth?

Time domain EM

Time vs Frequency Domain EM

Frequency domain
Energizes the earth with a few discrete frequencies

The response is analyzed in frequency domain
(Amplitude, phase, inphase, quadrature versus frequency)

Time domain EM
Energizes the earth with a wide, continuous range frequencies

The response is analyzed in time
(Amplitude versus time)

Time Domain Electromagnetics

Overview

- Time domain electromagnetics also known as TEM or TDEM
- Transmits a time varying field, typically attempting to capture a wide continuous range of frequencies
- Performed in the air, ground and in marine settings.
- Depending on the survey parameters and environment can see 2km+ depth (MTEM)

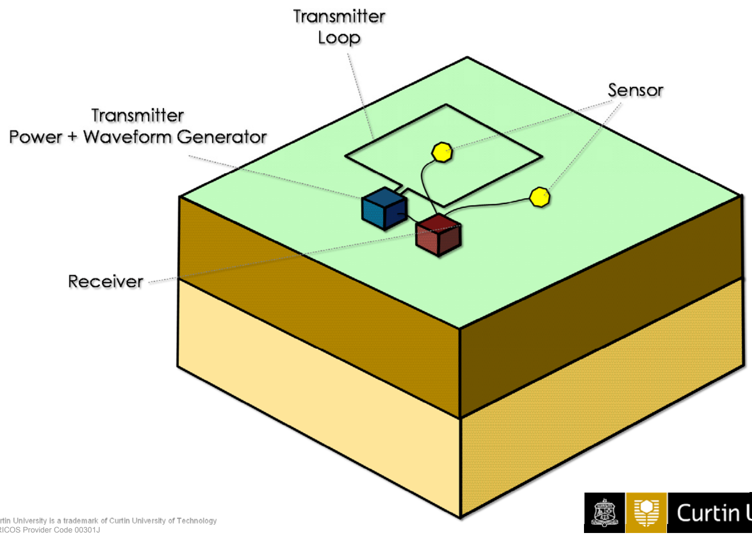
Time Domain Electromagnetics

Overview

- Time domain electromagnetics also known as TEM or TDEM
- Transmits a time varying field, typically attempting to capture a wide continuous range of frequencies
- Performed in the air, ground and in marine settings.
- Depending on the survey parameters and environment can see 2km+ depth (MTEM)
- **This lecture will focus on ground TDEM systems that have a shallower depth of investigation**

Time Domain Electromagnetics

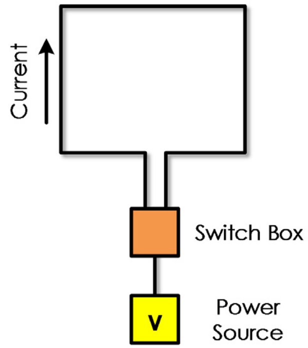
Overview Setup



Time Domain Electromagnetics

Overview Ground EM: The Transmitter

- The ground based TEM transmitter consist of a **Magnetic Loop**
- This loop is typically a 100x100 or 200x200 m rectangular loop
- To transmit a current of around 5 Ampere($I>5A$)
- The current flows the loop
- The current needs to then stop in the loop in a short amount of time <0.1ms

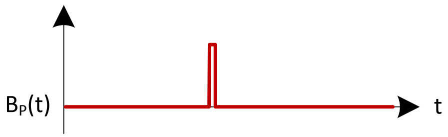


Time Domain Electromagnetics

Overview

- There are two important modes of excitation
- The waveform controls the frequency content which in turn controls the depth of investigation and resolution.

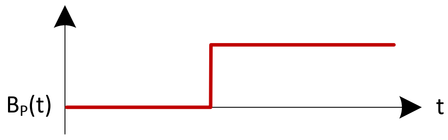
Impulse Response



The impulse response frequency spectrum is equal across all frequencies (Dirac Delta Function)

The holy grail of geophysical signals

Step Response



In reality, the impulse response is impossible. The closest practical function we can produce is the step function.

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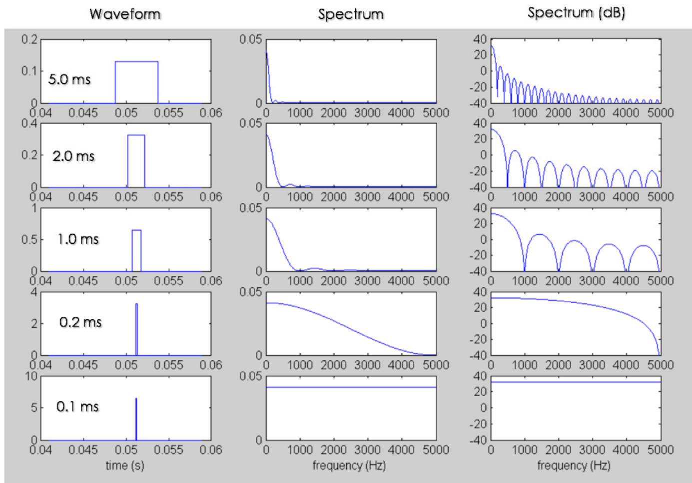
Time Domain EM

Impulse versus boxcar frequency response



Modified from : ACL, 2013
http://www.phon.ucl.ac.uk/courses/spsci/S&S-AS&AVM/Week%205%202013%20Impulse%20responses%20print.pdf

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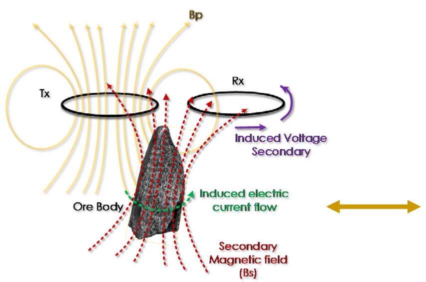
Time Domain Response

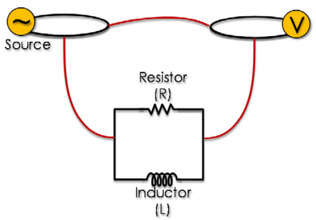
LR Circuits

- Consider the LR Mutual Inductance circuit
- The received secondary voltage from a time varying change in current follows

$$\frac{e_S}{I} = \left(\frac{L_{12}L_{23}}{L_{22}}\right)\left(\frac{u(t)}{\tau}\right)e^{-\frac{t}{\tau}}$$

$$\text{where } \tau = \frac{L_2}{R_2}$$





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$$\frac{e_S}{I} = \left(\frac{L_{12}L_{23}}{L_{22}}\right)\left(\frac{u(t)}{\tau}\right)e^{-\frac{t}{\tau}}$$

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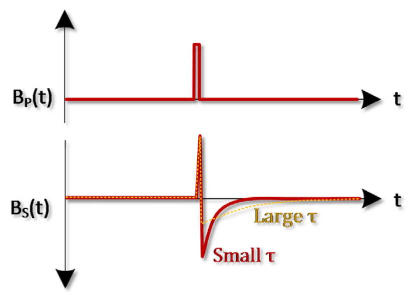

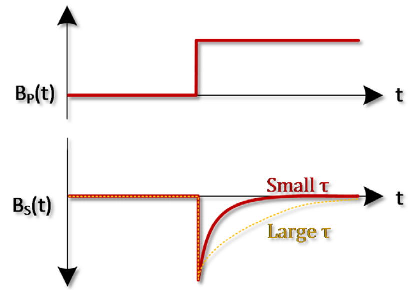

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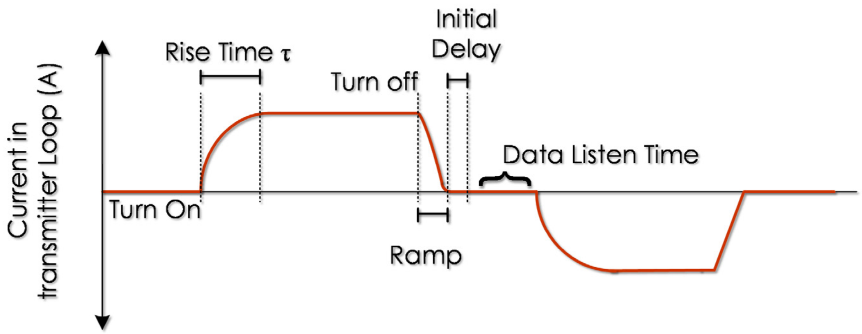
Ground TEM Overview

The Transmitted Waveform



Ground TEM Overview

The Transmitted Waveform : Rise Time

- To generate a large magnetic flux $\left(\frac{dB}{dt}\right)$ the current needs to be drop from I_{Max} to 0 amps in a short period of time.
- Prior to turn off, the current needs to reach and maintain I_{Max} (equilibrium $\frac{dB}{dt}$=0)
- The current is built exponentially
- The behaviour of the current during rise time is determined by:

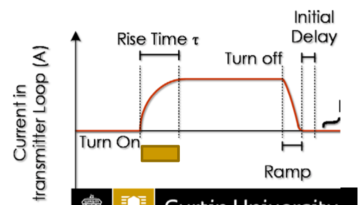
$$I_t = I_{Max}\left(1 - e^{-\frac{t}{\tau}}\right)$$

Where,

$$\tau = \frac{L}{R}$$

R ∝Loop Size

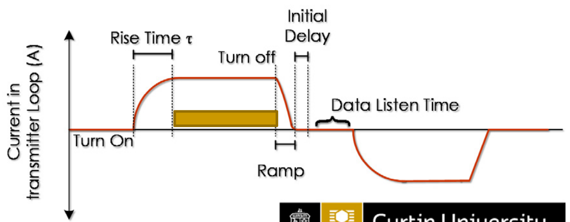
L ∝Number of turns



Ground TEM Overview

The Transmitted Waveform : Current in the Loop

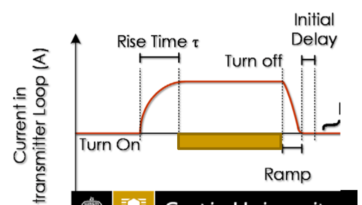
- The maximum current in the loop follows Ohm's Law
- $I_{Max} = \frac{V_0}{R}$
- V_0 –Voltage of source
- R –Resistance of loop



Ground TEM Overview

The Transmitted Waveform : On Time

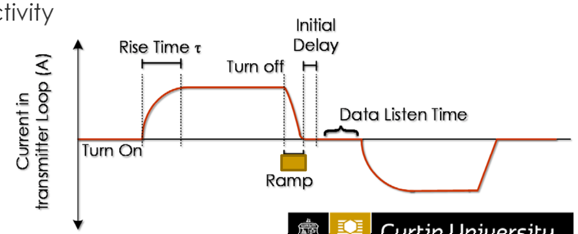
- The on-time (i.e., the time between reaching and turn off) is important
- The rise time will generate a magnetic flux $\left(\frac{dB}{dt}\right)$ and you must wait to record so this flux generated decays enough to not influence the recorded response



Ground TEM Overview

The Transmitted Waveform : Factors influencing Turnoff

- The best TEM waveform has a sharp turn off ramp
- The current TEM waveform turnoff time is dependent on
  - Loop size
  - Number of turns
  - Resistance of loop
  - Transmission current
  - Near surface conductivity



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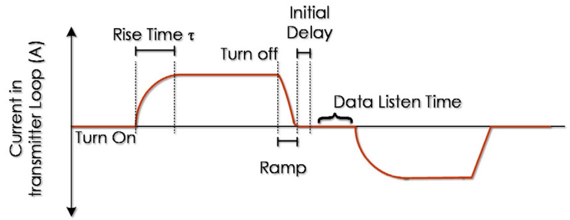
Ground TEM Overview

The Transmitted Waveform : Converting Potential energy to EMF



Think of a the waveform as lifting a full bucket

You build up potential energy (Voltage) as you lift it off the ground. You also perform the same amount of work regardless if you lift the bucket 1 m off the ground slowly or fast. Dropping it releases the potential energy (Voltage). The speed at which it drops impacts the resulting kinetic energy (EMF).

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Ground TEM Overview

Waveform : Duty Cycle

- The duty cycle percentage defines how long the transmitter current is turned compared to that of the off time.

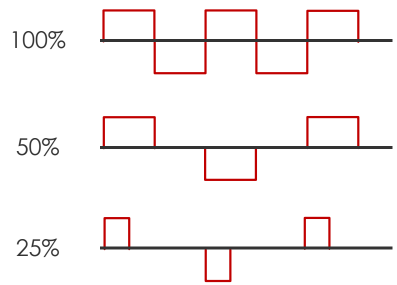
Duty Cycle

1. The proportion of time a switch is 'on.'

2. The percent of time in which current is delivered during a complete cycle of a transmitter (such as an IP transmitter).

–SEG Wiki

Common Duty Cycles



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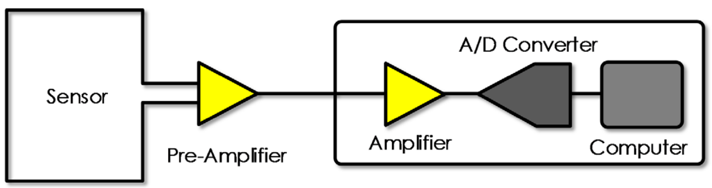
Ground TEM Overview

The Receiver : Overview

- Receivers consist of
  - A sensor either a magnetic coil ($\frac{dB}{dt}$ sensor) or magnetometer (B-Field sensor)
  - Analogue to Digital converter
  - Pre-Amplifier
  - Recording device/Computer



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Ground TEM Overview

The Receiver : The Recovered Voltage

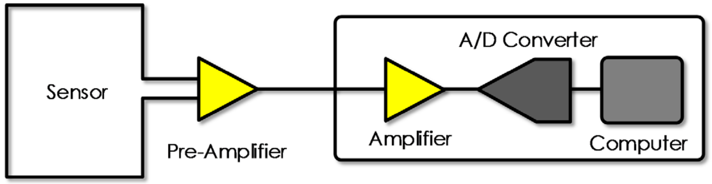
- For a roving vector receiver (RVR) or magnetic loop receiver the induced voltage recorded by the receiver follows Faraday's law

$$EMF = -G \cdot A \cdot N \frac{dB}{dt}$$

G – Gain

A – Effective Area of Receiver coil

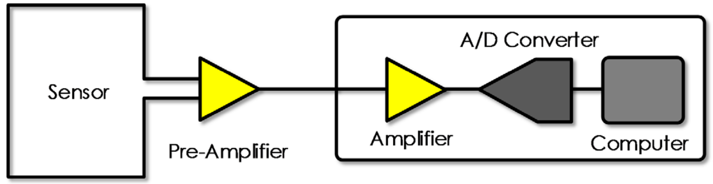
N – Number of receiver coil turns



Ground TEM Overview

The Receiver : Analogue to Digital Conversion

- The receiver converts the analogue voltage into a digital signal to be stored on the computer
- This means converting the <u>continuous</u> analogue signal into a <u>discrete</u> digital value (See A superficial guide to Matlab: Section Bits & Section Bytes)
- The dynamic range of the instrument is ratio of the maximum value to the minimum value the instrument can record
- Recording at multiple gain levels may be required (e.g., 1 and 20) to recover the full signal (both large and small voltages)



Ground TEM Overview

The Receiver : Dynamic Range Definition

Dynamic Range Definition

1. The ratio of the maximum reading to the minimum reading (the minimum often being the noise level) which can be recorded by and read from an instrument without change of scale.

2. The ability of a system to record very large and very small amplitude signals and subsequently recover them. The smallest recoverable signal is often taken to be the noise level of the system, and dynamic range as the ratio of the largest signal that can be recorded with no more than a fixed amount of distortion (often 1 to 3%) to the rms noise;

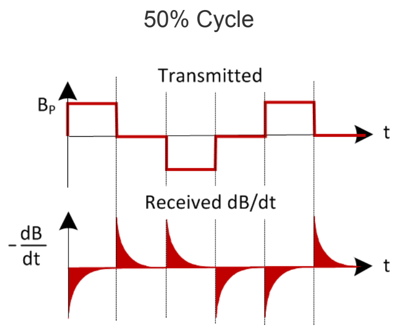
- Sheriff's Encyclopaedic Dictionary of Applied Geophysics, fourth edition

Ground EM Overview

The Transmitted waveform and received signal

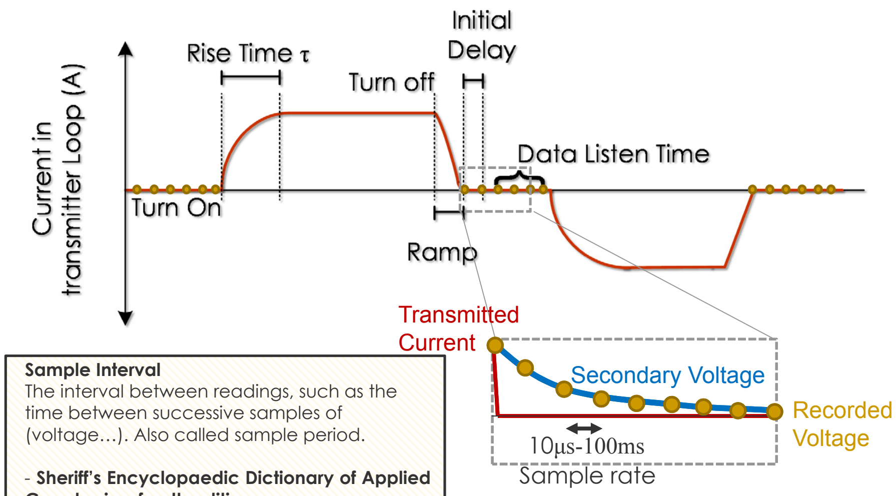
The induced secondary magnetic field occurs as a result of the changing primary magnetic field.

A $\frac{dB}{dt}$ occurs at two points, during the rise time and during the off time.



Ground TEM Overview

The Receiver : Dynamic Range Definition



Sample Interval
The interval between readings, such as the time between successive samples of (voltage…). Also called sample period.

- **Sheriff's Encyclopaedic Dictionary of Applied Geophysics, fourth edition**

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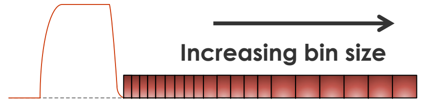
Receiver Channels

Time Binning

The secondary magnetic field decays rapidly and requires a larger bin widths at later times bin to be accurately measured as the signal becomes smaller and smaller rapidly in time.
The receiver channel design depends on
- Geo-electrical target (shallow or deep)
- Vertical resolution required (i.e., complex overburden)
- Receiver sensor
- Noise (i.e., using all sample points without binning will have significantly higher noise)
- Survey requirements
- Waveform



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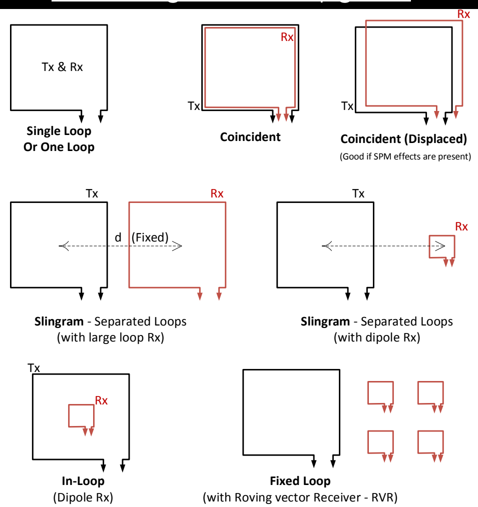
Survey Loop Geometry

See Nabighian Vol. 2 pg 455.



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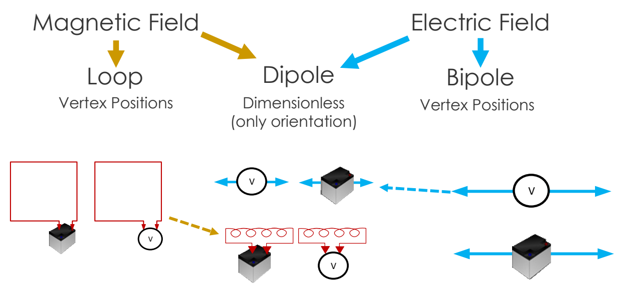
Receivers and Transmitters

Interchangeability

Conceptually Transmitters and Receivers are the same
(Except one transmits and one receives)



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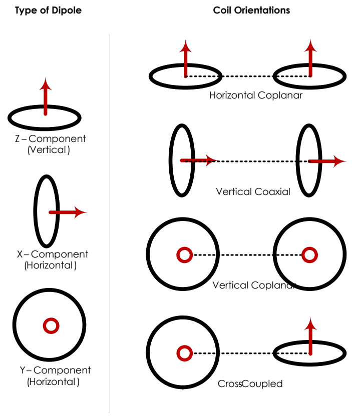
Survey Loop Geometry

XYZ Orientation

Not only are there many transmitter-receiver geometric relationships, but the direction of the transmitter and receiver vary!

See Parasnis pg. 215
Nabighian Vol 2. pg 291



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Example Survey

Documentation in the field

TEM Survey Parameters			
	Loop Configuration	Coincident/ Slingram	
	Line Spacing	100m	
	Station Spacing	50m	
Transmitter(Tx)		**Receiver (Rx) (Slingram)**	
Transmitter Loop	100m×100m	Receiver Type	RVR
Number of Turns	1 Turn	Receiver Area	10000m²
Transmitter Area	10000m²		
Receiver (Rx)		**Receiver (Rx) (Coincident Loop)**	
Receiver Instrument	SMARTem V	Receiver Loop	100m×100m
Number of Channels	38	Number of Turns	1 Turn
Early Gains	1	Transmitter Area	10000m²
Late Gains	20	Offset Distance	2m
Power		**Waveform**	
Current	Effective ~11A	Ramp	0.04ms
Voltage	Effective ~25V	Initial Delay	0.022ms
Power Source	2×12V Batteries	Rise Time	0.05ms
		Frequency	1.6Hz Composite
		Cycle Type	50% Duty Cycle
		Stacks	64

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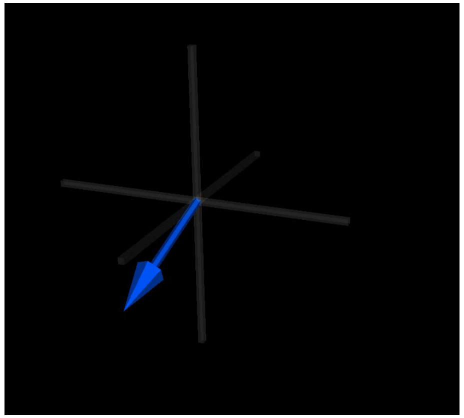
Three Dimensionality of EM Fields

Why do we need to measure in multiple directions?

The electromagnetic field is three-dimensional. In fact we measure it as a time varying vector.



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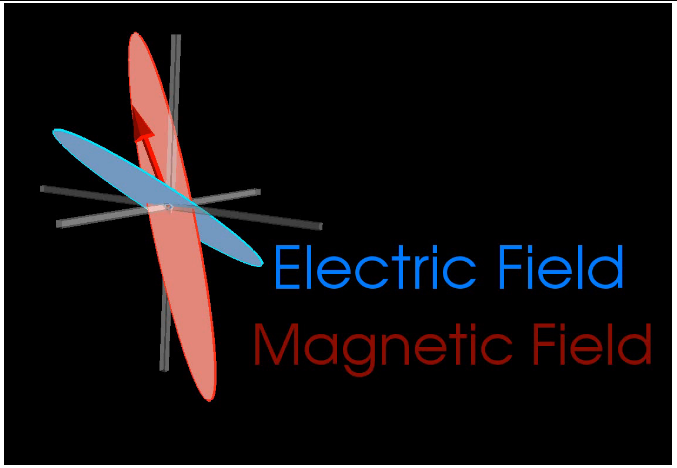
Three Dimensionality of EM Fields

Why do we need to measure in multiple directions?



The magnetic field is also a three dimensional vector that can be recorded.

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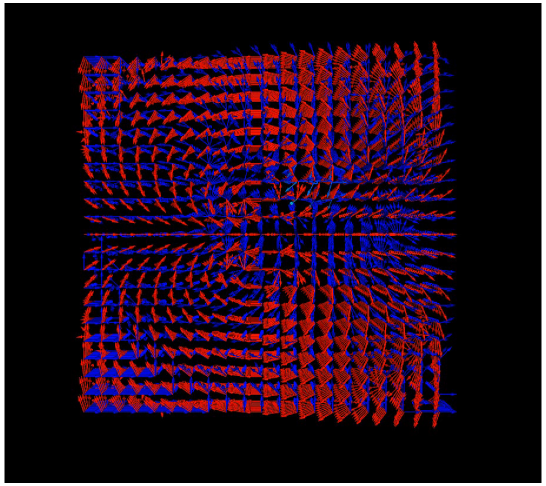
Why do we need to measure in multiple directions?

These fields vary in all directions and can be complex to interpret.

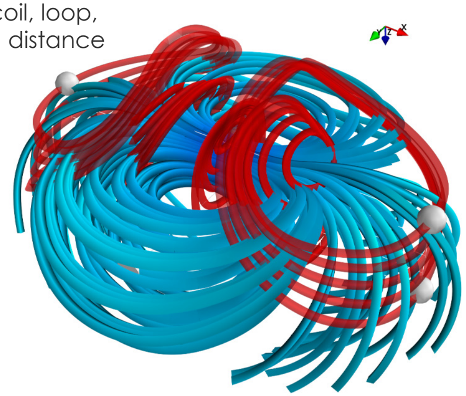


These vectors represent a point source in space. The electric and magnetic fields are continuous, three dimensional and can be extremely complex.

Survey Loop Geometry

Coming up dipoles

While there are many different forms of transmitters (i.e., coil, loop, bipole and dipole), from a distance they all look like dipoles.



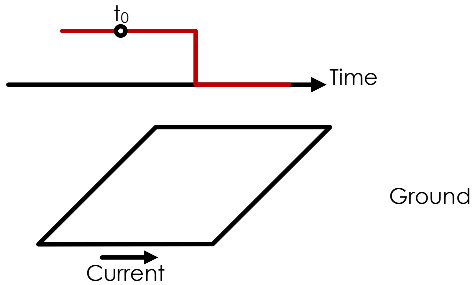
Smoke Rings

Electromagnetic smoke rings

Smoke Rings

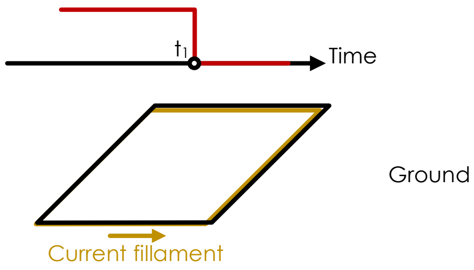
What happens during on-time

1) At t_0 the current in the loop is constant. This means there is a constant B-field, but no $\frac{dB}{dt}$



Smoke Rings

What happens at turnoff



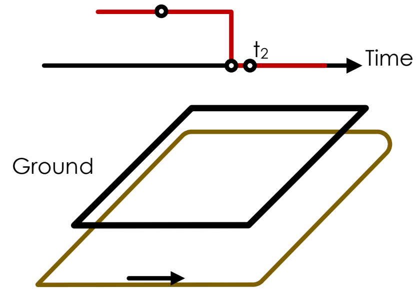
2) At the moment of a current change (turn off t_1) a filament of current forms under the loop to maintain the magnetic field.

   In accordance to Lenz's Law, the current filament acts to oppose the primary B-Field

   Energy just doesn't disappear

Smoke Rings

What happens shortly after turnoff



3) The current diffuses and resistive looses reduce the total current. Both act to reduce the amount of current density over time.

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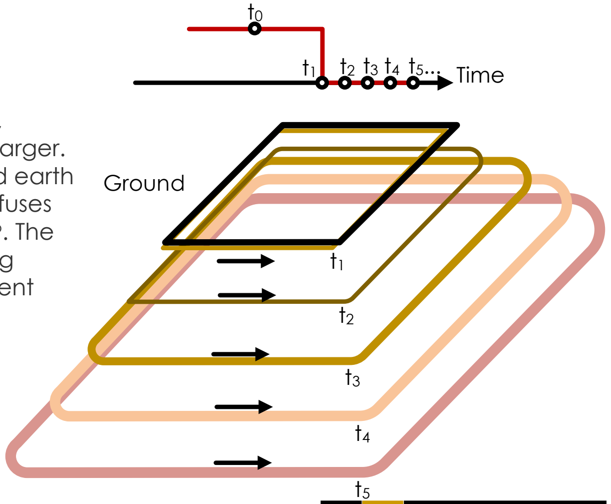
Smoke Rings

The diffusion of the smoke ring



4) The smoke ring diffuses, expanding larger and larger. In a horizontally layered earth the current filament diffuses out at an angle of ~47°. The speed of the expanding 'smoke ring' is dependent upon the sub-surface conductivity.

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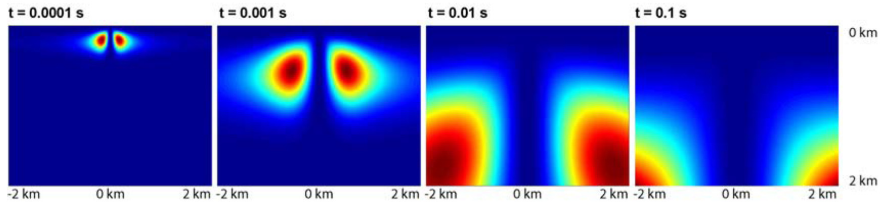
Smoke Rings

Contour Plot of Electrical Current Density

The current filament becomes more diffuse in time as it travels through the rock.



Credit University of Alberta, M. Unsworth, 2015, from
https://www.ualberta.ca/~unsworth/UA-classes/223/notes223/223D5-2009.pdf
A worthwhile read.

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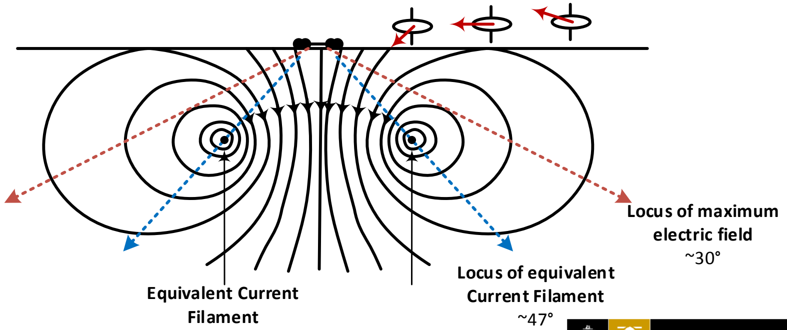
Smoke Rings

Electromagnetic smoke rings

Remember, Amperes law states that a circulating magnetic field is generated from an electric field ($\nabla \times H = J + \frac{\partial D}{dt}$). This magnetic field is typically measured by ground based magnetic loop receivers.



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LECTURE 05

Profiling with TEM S2 2015

- Understanding channels
- Smoke Ring Revisited
- Early Times versus Late Times
- Profiles and Pseudolog Plots
- Forward Modelling
- Inversion
- The Solution Space and Electrical Equivalence

TEM Recap

What happened last week?

What is an impulse function?
What is a step function?
What are the main components of a TEM waveform?
What are channels?
What are the different types of loop geometries?
What is a Smoke Ring?

TEM

Question?

You are tasked to perform a ground TEM survey 100km east of Kalgoorlie.

What things would you need to bring to the field to perform a Ground TEM Survey?

Defining Some terms used in this Lecture

Some terms you will come across

Half-space vs Whole-space
Homogeneous vs Heterogeneous Earth
Isotropic vs Anisotropic
Apparent resistivity vs resistivity

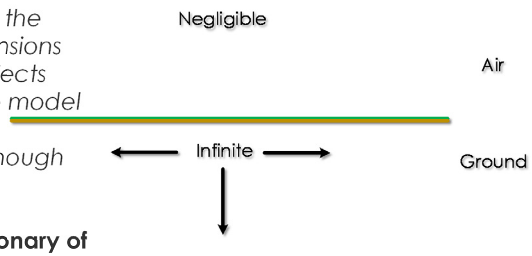
Definitions

What is a Half-space?

Half-Space

"A mathematical model bounded only by one plane surface, i.e., the model is so large in other dimensions that only the one boundary affects the results. Properties within the model are usually assumed to be homogeneous and isotropic, though other models are also used."

- **Sheriff's Encyclopaedic Dictionary of Applied Geophysics, fourth edition**



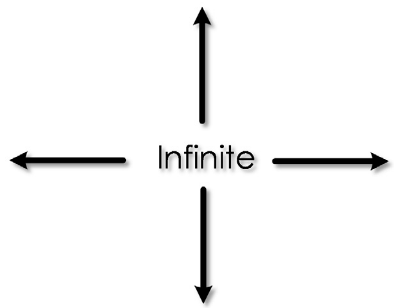
Definitions

What is a Whole-space?

Whole-Space

A whole-space is an infinite region of space

A theoretical response of an EM source in a whole-space is one where there is a negligible effect of the air-earth interface. (i.e., induction logging tool deep within the earth)

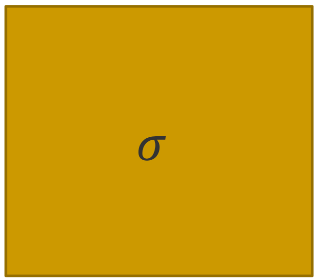


Definitions

Homogeneous

Homogeneous Earth

The same throughout; uniformity of a physical property throughout a material.

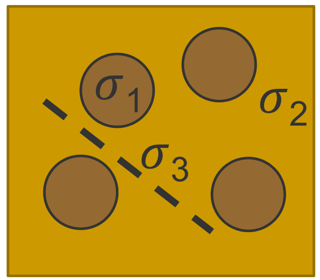


Definitions

Heterogeneous

Heterogeneous Earth

Lack of spatial uniformity. Opposite of homogeneity.



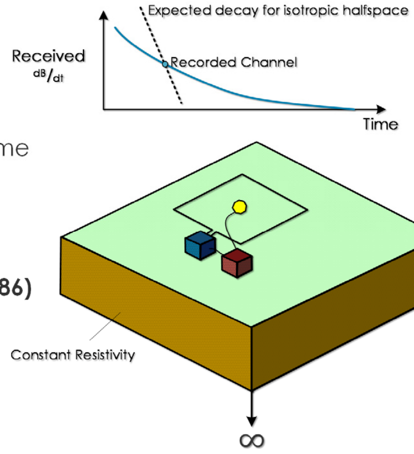
Definitions

Heterogeneous

Apparent Resistivity

"the resistivity of a homogeneous halfspace which will produce the same response as that measured over the real earth with the same acquisition parameters"

Spies and Eggers (1986)

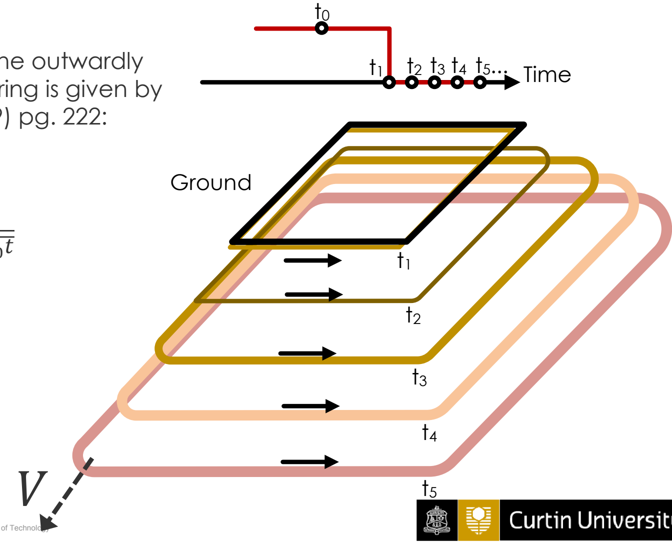


Understanding Channels

Consider the Smoke Ring

The velocity of the outwardly diffusing smoke ring is given by Nabighian (1979) pg. 222:

$$V = \frac{2}{\sqrt{\pi \sigma \mu_0 t}}$$

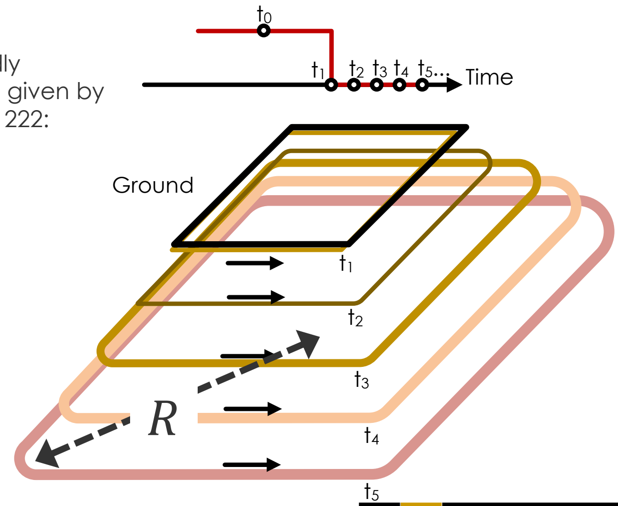


Understanding Channels

Consider the Smoke Ring

The radius of outwardly diffusing smoke ring is given by Nabighian (1979) pg. 222:

$$R = \sqrt{\frac{4.37 \times t}{\sigma \mu_0}}$$



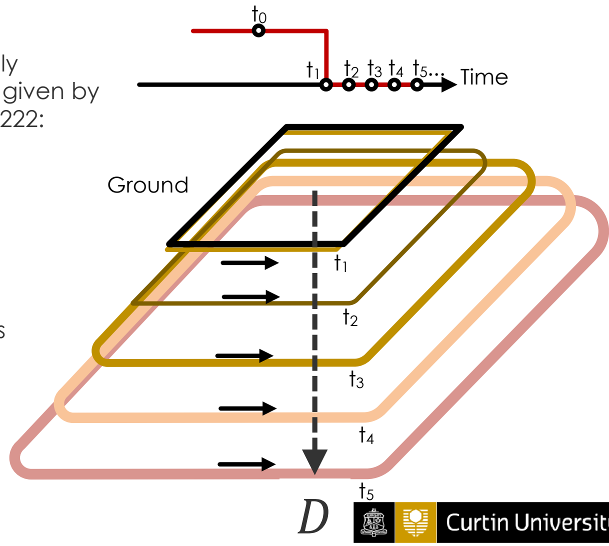
Understanding Channels

Consider the Smoke Ring

The depth of outwardly diffusing smoke ring is given by Nabighian (1979) pg. 222:

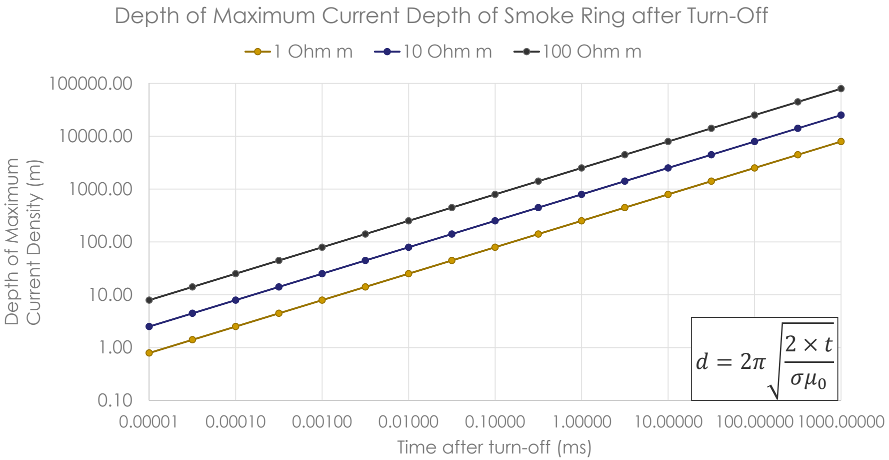
$$d = 2\pi \sqrt{\frac{2 \times t}{\sigma \mu_0}}$$

Where t is time in µs



Understanding Channels

Consider the Smoke Ring



Diffusion Depth/Width Equation

Smoke Ring Depth

The depth of maximum current density at a time (t) after an impulse response in an homogenous earth of resistivity (ρ)

$$d = 731 \times \sqrt{\rho t}$$

ρ – Resistivity (Ω•m)
t – Time (ms)

Diffusion Depth/Width Equation

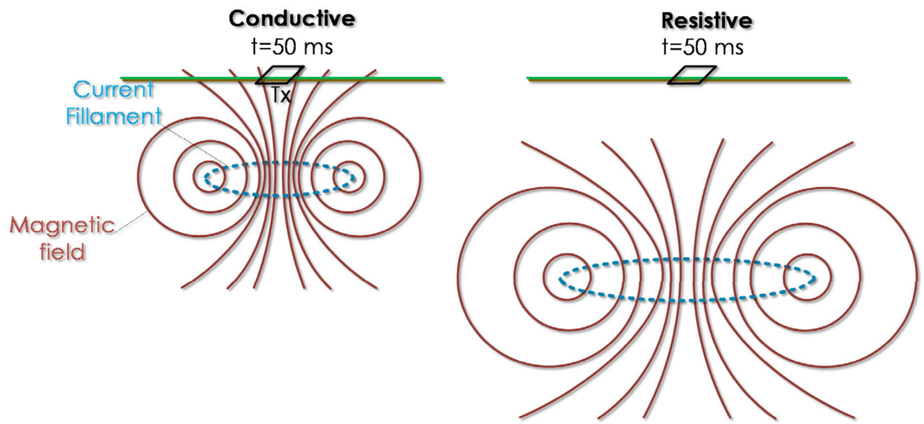
Smoke Ring Depth: What you should take away?

$$d = 731 \times \sqrt{\rho t}$$

The smoke ring diffuses faster and travels deeper in a shorter amount of time in resistive earth over a conductive earth.

Diffusion Depth/Width Equation

Smoke Ring Depth: What you should take away?



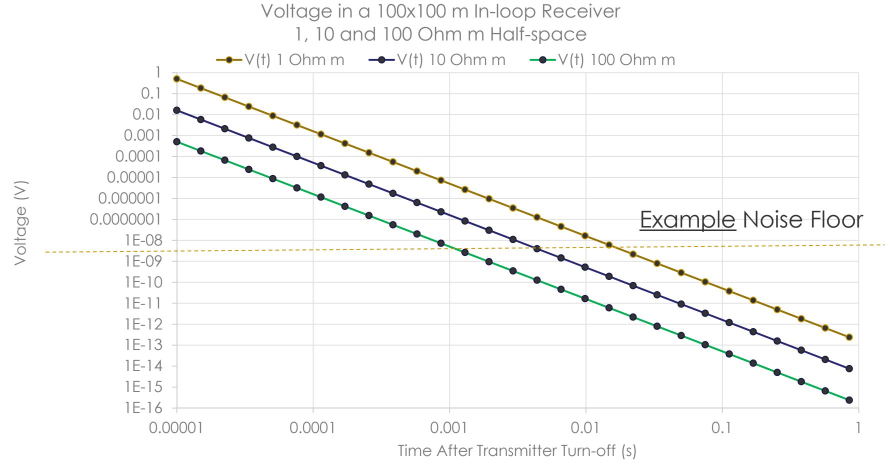
Depth of Investigation

Received Voltage for an In-loop survey

The received voltage for a in-loop survey over a homogeneous half-space is:

$$V(t) = 1.6 \times 10^{-17} \times I \times A \times \sigma^{\frac{3}{2}} \times t^{-\frac{5}{2}}$$

I – Current(A)
A – Transmitter Area
σ – Half-space conductivity
t – Time



Depth of Investigation

Noise Threshold

$$V(t) = 1.6 \times 10^{-17} \times I \times A \times \sigma^{\frac{3}{2}} \times t^{-\frac{5}{2}}$$

I – Current(A)
A – Transmitter Area
σ – Half-space conductivity
t – Time

Example
Consider a SmartTEM V system with a transmission current of 10A and loop dimension of 100 m x100 m (10,000 m²) $\rightarrow \text{Moment} = 1 \times 10^5 Am^2$

If the noise of the system is $\eta = 30nV/A$ (i.e., 30nV @ 1Am)
If the noise scales with receiver transmitter moment with 0.5nV/m²

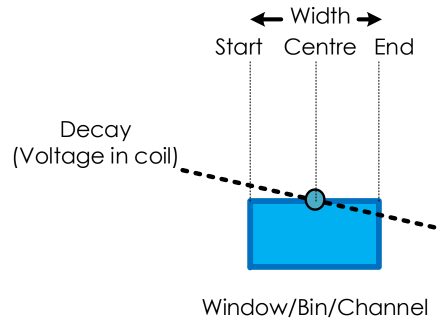
Substitute η into the equation and solve for t

! Remember voltage scales with transmitter moment

Understanding Channels

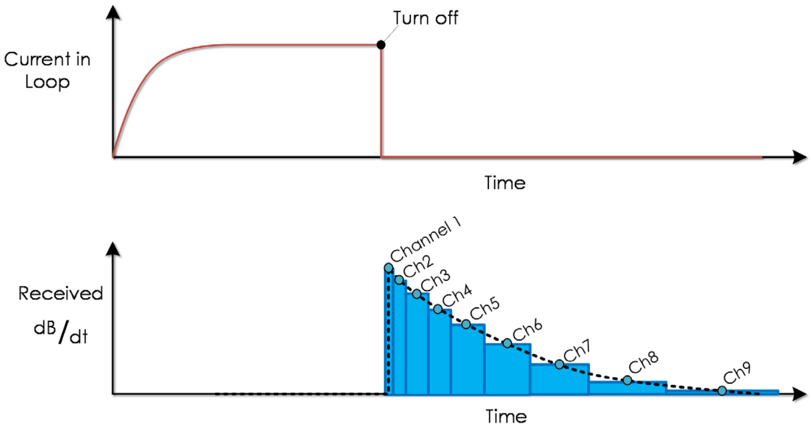
What are channels

A channel is the average of the samples within a time range. Channel have a start and end and are plotted usually at the centre of the bin.



Understanding Channels

What are channels?



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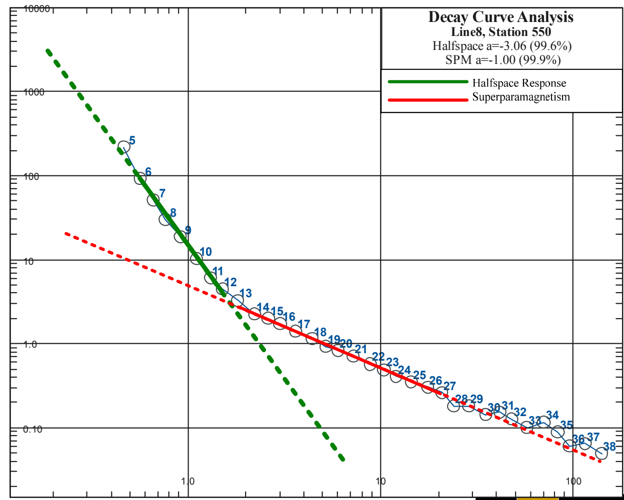
Example Decay Curve

Channels/Windows/Time Bin Example



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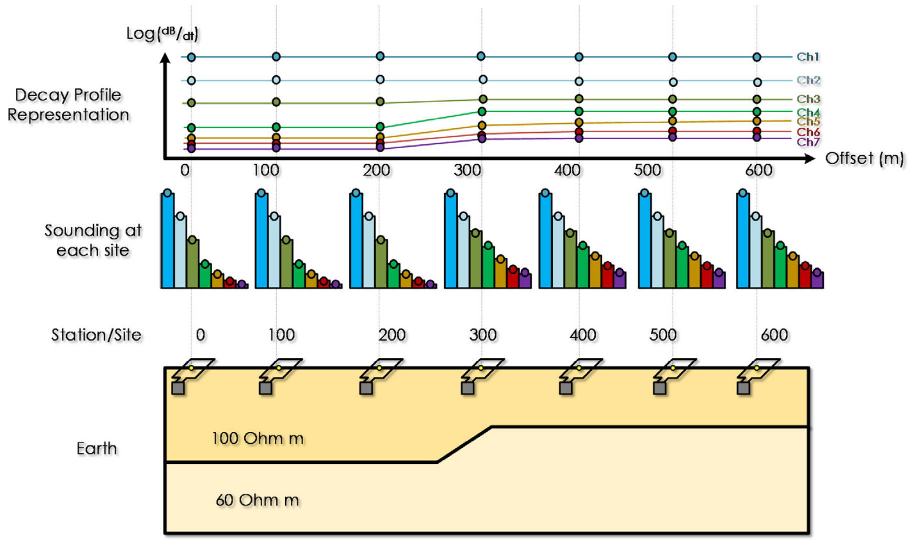

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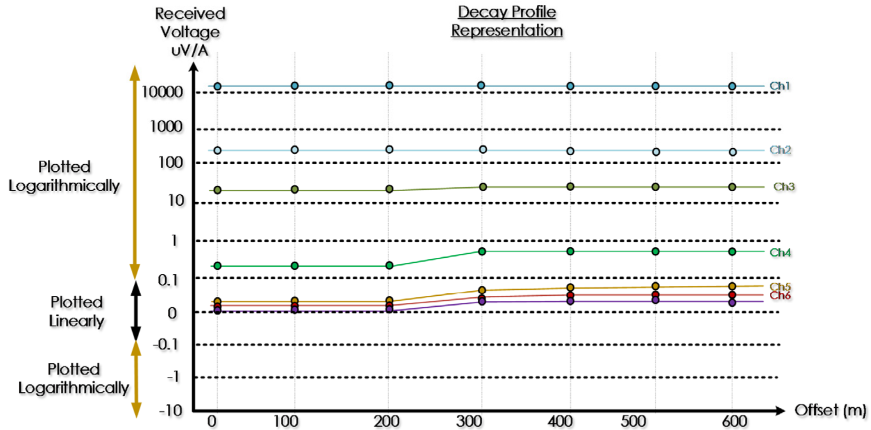
Profiles

Plotting TEM Data : Pseudo Log plot



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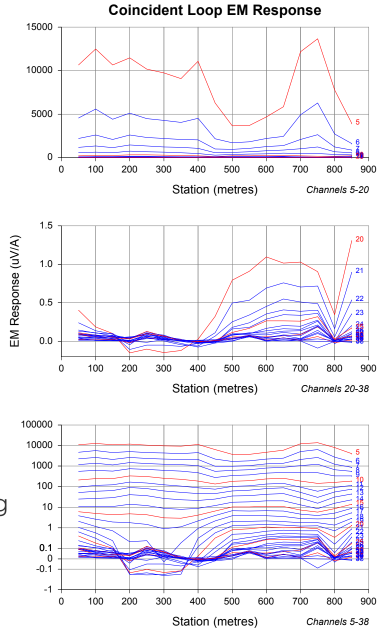
Linear Plot
Ch 5-20

Linear Plot
Ch 20-38

Pseudo-log
Ch 5-20



WINDOW TIMES (ms)
From the start of the Ramp

1	: 0.0940	20	: 5.869
2	: 0.1440	21	: 7.069
3	: 0.1940	22	: 8.669
4	: 0.2440	23	: 10.27
5	: 0.3190	24	: 11.87
6	: 0.4190	25	: 14.27
7	: 0.5190	26	: 17.47
8	: 0.6190	27	: 20.67
9	: 0.7690	28	: 23.87
10	: 0.9690	29	: 28.67
11	: 1.169	30	: 35.07
12	: 1.369	31	: 41.47
13	: 1.669	32	: 47.87
14	: 2.069	33	: 57.47
15	: 2.469	34	: 70.27
16	: 2.869	35	: 83.07
17	: 3.469	36	: 95.87
18	: 4.269	37	: 115.1
19	: 5.069	38	: 140.7

SURVEY PARAMETERS

Configuration	: Coincident Loop
Station Spacing	: 50 m

RECEIVER

Receiver	: Sirotem MkIII
Frequency	: 1.56
Number Channels	: 38
Rx Loop	: 100m x 100m
Rx Area	: 10000 m^2
N Turns	: 1
Offset Distance	: 2m

TRANSMITTER

Transmitter	: Geophysics Transmitter
Loop	: 100m x 100m
Tx Area	: 10000 m^2
Tx Loop Side	: 100 m
Tx Turns	: 1
Effective Current	: 11A
Effective Voltage	: 25V
On Time	: 160 ms
Off Time	: 160 ms
Turn Off	: 0.2 ms
Turn On	: 0.05 ms

CDI

Conductivity Depth Images

- Conductivity depth images (CDI) are a rough and quick transformation method to estimate sub-surface geo-electrical distribution.
- There are many available, but the solution of Macnae et al.'s algorithm is presented.
- It uses the notion of a halfspace resistivity to calculate each V(t) that fits V(t) to use the diffusion depth at a time t_0. That is, The algorithm determines the relationship between recorded channels and depth. It establishes at which time and depth a step-response amplitude is equal to the current filament loop.

$$\sigma = \frac{1}{\mu_0} \frac{\partial^2 t}{\partial z^2}$$

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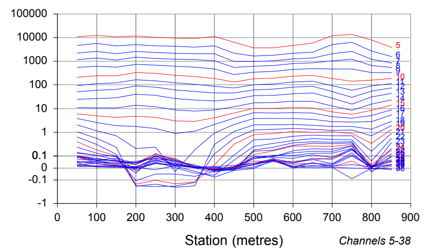
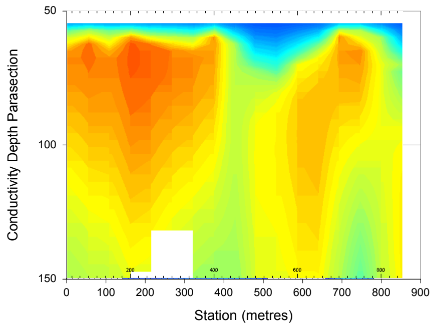
CDI Transform

An Example





- An Example CDI image
- It is a rough guide for understanding conductivity distribution with depth
  - Red – Conductive
  - Blue – Resistive
- CDI's are not inversion
- Example of TEM : Nickel exploration

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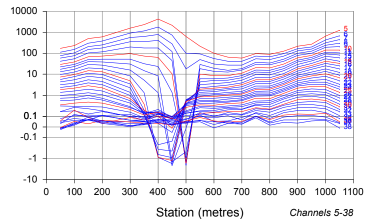
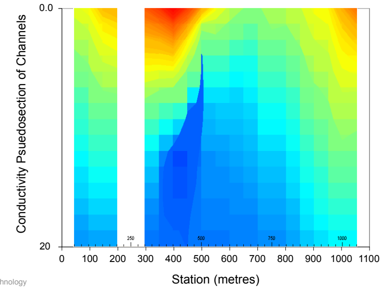
Interpret this Profile

What is noise? Is the near surface resistive or conductive?





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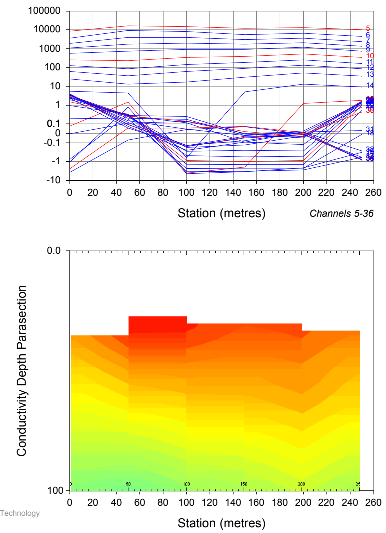

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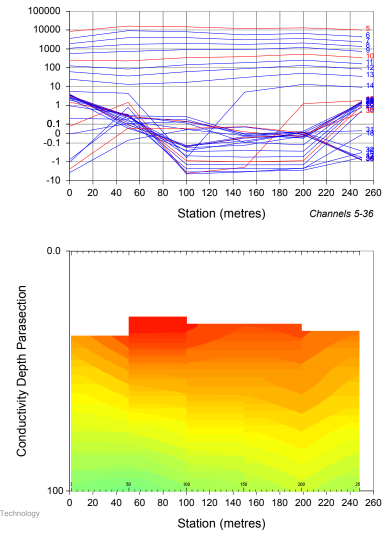
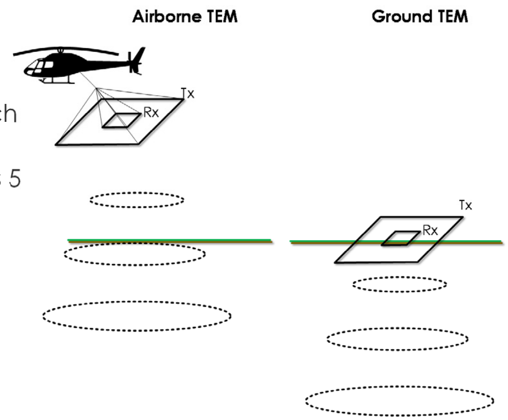


Difference between airborne and ground

The difference is air

- The Air is a lossless medium and no energy is lost
- Data can be collected much more rapidly in the air (thousands of stations versus 5 or six by ground crew)
- Airborne is limited by listen time, power constraints and transmitter-receiver geometries



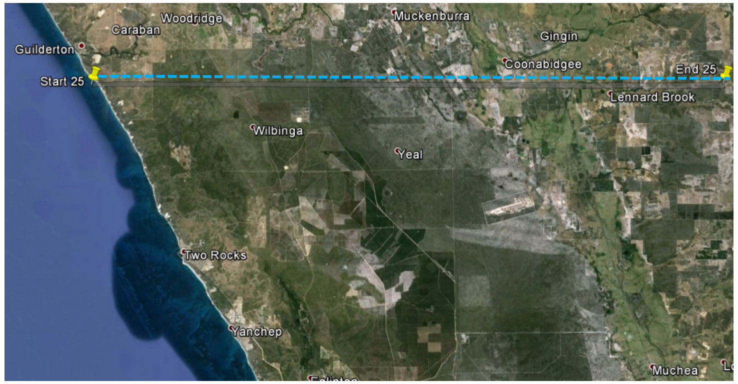
Difference between airborne and ground

Example AEM Survey

https://www.youtube.com/watch?v=BjJ9gX0nQAQ

AEM Profile

Example Survey



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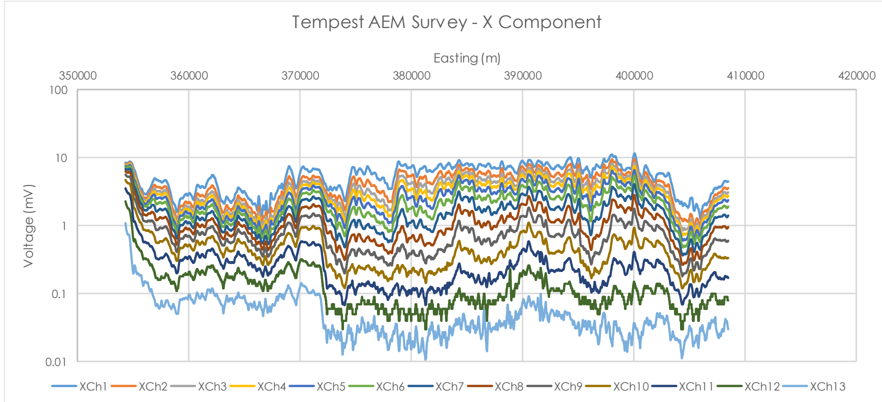
AEM Profile

X-Component



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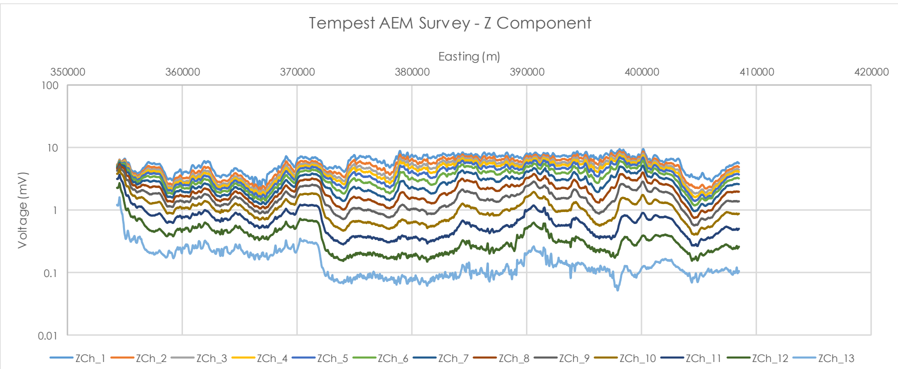
AEM Profile

Z-Component



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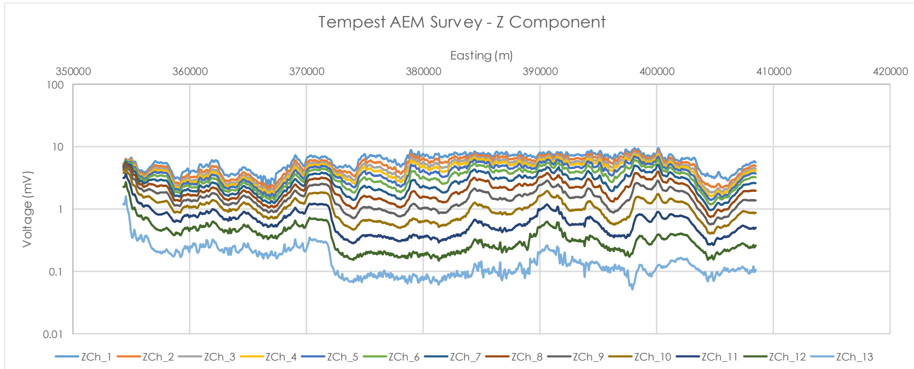

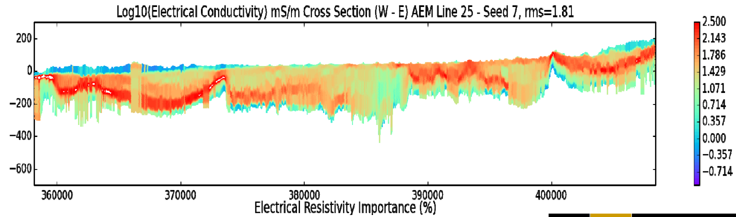

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Forward Modelling

What is Forward Modelling ? Computing a synthetic response

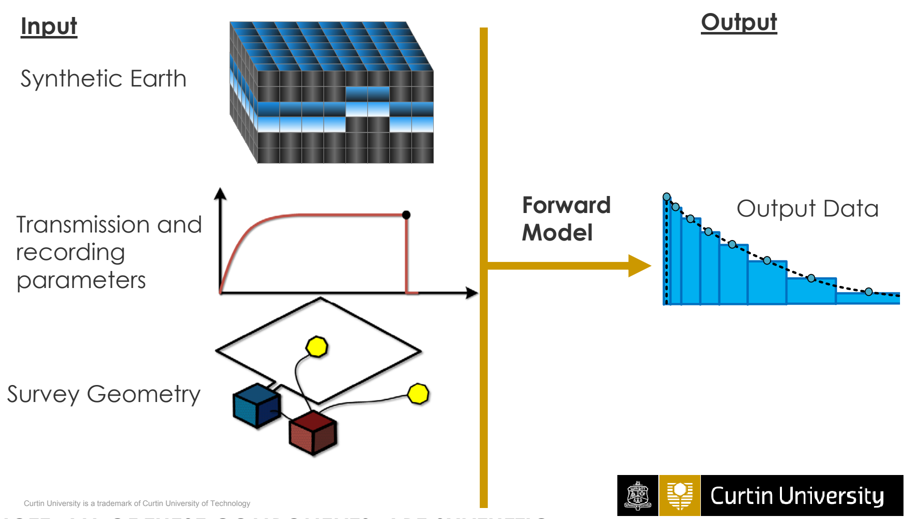
Forward Modelling

Determining the expected effects from a model, solving a direct problem, such as predicting the electric potential for a given distribution of resistivity current sources.

(*Sheriff*)

Forward Modelling

What is Forward Modelling ? Computing a synthetic response



NOTE: ALL OF THESE COMPONENTS ARE SYNTHETIC

Forward Modelling

What is Forward Modelling ? Computing a synthetic response

Given a 1D problem, another way of looking at forward modelling is terms of data (**d**) and model space (**m**)

$$d = Gm$$

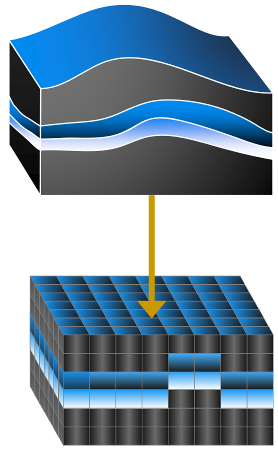
G is the forward modelling operator
d is the model response
m is the model parameters, including 1D layer thicknesses and conductivities

Earth Representations

So you have the earth, infinitely complex. We must simplify

We can't model the earth in it's full complexity and therefore must be simplified to be represented mathematically. There are many forward modelling approaches:

- 1D – Layered Earth Modelling
- 1D + Plates – Layered earth modelling with plates (filament modelling)
- 2D Finite Difference
- 2D Finite Element
- 2.5D Finite Difference
- 2.5D Finite Element
- 3D Finite Difference
- 3D Finite Element
- 3D Integral equation



Inversion

What is Inversion? Deriving Subsurface Conductivity

Inversion

Deriving from field data a model to describe the subsurface that is consistent with the data; determining the cause from observation of effects.

(*Sheriff*)

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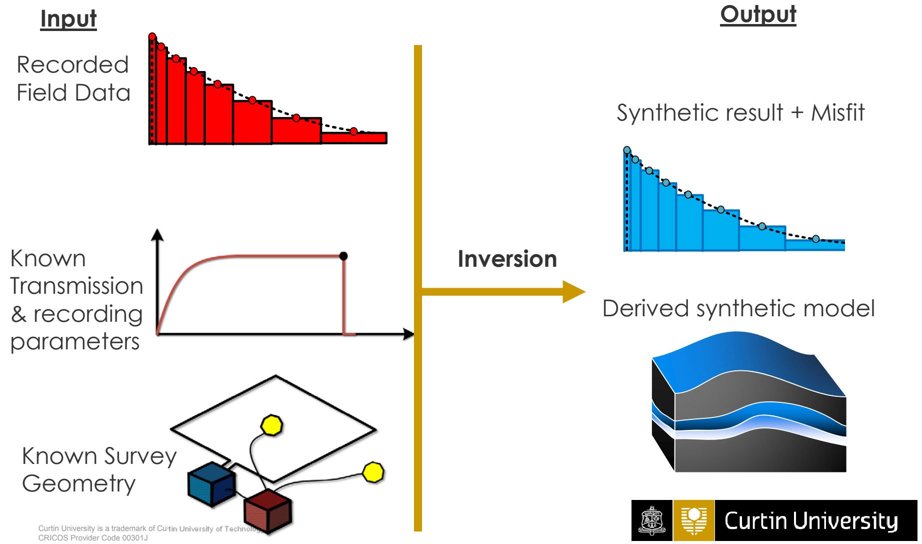
Inversion

What is Inversion? Deriving Subsurface Conductivity



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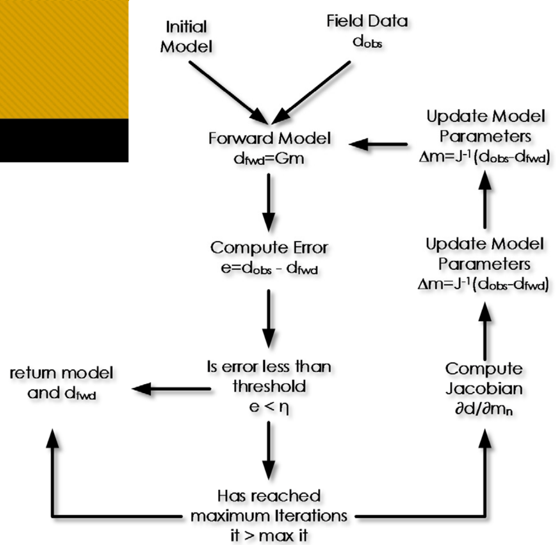
Inversion

Procedure

Inversion is an iterative process and will continue updating the model until,

- The error is minimized
- The maximum number of iterations is reached
- The model diverges



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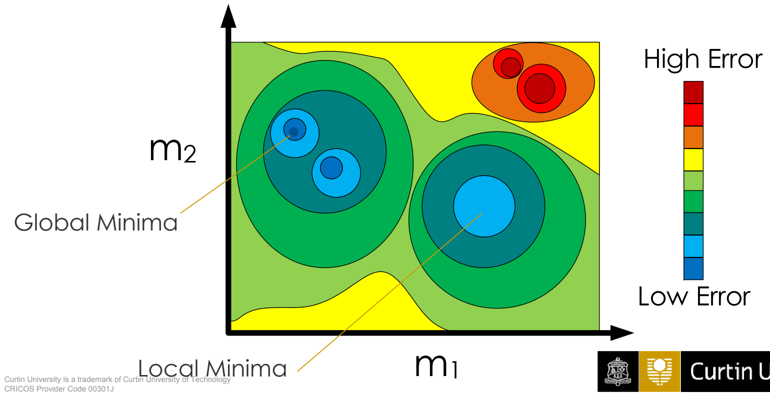
Non-Uniqueness

Solution Space

Consider the following scenario:

You have to determine a layer's thickness (m_1) and conductivity (m_2). If you computed all solutions and plotted the resulting error. You produce this map.



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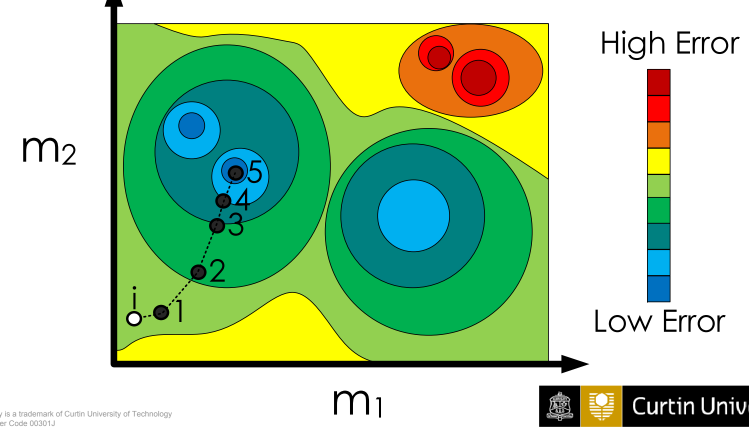
Non-Uniqueness

Solution Space: Solution 1

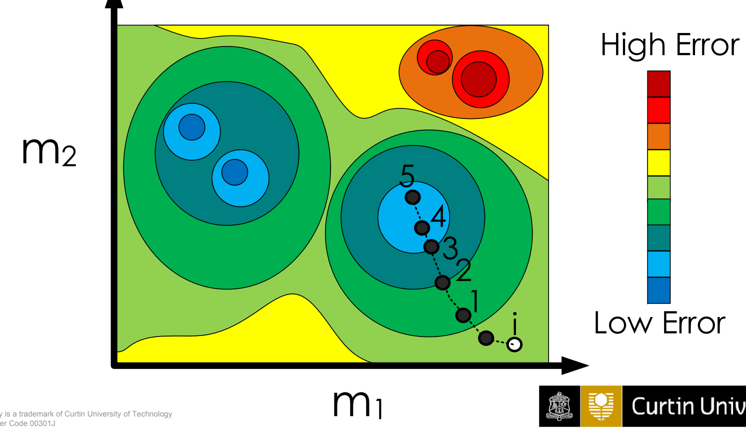
You start the inversion at location i and plot the inversion process. It finishes after 5 iterations after the inversion cannot reduce the error.



Non-Uniqueness

Solution Space: Solution 2

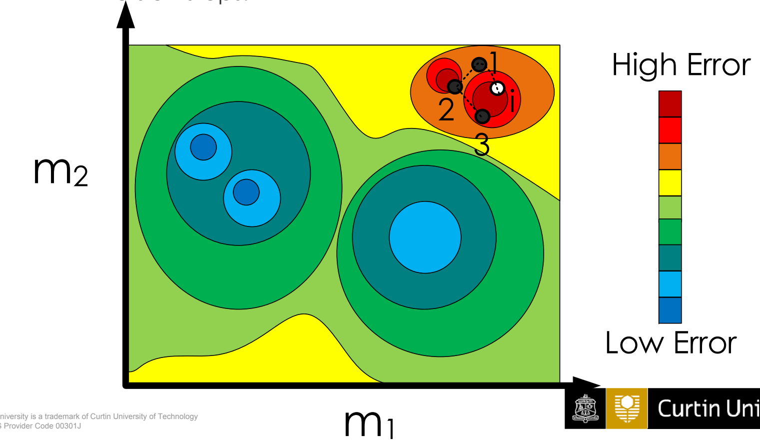
You start a new inversion at location i and plot the inversion process. It also finishes after 5 iterations after the inversion cannot reduce the error.



Non-Uniqueness

Solution Space: Non-Solution (diverged)

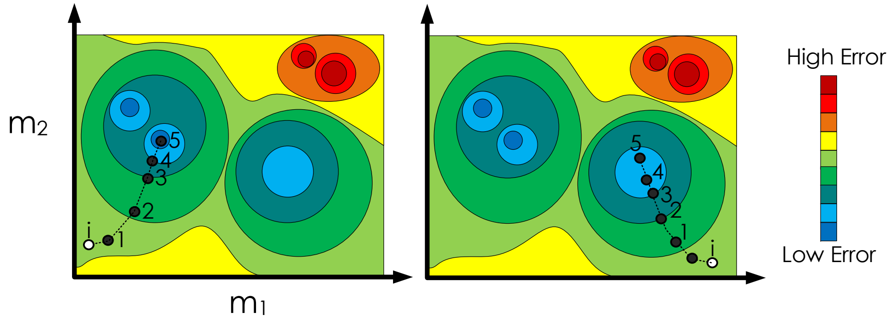
You start then begin a new inversion at location i. The error begins to drop after 2 iterations, but then increases after the next iteration, diverging from any solution. The inversion stops.



Non-Uniqueness

Solution Space: Solution 2

Which is the correct solution?

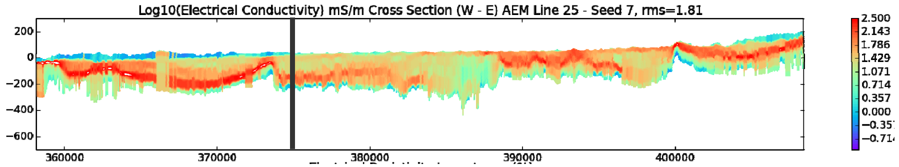


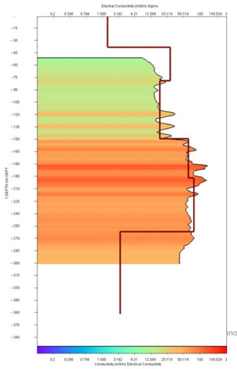
Despite both solutions converging on a solution you will need extra information to determine which solution is correct. (e.g., well logs, geological knowledge etc..)

EM is NON-UNIQUE which gives rise to multiple solutions

Non-Uniqueness

Case Study





Consider the previous example. When matched up with a known well log, there was a reasonable fit in the upper layers.

But… are there better models?

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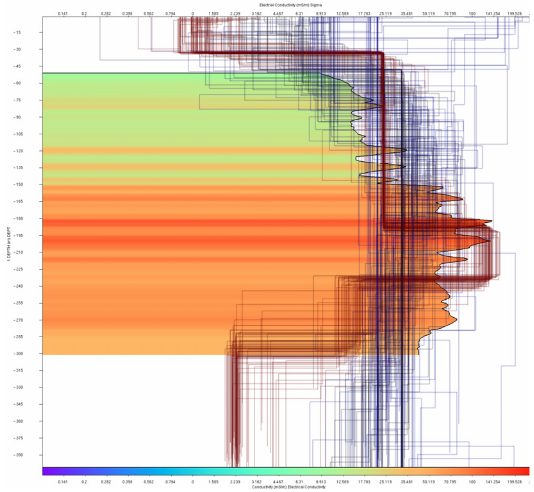
Non-Uniqueness

Case Study : 200 models



200 random seed (starting/initial/input) models were generated and inverted over this borehole. The blue lines represents data with high misfit while the red lines represent the solutions with low misfit.

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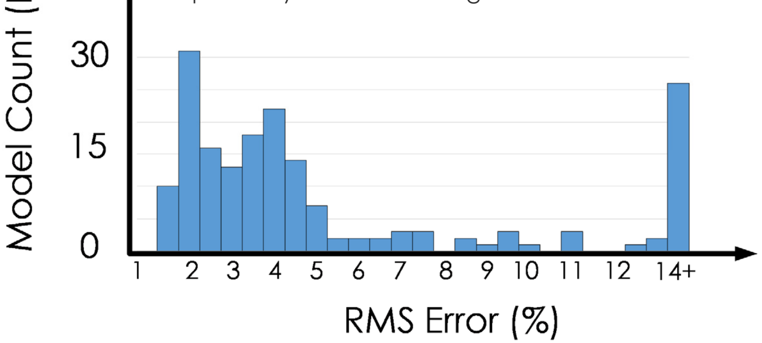
Non-Uniqueness

Case Study : 200 models

There is a large variability in the range solutions from the 200 models. Most converged but those above 8% probably did not converge.



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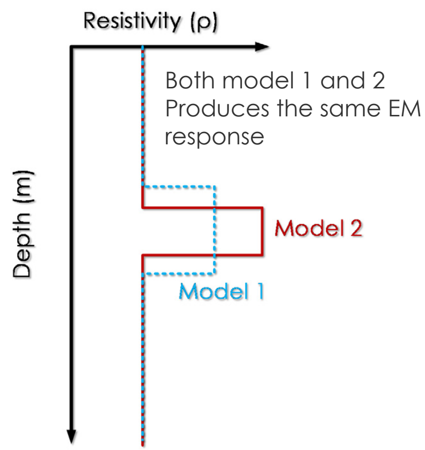
Equivalence

Different model, similar response…



Electrical Equivalence

Combinations of layer resistivities and thicknesses that would produce practically indistinguishable electrical sounding responses. Also called layer equivalence.

Sheriff Dictionary

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LECTURE 06

Response of Discrete Targets S2 2015

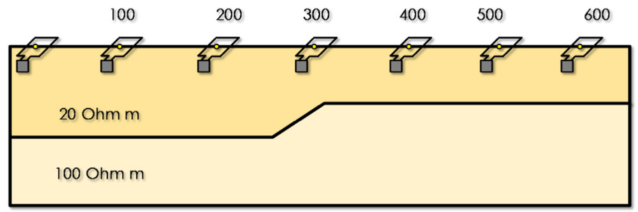
- Galvanic versus Inductive Current Flow
- What are Plates?
- Filament modelling of plates
- TEM Anomaly Flat Body
- TEM Anomaly Vertical Body
- TEM Anomaly Inclined Body

Lecture 05 Overview

Part 1

What is a channel?
What is a decay curve?
What is a profile?
What is a pseudolog plot

Draw an inloop profile for the following scenario :



Lecture 05 Overview

Part 2

What is a CDI?
What is forward modelling?
What is inversion?
What is electrical equivalence?
What is the resistivity thickness product?

Electrical Currents in the Earth

Inductive Current in a Plate

Consider a conductive target in free space. The transient decay of the primary magnetic field in the body rapidly decays to zero.

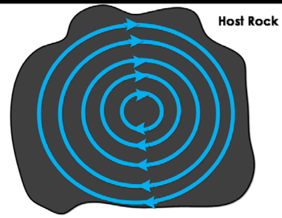
A inter-body EMF is induced in that target proportional to the time varying magnetic field ($\frac{dB}{dt}$) in accordance of F(E)aradays Law = $-\frac{dB}{dt}$. This causes Vortex Currents (J) to flow within that body. (McNeill et al., 1984)

McNeill, J. D., R. N. Edwards, and G. M_ Levy. "Approximate calculations of the transient electromagnetic response from buried conductors in a conductive half-space." *Geophysics* 49.7 (1984): 918-924.

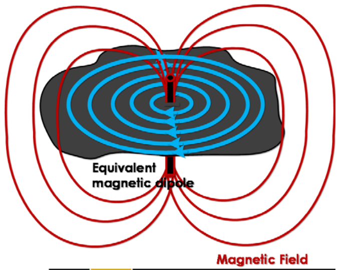
Electrical Currents in the Earth

Inductive Current Flow (Vortex Flow)

Inductive: Eddy currents circulate approximately independently of the host rock.



The circulating currents/inductive response effectively forms a magnetic field dipole



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Electrical Currents in the Earth

Galvanic Current in a Plate

Galvanic currents also known as current channeling, current gathering or current streaming.

The current that flows in a conductive plate-like body does so in accordance with Ohm's Law. The current that diverted around the plate moves along the secondary electric field lines. (McNeill et al., 1984)

McNeill, J. D., R. N. Edwards, and G. M_ Levy. "Approximate calculations of the transient electromagnetic response from buried conductors in a conductive half-space." *Geophysics* 49.7 (1984): 918-924.

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Electrical Currents in the Earth

Galvanic Current Flow

Galvanic Current: Current is focussed within a conductive target. The secondary electric field response effectively forms an electric field dipole

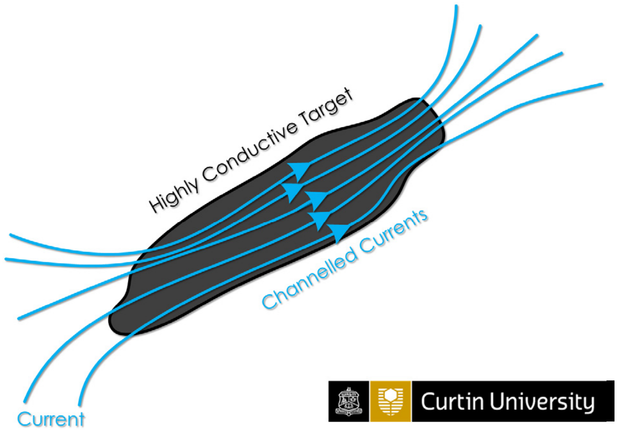
The decay is exponential:

For a B-Field Sensor

$$B_S \propto B_P e^{-\frac{t}{\tau}}$$

For a Coil Sensor $\left(\frac{dB}{dt}\right)$

$$\frac{dB}{dt} \propto e^{-\frac{t}{\tau}}$$



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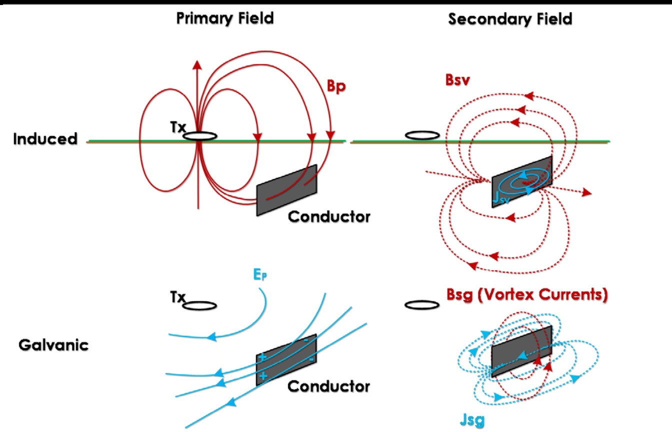
Comparison of Inductive versus Galvanic

EM Fields and a thin conductive plate



E_P: Primary Electric Field
J_{sv}: Secondary Induced Currents
J_{sg}: Secondary Galvanic Currents

B_P: Primary Magnetic Field
B_{sv}: Secondary Induced Magnetic Field
B_{sg}: Secondary Galvanic Magnetic Field

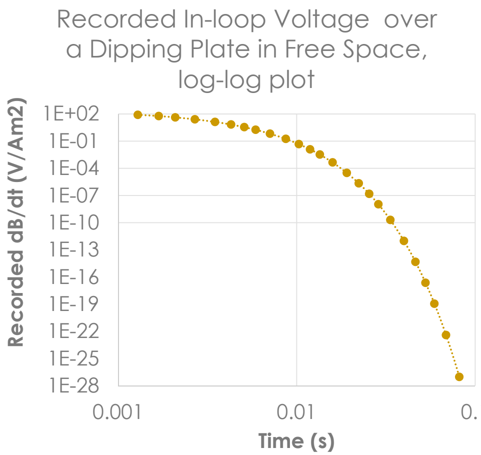
Reproduced from McNeill, J. D., R. N. Edwards, and G. M_ Levy. "Approximate calculations of the transient electromagnetic response from buried conductors in a conductive half-space." *Geophysics* 49.7 (1984): 918-924.

Decay in a Bounded Conductor

Exponential Decay of Plates

The TEM response and late times is exponential for a conductive discrete targets.

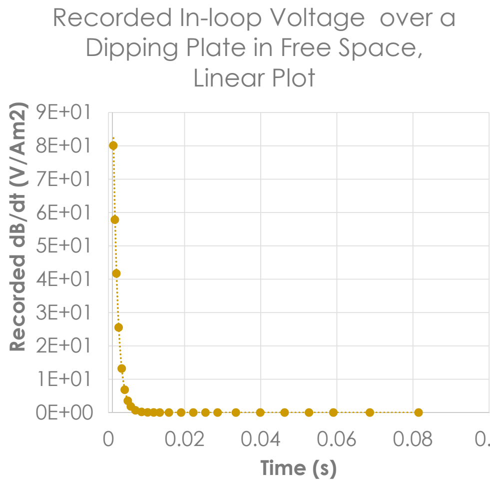
$$\frac{dB}{dt} \propto e^{-\frac{t}{\tau}}$$



Decay in a Bounded Conductor

Exponential Decays of Plates

The TEM Response decays extremely rapidly and typically are plotted on a log-log plot.



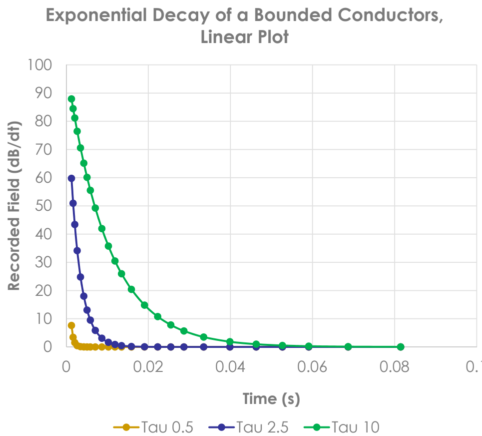
Decay in a Bounded Conductor

The Time Constant of the bounded conductor (Tau)

τ (Tau) the time constant of the bounded conductor controls the exponential decay rate.

Larger conductors and plates with larger conductance's will have larger time constants.

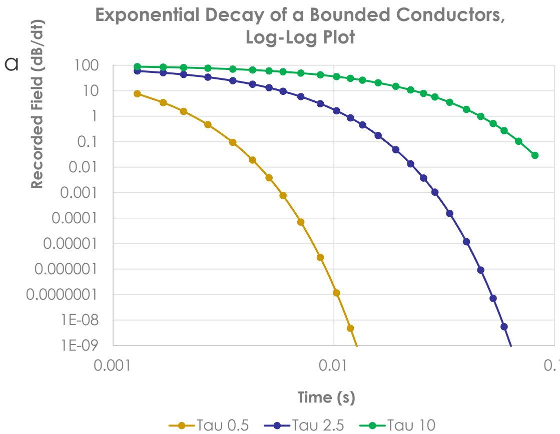
$$\frac{dB}{dt} \propto e^{-\frac{t}{\tau}}$$



What are Discrete Targets?

Plates and what are they?

A larger time constant means a target becomes easier to detect.

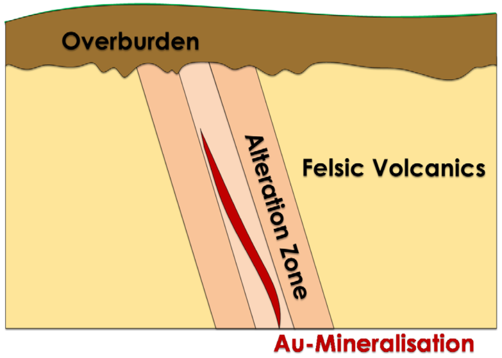


Filament Modelling

Plates and what are they?

Generally plates can be considered zones of conductive thin massive sulphides. (e.g., VMS deposit in a resistive host)

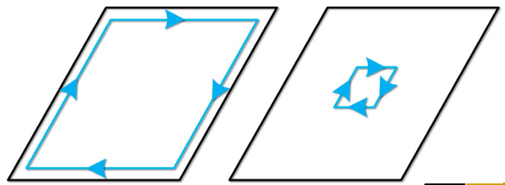
VMS sheet deposits in mafic or felsic hosted rock
- Ni-Cu
- Cu-Zn
- Zn-Pb
- Au-mineralization zones



Filament Modelling

Computing the Response of Plates : Current Filament Modes

Current filament approximation (Barnett,1984) is used to fit current filaments to the observed eddy current distribution in plates (Nabighian, 1988). The modelling of plates rely upon the computation of modes of eddy currents in a conductive sheet. These modes are similar to the perimeter of the shape. At early times the eddy currents circulate the edges of the body, while at late times eddy currents circulate the centre of the body.



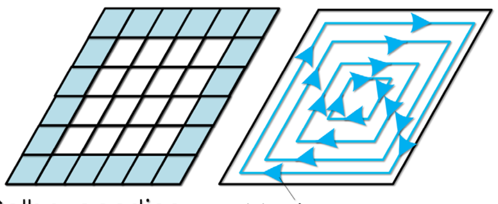
Barnett, C.T., 1984, Simple inversion of time-domain data: Geophysics, v49, p925-933
Nabighian, Misac N., ed. "Electromagnetic methods in applied geophysics: theory." (1987).

Filament Modelling

Computing the Response of Plates : Current Filament Modes

Many Modelling Programs use a current filament model of a discrete conductor.
- Maxwell
- Multiloop

In practice the plate is composed of cells and the current filament in each cell is computed.

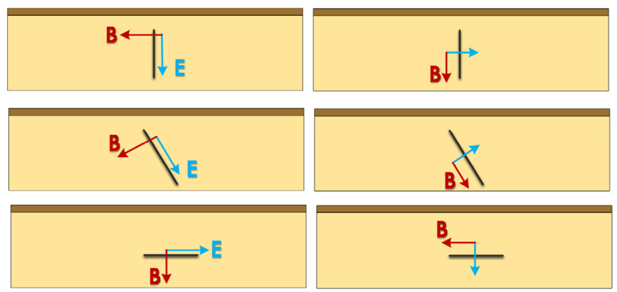


Other programs have derived a full analytic solution, computing the solution for each frequency and carrying out an ifft to retrieve the time domain response.

Coupling of Plates

Coupled versus Null-Coupled

The plate is coupled (plate induces a secondary field) with the transmitter when the electric field (current flow) is parallel with the plate's face. That is, when the magnetic field crosses through the body's face. If there is no tangential component crossing the plate, it is considered null coupled and a secondary response cannot be detected.



Coupling

Coupling with Plates

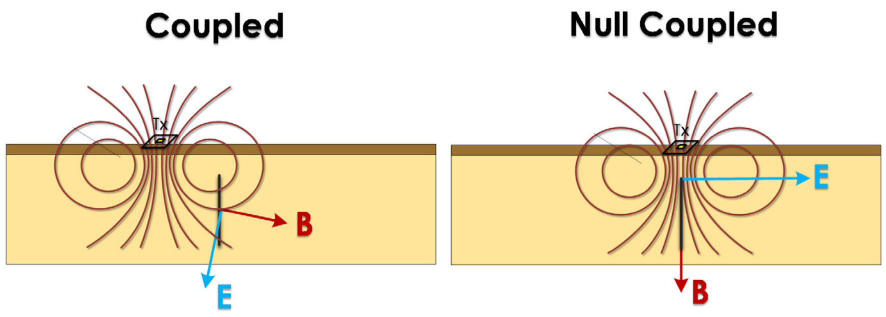


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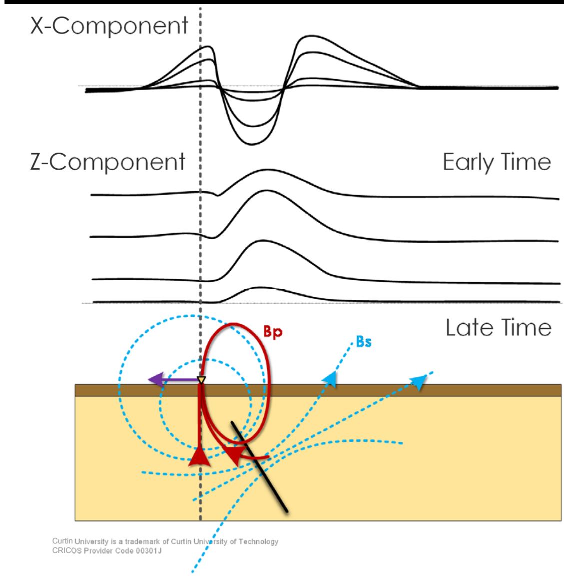
Plate Response: Dipping

In-loop



The conductive plate will oppose the primary magnetic field (Bp - Red), resulting in a secondary field (Bs - blue).

This resulting in loop receiver will record the secondary field component (purple arrow). In this scenario, there is no contribution to the vertical field, but there is a horizontal component.

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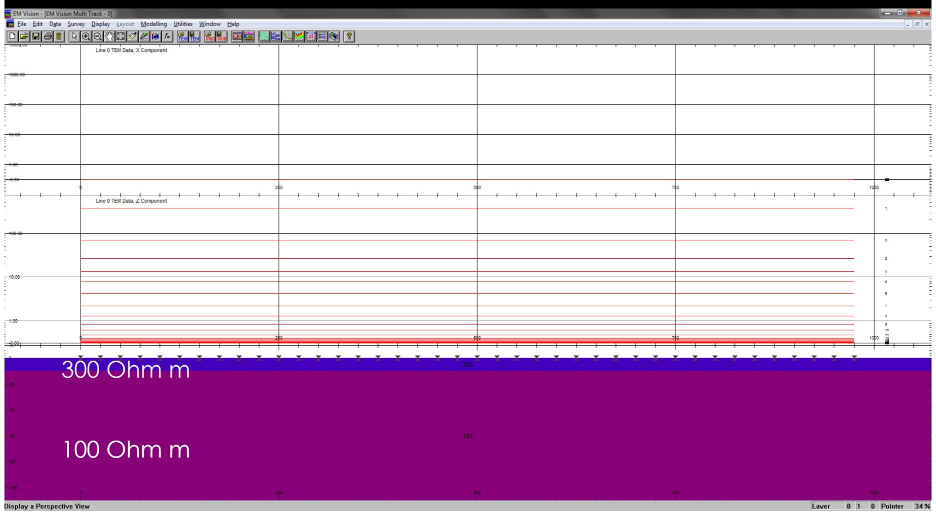
In-Loop - Layered Earth Response

No Plate – 1D Earth



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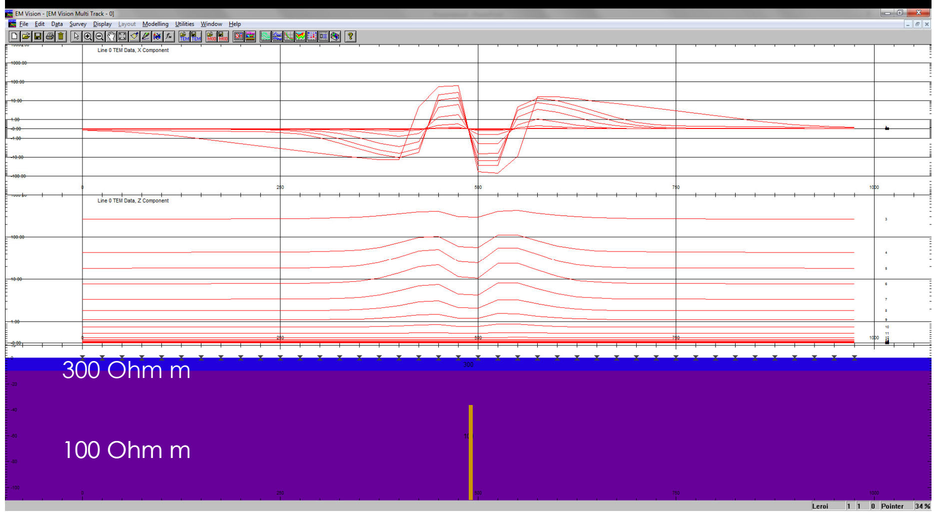
In-Loop - Layered Earth with Vertical Plate



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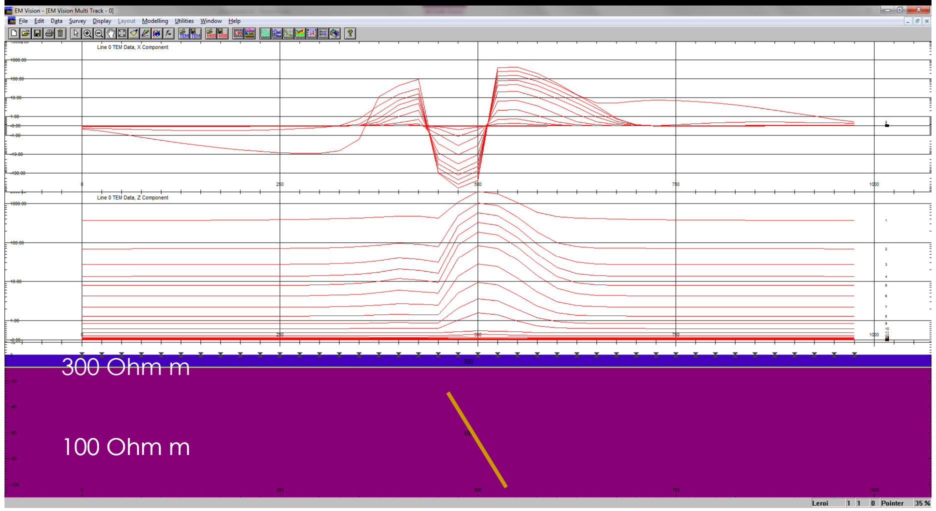
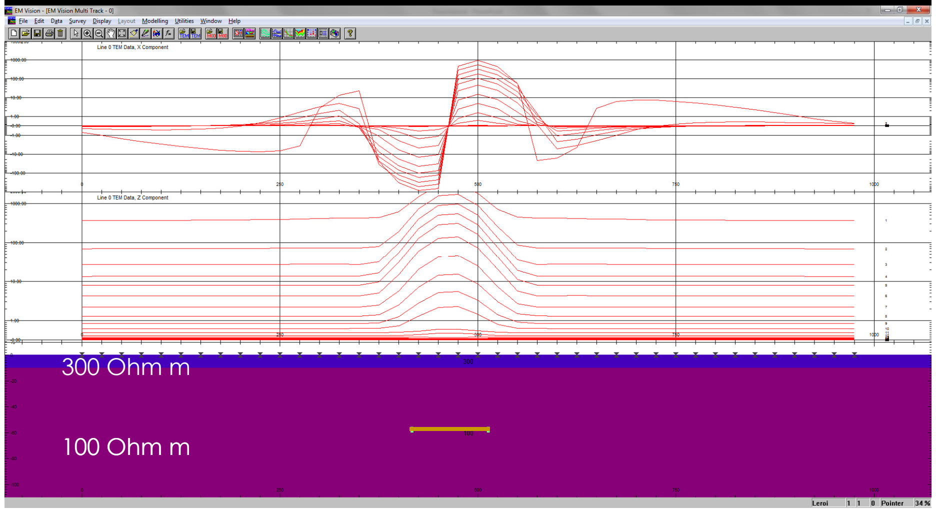
In-Loop - Layered Earth with Dipping Plate

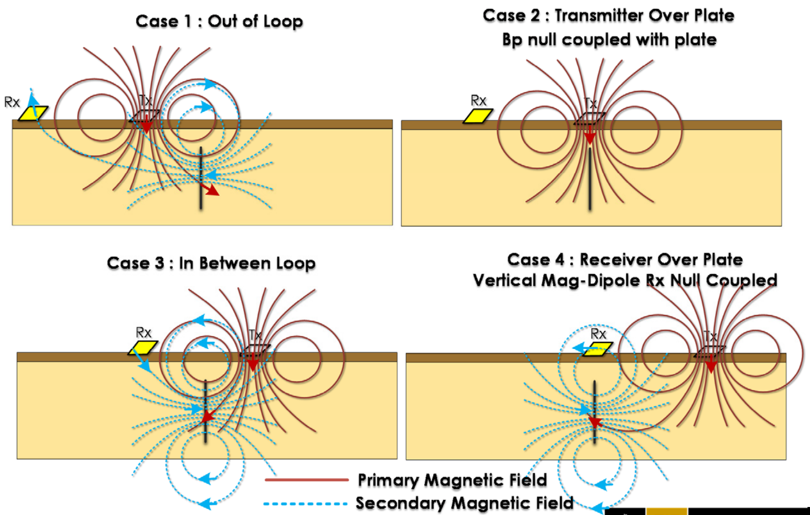


In-Loop - Layered Earth with Flat Plate

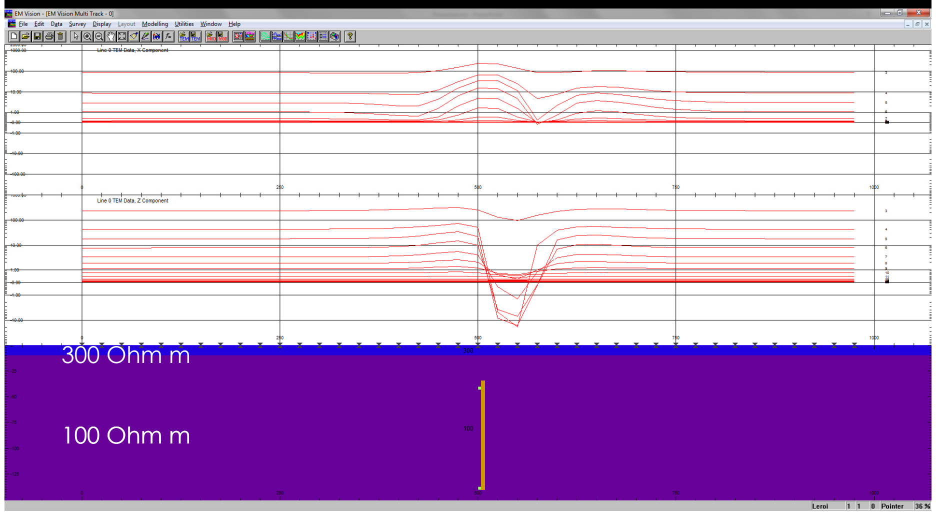


Sling-Ram

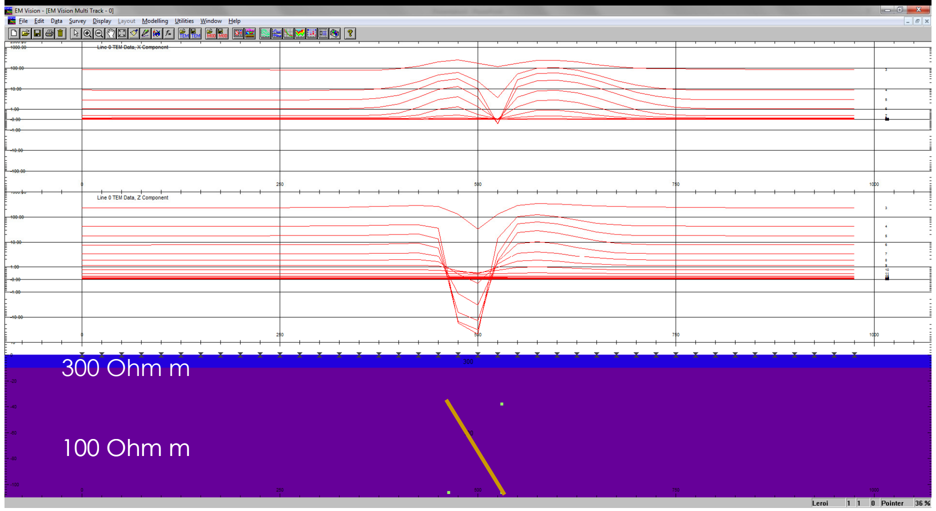
The Four Cases over a Vertical Plate



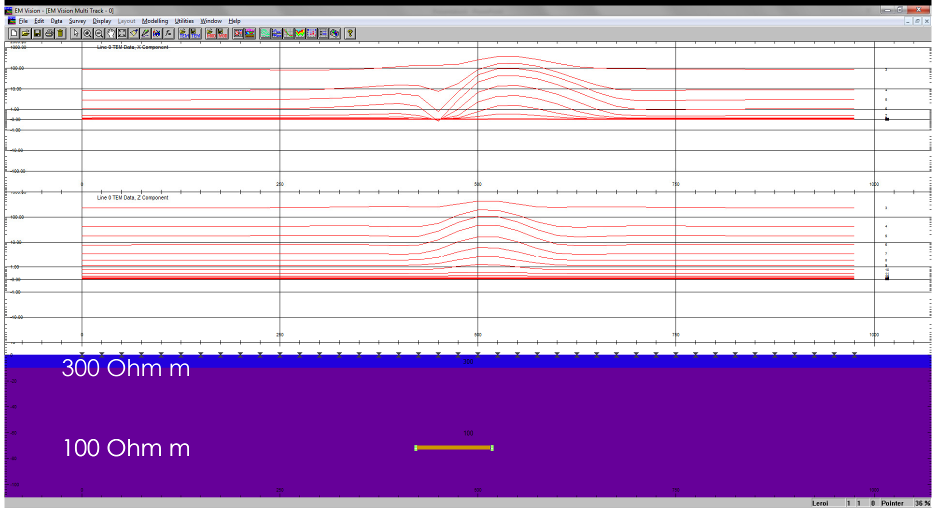
Sling-Ram – Vertical Plate



Sling-Ram – Dipping Plate



Sling-Ram – Flat Plate



Effect of Overburden

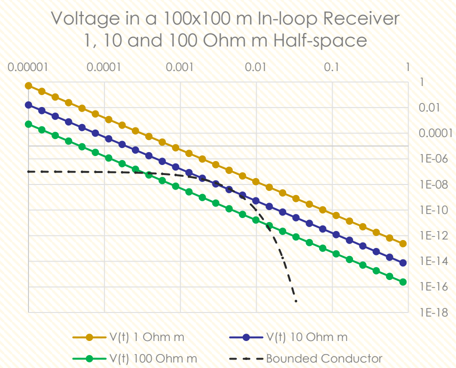
In layered earth, the voltage decays with a power law decay while bounded conductors decay exponentially and may be detected late time. If the cover is too conductive it can mask the impact of a bounded conductor.

Remember

The received voltage for a in-loop survey over a homogeneous half-space is:

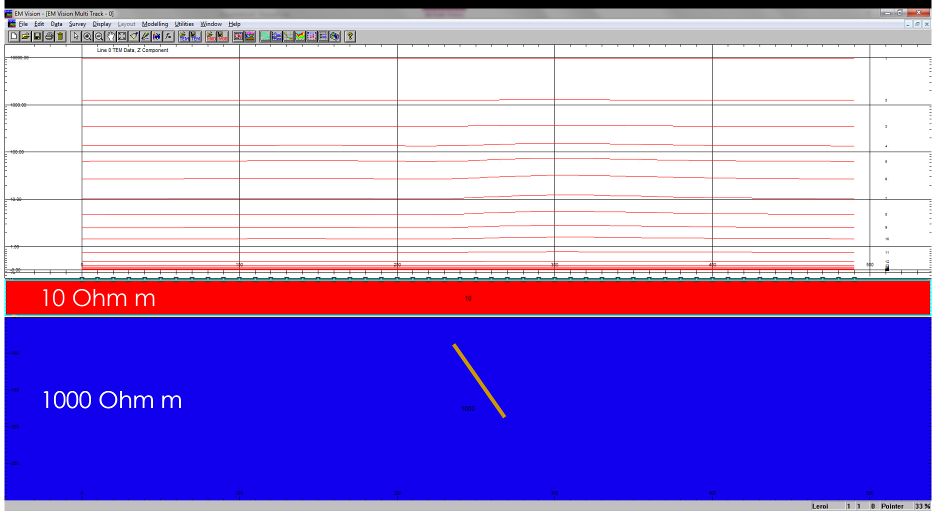
$$V(t) = 1.6 \times 10^{-17} \times I \times A \times \sigma^{\frac{3}{2}} \times t^{-\frac{5}{2}}$$

I – Current(A)
A – Transmitter Area
σ – Half-space conductivity
t – Time



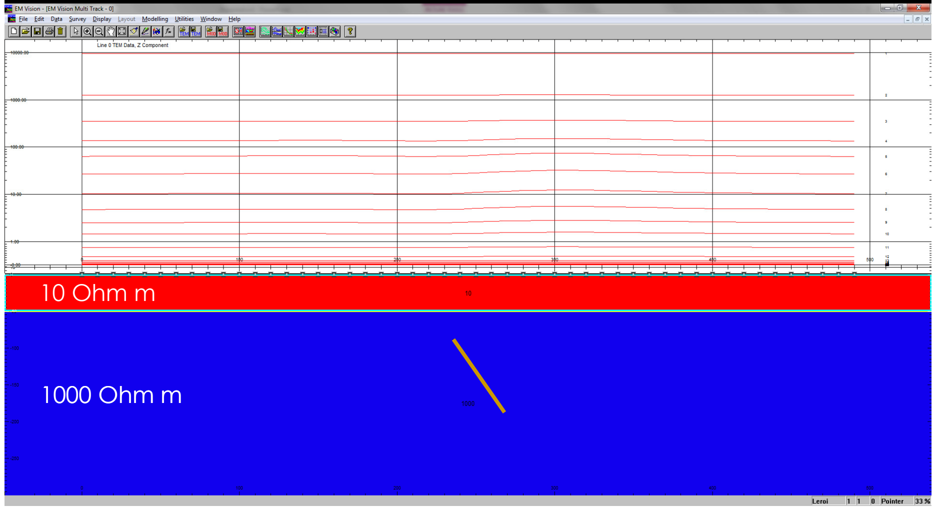
Effect of Overburden – Inloop Response of Conductive Plate in resistive halfspace

Conductive 50 m thick 10 Ohm•m Overburden



Effect of Overburden – Inloop Response of Conductive Plate in resistive halfspace

Conductive 50 m thick 10 Ohm•m Overburden



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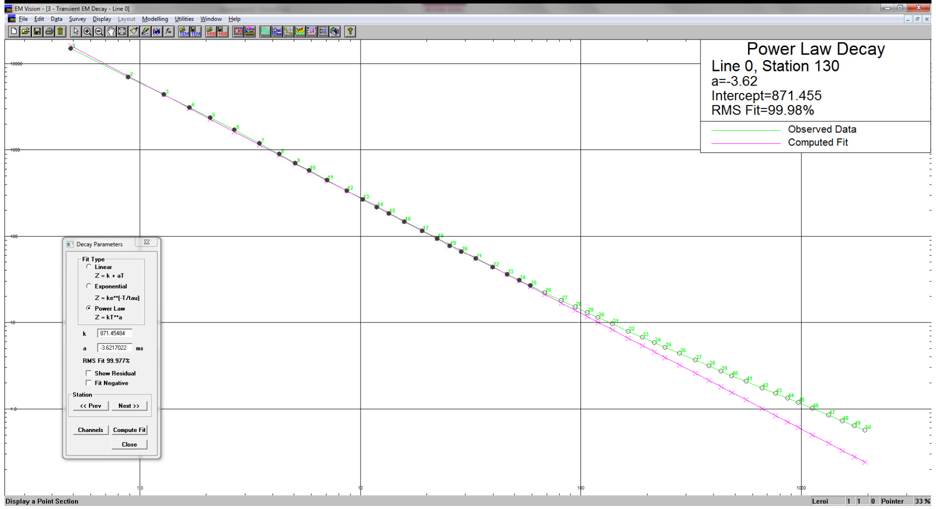
Effect of Overburden – Inloop Response of Conductive Plate in resistive halfspace

Conductive overburden – Power Law Decay of Overburden



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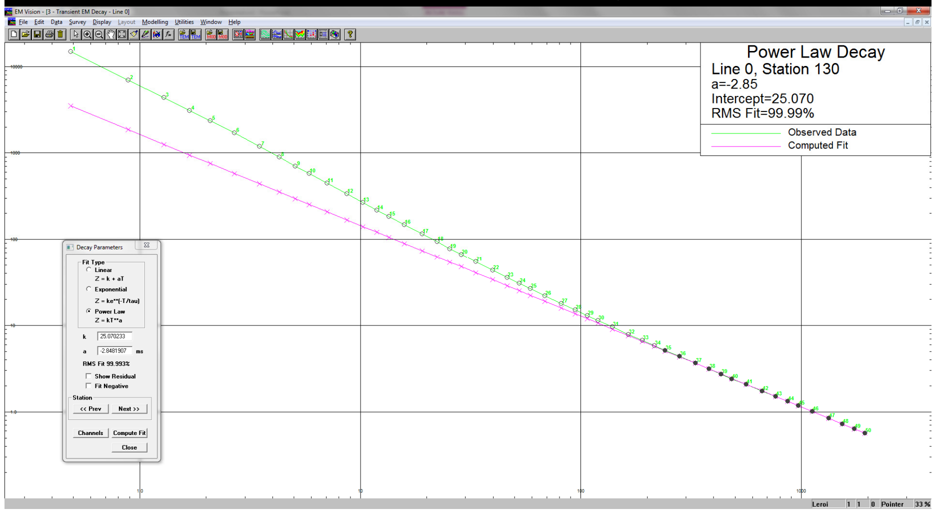
Effect of Overburden – Inloop Response of Conductive Plate in resistive halfspace

Conductive overburden – Power Law Decay of Half-Space



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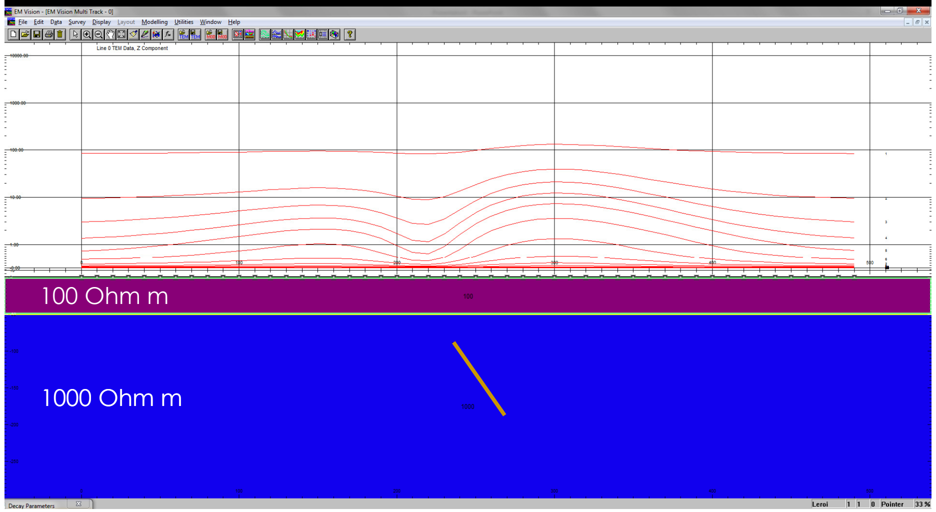
Effect of Overburden – Inloop Response of Conductive Plate in resistive halfspace

'Resistive' 50 m thick 100 Ohm•m Overburden



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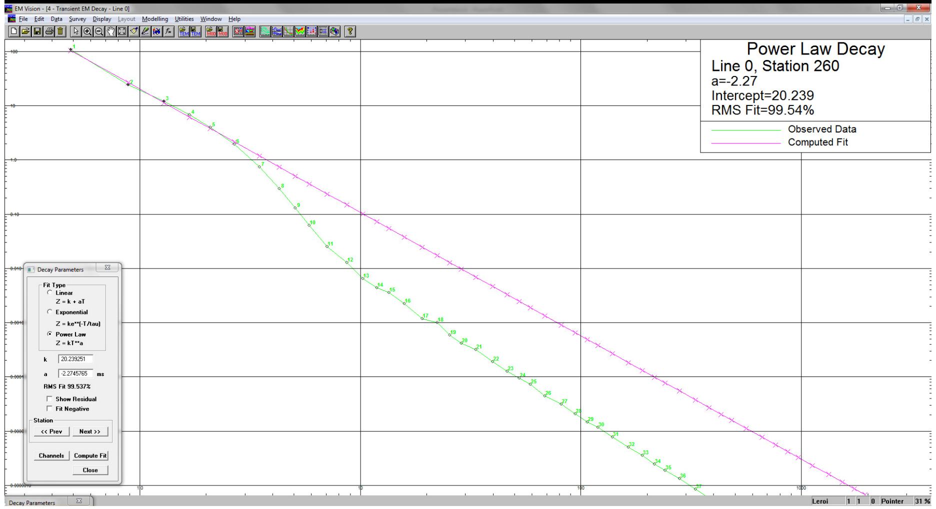
Effect of Overburden – Inloop Response of Conductive Plate in resistive halfspace

Resistive overburden – Power Law Decay of Overburden



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Effect of Overburden – Inloop Response of Conductive Plate in resistive halfspace

Resistive overburden – Exponential Decay of Plate

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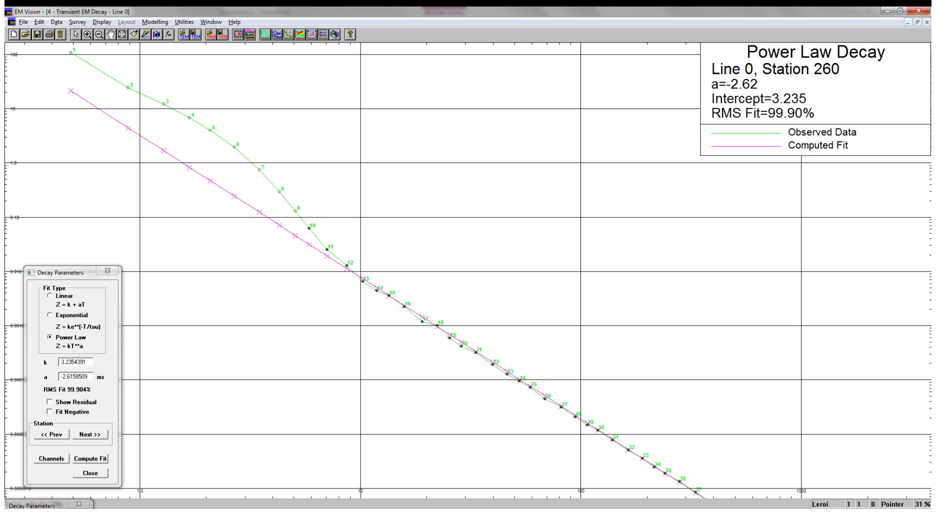
Effect of Overburden – Inloop Response of Conductive Plate in resistive halfspace

Resistive overburden – Power Law Decay of Halfspace



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LECTURE 07

Decay Curves and Soundings S2 2015

- Decay Curves: power law versus exponential decay
- Layered half-space decay
- Thin layered earth decay
- Superparamagnetism (SPM)
- Bounded Conductors
- Static Shifts
- Soundings

Lecture 06 Recap

Response of Discrete Targets

What is the difference between galvanic and inductive Current Flow?

How is a bounded conductor identified?

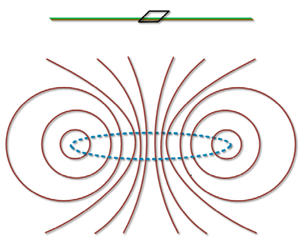
Why is it difficult to detect bounded conductors beneath conductive cover?

Understanding TEM Decay Curves

The Halfspace Response

The half-space response is due to the decaying, diffusing eddy currents in resistive layered media.

It can be identified by a power law decay.

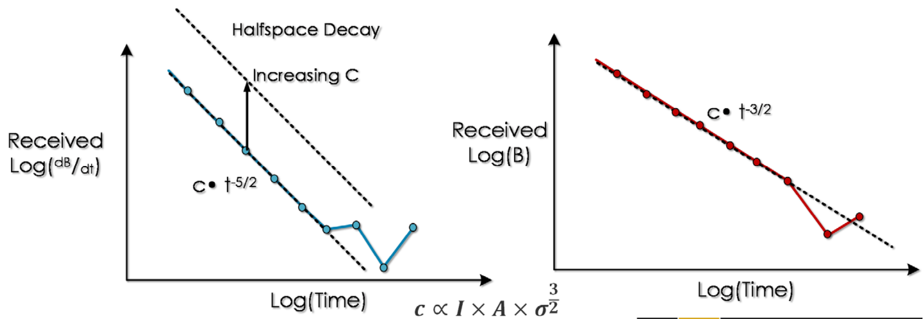


Coil Sensor	Magnetometer
Derivative of magnetic field $\left(\frac{dB}{dt}\right)$	Total magnetic field (B)
$V\left(\frac{dB_z}{dt}\right) \propto t^{-\frac{5}{2}}$	$B_z \propto t^{-\frac{3}{2}}$
$V(t) = 1.6 \times 10^{-17} \times I \times A \times \sigma^{\frac{3}{2}} \times t^{-\frac{5}{2}}$	

Understanding TEM Decay Curves

The Halfspace Response

Coil Sensor	Magnetometer
Derivative of magnetic field $\left(\frac{dB}{dt}\right)$	Total magnetic field (B)
$V\left(\frac{dB_z}{dt}\right) \propto t^{-\frac{5}{2}}$	$B_z \propto t^{-\frac{3}{2}}$



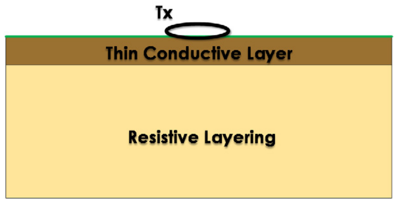
$c \propto I \times A \times \sigma^{\frac{3}{2}}$

Understanding TEM Decay Curves

The Thin Conductive Layer Response

The thin layer response

- Characterised by a power law decay that is steeper than the halfspace response.
- Caused when thin, conductive overburden overlies the resistive basement.

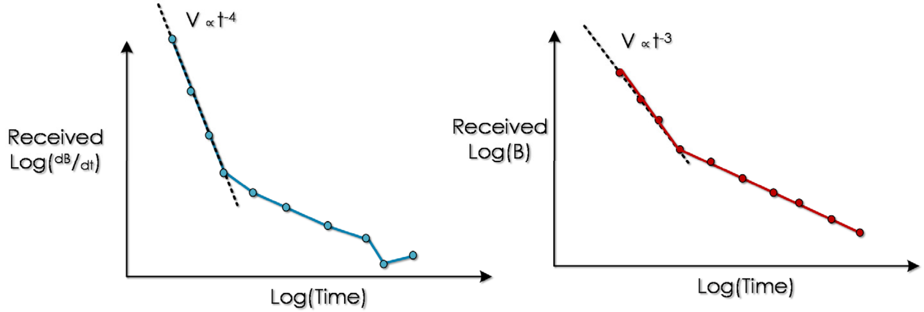


Coil Sensor	Magnetometer
Derivative of magnetic field $\left(\frac{dB}{dt}\right)$	Total magnetic field (B)
$V(\frac{dB_z}{dt}) \propto t^{-4}$	$B_z \propto t^{-3}$

Understanding TEM Decay Curves

The Thin Conductive Layer Response

Coil Sensor	Magnetometer
Derivative of magnetic field $\left(\frac{dB_z}{dt}\right)$	Total magnetic field (B_z)
$V(\frac{dB_z}{dt}) \propto t^{-4}$	$B \propto t^{-3}$

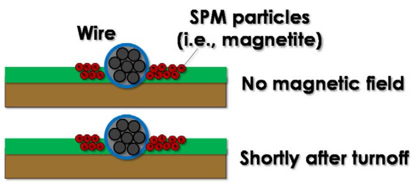


Understanding TEM Decay Curves

Superparamagnetic (SPM) Effect

"An SPM effect in rocks is connected with the process of magnetic moment change of orientation of very fine grains of ferromagnetic materials in the initial stage after a sharp change of the excitation magnetic field" (Barusukov et al., 2001)

Coil Sensor
Derivative of magnetic field $\left(\frac{dB_z}{dt}\right)$
$V(\frac{dB_z}{dt}) \propto t^{-1}$



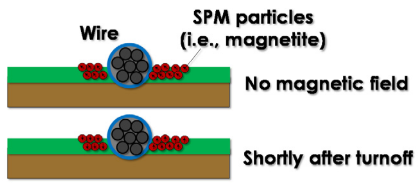
For extra information also visit
Barsukov, PAVEL O., and E. B. Fainberg. "Superparamagnetic effect over gold and nickel deposits." *European Journal of Environmental and Engineering Geophysics* 6 (2001): 61-72.
Nabighian Vol. 2 pg 452 or
Kratzer et al., Detection and correction of SPM effects in airborne EM surveys, 2012

Understanding TEM Decay Curves

Superparamagnetic (SPM) Effect

- SPM is created by extremely small particles of magnetite and maghemite
- SPM effects can be treated as frequency dispersion in magnetically susceptibility rocks
- Intensive SPM effects exist in areas of volcanic sedimentary; superficial clay formations covering parent rocks
- Manifests itself most intensively in cases when closely located or coincident transmitter and receiver loops are used
- Late time SPM effects can be seen as a low gradient power law decay of t^{-1}.

Coil Sensor
Derivative of magnetic field $\left(\frac{dB_z}{dt}\right)$
$V(\frac{dB_z}{dt}) \propto t^{-1}$



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Nabighian Vol. 2 pg 452 or
Kratzer et al., Detection and correction of SPM effects in airborne EM surveys, 2012

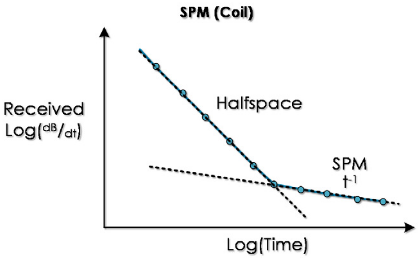
Understanding TEM Decay Curves

Superparamagnetic (SPM) Effect

According to Barsukov et al. (2001) The SPM effect can be reduced by:

1) Reducing the mutual inductance of antennas
2) Increasing the size of coincident antennas
3) Lifting the coincident antennas above the surface of the ground

Some people consider the SPM effect noise due to masking late time data, however some consider it a useful exploration signature for certain types of mineral deposits.

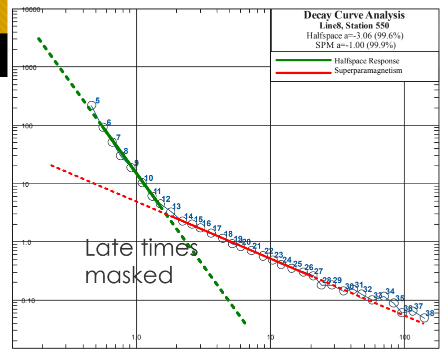


Barsukov, PAVEL O., and E. B. Fainberg. "Superparamagnetic effect over gold and nickel deposits." *European Journal of Environmental and Engineering Geophysics* 6 (2001): 61-72.

Case Study 2: Nickel Exploration Cue

Superparamagnetic (SPM) Effect

- Superparamagnetic effects were common in this survey area because of the large amount of hematite in the near surface
- Paramagnetic materials, such as magnetite are slightly susceptible and can be magnetized

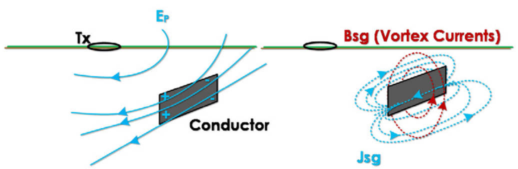


Understanding TEM Decay Curves

Bounded Conductors

Bounded conductors

- Due to eddy currents being formed in the conductive body
- Massive sulphides or graphitic conductive bodies produces these decays (See lecture 06)
- Characterised by an exponential decay.

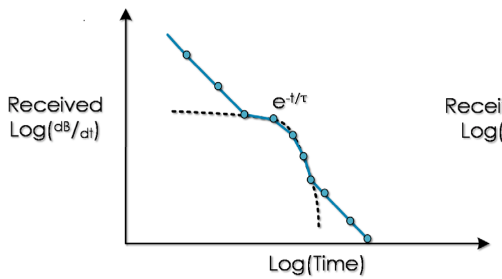


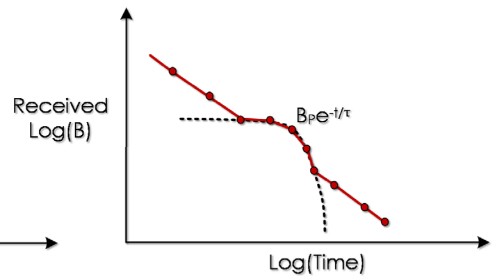
Coil Sensor	Magnetometer
Derivative of magnetic field $\left(\frac{dB}{dt}\right)$	Total magnetic field (B)
$V\left(\frac{dB}{dt}\right) \propto e^{-\frac{t}{\tau}}$	$B \propto B_P e^{-\frac{t}{\tau}}$

Understanding TEM Decay Curves

Bounded Conductors

Coil Sensor	Magnetometer
Derivative of magnetic field $\left(\frac{dB}{dt}\right)$	Total magnetic field (B)
$V\left(\frac{dB}{dt}\right) \propto e^{-\frac{t}{\tau}}$	$B \propto B_P e^{-\frac{t}{\tau}}$

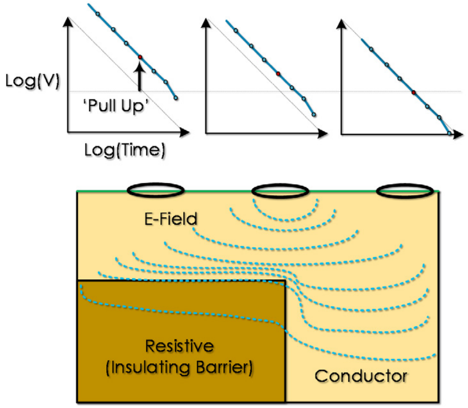




Understanding TEM Decay Curves

Current Channelling

"The terms current gathering and current channelling are used interchangeably in the literature to describe two different classes of EM response. Since there is no standard useage, we use the following definitions to describe the terms. Current channelling is a restriction on current migration due to an insulating barrier or a constricting or narrowing of a conductor."
- Spies et al., 1984



Spies, Brian R., and Patricia D. Parker. "Limitations of large-loop transient electromagnetic surveys in conductive terrains." *Geophysics* 49, no. 7 (1984): 902-912.

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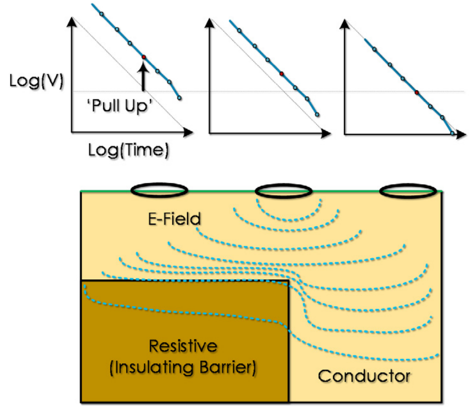
Understanding TEM Decay Curves

Current Channelling

Current channelling

- Occurs when there is greater amplitude at a particular station than surrounding stations
- It's appearance is that of an apparent 'pull-up' in the TEM response
- Attributed to the presence of a shallow weak conductor bounded by an resistive insulating barrier
- Current channelling can be seen on the decay curve as a slow decay but with raised amplitude
- If no exponential decay can be seen in the curves near "potential" anomalies , then it could be a result of current channelling with some relatively large weak conductors



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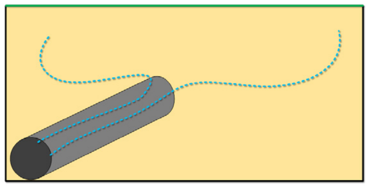
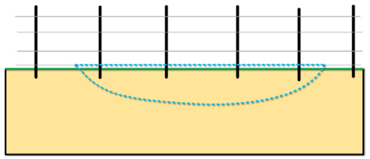
Understanding TEM Decay Curves

Current Channelling Man Made

Cultural structures can also produce current channelling effects:

- Pipes
- Power lines
- Fences





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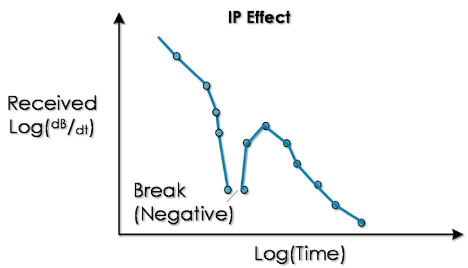
Understanding TEM Decay Curves

Induced Polarization

"When a uniform ground has a conductivity which may be described by a Cole-Cole relaxation model with a positive time constant, then the transient response of such a ground will show evidence of induced polarization (IP) effects. <u>The IP effects cause the transient initially to decay quite rapidly and to reverse polarity</u>. After this reversal the transient decays much more slowly, the decay at this stage being about the same rate as a non-polarizable ground."

(Lee, 1981)



Lee, T. "Transient electromagnetic response of a polarizable ground." Geophysics 46, no. 7 (1981): 1037-1041.

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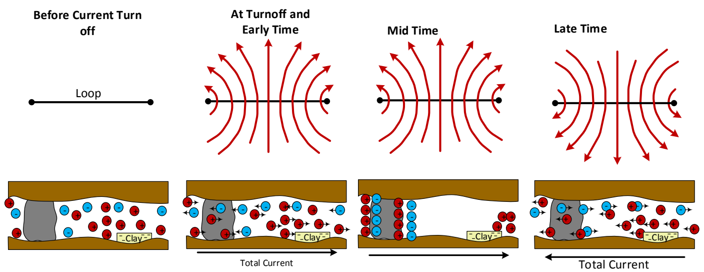
Understanding TEM Decay Curves

Induced Polarization

Induced Polarization

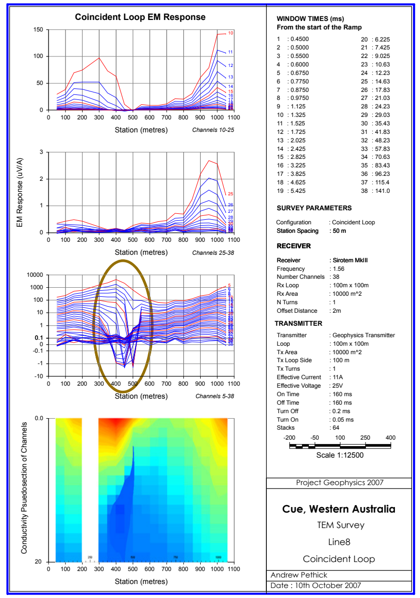
- Energy is stored in the ground and later released
- Think of this effect as a leaky capacitor in the LCR circuit
- Caused by electrode polarization/Over voltage effect caused by ionic movement in fluid filled pore spaces when metallic and clay minerals are present.



Case Study 2: Nickel Exploration Cue (IP Effect)

Case Study: Cue, Nickel Exploration

- IP effects early channels, decaying quickly into a negative response
- Resulted from either graphite or pyritic mineralisation
- Over voltage effect caused by the transition from an electric to ionic conduction, in effect a natural electrochemical half cell
- The inducing EM field generates a current, charging the equivalent of a poor battery or leaky capacitor
- This electronic storage is commonly seen in massive or disseminated sulphides and graphite.



Case Study 3: Hart and Lane, 2001

Detection of conductor beneath conductive cover

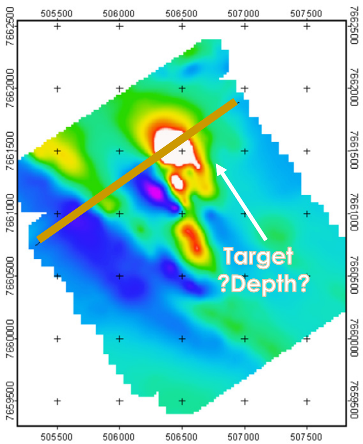
Location
- Bull Creek Prospect, NW Queensland

Target
- Magnetite-pyrrhotite mineralisation

Target Properties
- Magnetic and conductive
- The mineralisation of Proterozoic age
- Buried beneath 30-50m cover

Cover Properties
- Overburden conductance values of 10 to 30 S

Geophysical Information
- Airborne electromagnetic systems
- Ground TEM (Moving loop)
- Drilling information



Ground magnetic data

Case Study taken from: Hart, J., Lane, R., 2001, Comparison of Airborne and Ground TEM systems for a conductor beneath conductive cover - an example from North-West Queensland, Australia, *ASEG 15th Geophysical Conference and Exhibition, August 2001, Brisbane.*

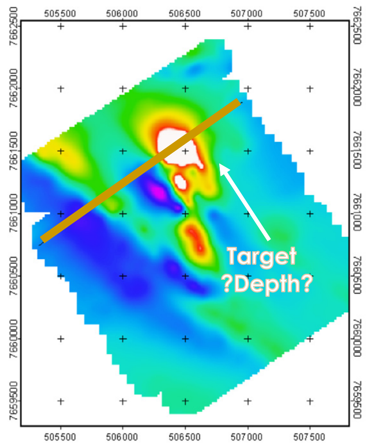
Case Study 3: Hart and Lane, 2001

Detection of conductor beneath conductive cover

Geological History

Alteration and mineralisation resulting in a coincident magnetic and conductive body occurred in three phases:

1. Widespread albite alteration (pyrrhotite rich event with lesser magnetite, pyrite and chalcopyrite)
2. Magnetite alteration (pyrite-rich with lesser pyrrhotite and chalcopyrite)
3. Two-stage Fe-rich



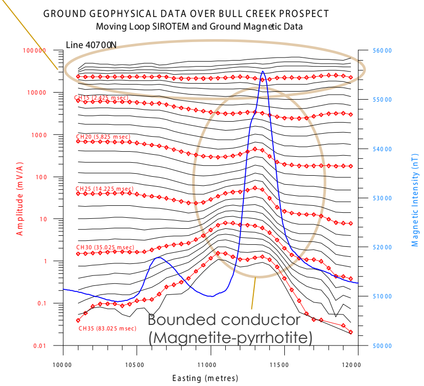
Ground magnetic data

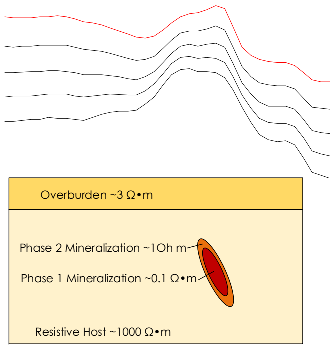
Hart, J., Lane, R., 2001, Comparison of Airborne and Ground TEM systems for a conductor beneath conductive cover - an example from North-West Queensland, Australia, *ASEG 15th Geophysical Conference and Exhibition, August 2001, Brisbane.*

Case Study 3: Hart and Lane, 2001

Detection of conductor beneath conductive cover

conductive overburden
causing early-time 'bunching'





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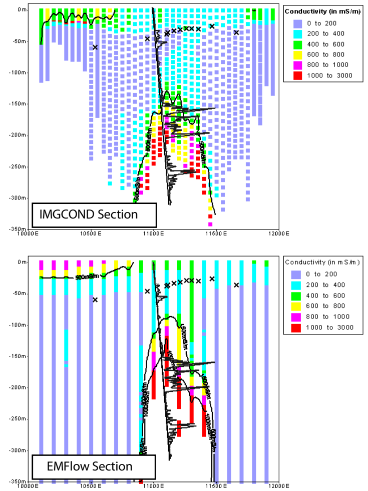
Case Study 3: Hart and Lane, 2001

Detection of conductor beneath conductive cover



So what was useful?

The TEM inversion provided "good estimates" of:

- Depth of overburden
- Depth to target
- Target geometry

"Conductivity sections derived from moving loop TEM data. Depth to basement from drilling is indicted with crosses. Drillhole BCD002 is shown along with downhole magnetic susceptibility." (Hart and Lane, 2001)

Hart, J., Lane, R., 2001, Comparison of Airborne and Ground TEM systems for a conductor beneath conductive cover - an example from North-West Queensland, Australia, *ASEG 15th Geophysical Conference and Exhibition, August 2001, Brisbane.*

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Case Study 4: Cunion, 2009

Ground TEM for Kimberlites Under Cover

Location

- Kalahari Kokong kimberlite field Bostwana

Target

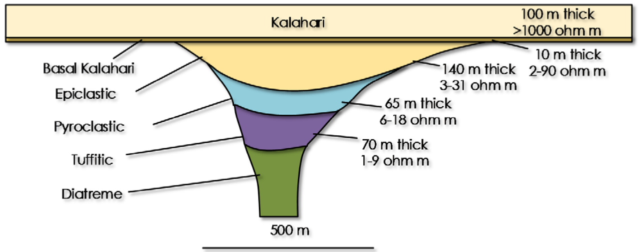
- Kimberlites

Cover Properties

- Resistive Kalahari-Cover ~120 m thick

Geophysical Information

Airborne electromagnetic systems (VTEM)
Ground In-loop TEM
Gravity and Magnetic



Case Study taken from: Cunion, Ed. "Comparison of ground TEM and VTEM responses over kimberlites in the Kalahari of Botswana*." *Exploration Geophysics* 40, no. 4 (2009): 308-319.

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Case Study 4: Cunion, 2009

Ground TEM for Kimberlites Under Cover

System ========>	Protem 57	Zonge ZT30	VTEM 2004
Loop type	Ground in-loop	Ground in-loop	Airborne in-loop
Loop size	100 m square	100 m square	26 m diameter
Loop area	10 000 m^2	10 000 m^2	531 m^2
No. of turns	1	1	4
Peak amperage	25	30	140
Peak moment NIA	250 000	300 000	297 000
Sounding separation	100 m	100 m	3 m (average)
Tx waveform	Square	Square	Trapezoid
Duty cycle	50%	50%	40%
Base frequency	6.25 Hz	4 Hz	30 Hz
# Rx channels	20	31	27
Rx decay time range	0.346 to 28.1 ms	0.126 to 48.1 ms	0.13 to 7.54 ms

Cunion, Ed. "Comparison of ground TEM and VTEM responses over kimberlites in the Kalahari of Botswana*." *Exploration Geophysics* 40, no. 4 (2009): 308-319.

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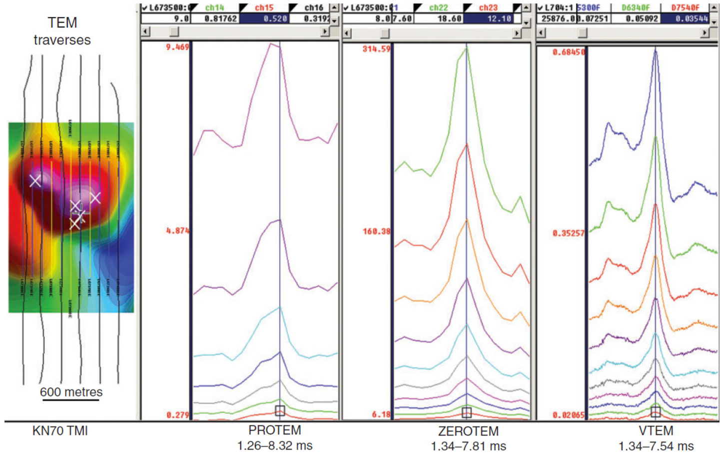
Case Study 4: Cunion, 2009

Ground TEM for Kimberlites Under Cover



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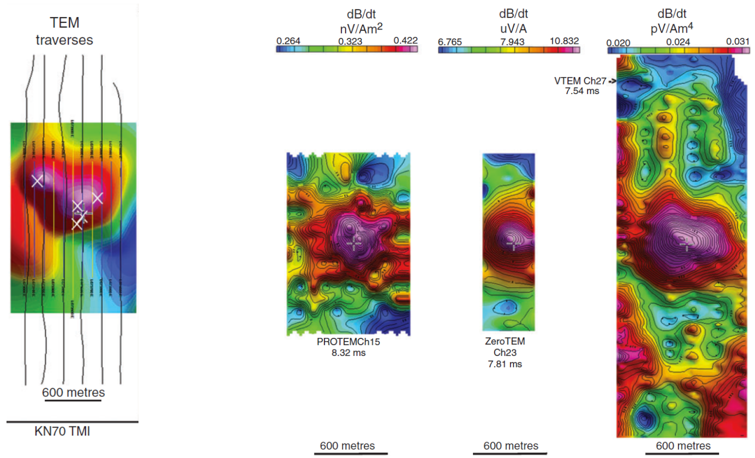
Case Study 4: Cunion, 2009

Ground TEM for Kimberlites Under Cover



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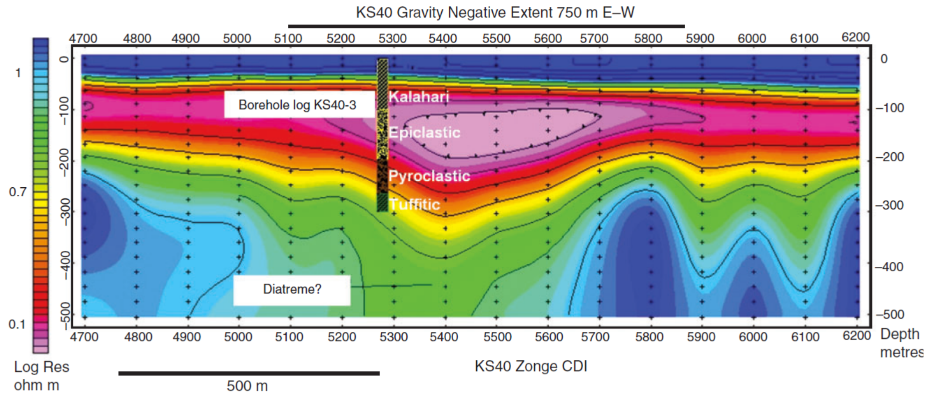
Ground TEM for Kimberlites Under Cover



Cunion, Ed. "Comparison of ground TEM and VTEM responses over kimberlites in the Kalahari of Botswana*." *Exploration Geophysics* 40, no. 4 (2009): 308-319.

Case Study 4: Cunion, 2009

Ground TEM for Kimberlites Under Cover

So what was useful?

- Targeted and characterized the kimberlite pipes, when TEM and gravity datasets are combined (i.e., conductive, low density anomalies)
- CDI's were useful to identify kimberlites when TEM responses were subtle and the enclosing basement was conductive

"TEM is an effective method in the Kokong kimberlite field for prioritising the aeromagnetic signatures of kimberlites buried by up to 120m of Kalahari cover. Both the VTEM and ground TEM systems return diagnostic TEM responses for 90% of the kimberlites traversed. The VTEM is as effective as the ground TEM systems when prioritising most kimberlite magnetic and gravity signatures."

(Cunion, 2009)

Cunion, Ed. "Comparison of ground TEM and VTEM responses over kimberlites in the Kalahari of Botswana*." *Exploration Geophysics* 40, no. 4 (2009): 308-319.

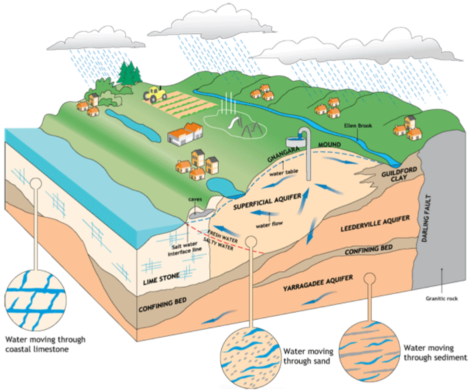
CASE 4 : Curtin University (Ongoing)

Department of Water – Hydrogeological

Aim

To determine subsurface electrical conductivities to assist the targeting and characterization of:

- Clay layers
- Potential Fresh water Aquifers
- Salt water intrusion zones
- Fault structural and geo-electrical properties



Reproduced from Gnangara Sustainability Strategy
http://www.water.wa.gov.au/sites/gss/gss.html, Accessed 01/10/2015

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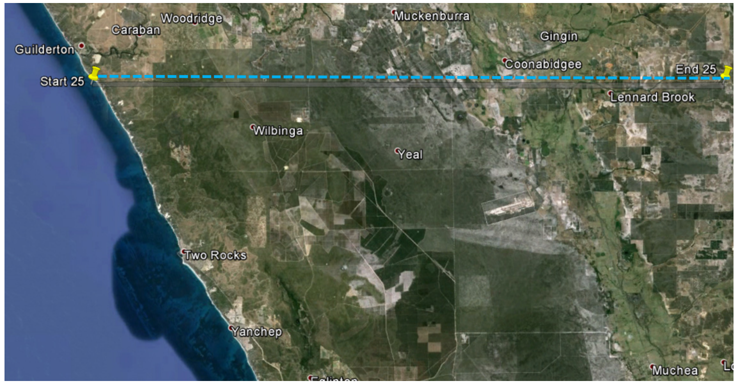
CASE 4 : Curtin University (Ongoing)

Example Survey



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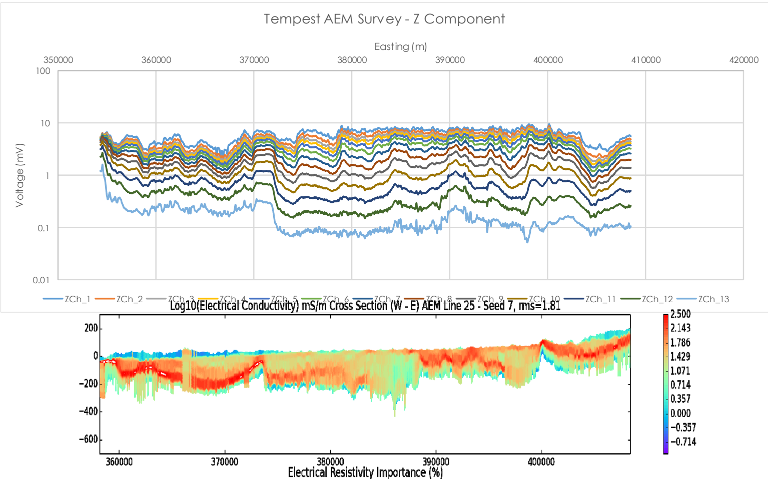
CASE 4 : Curtin University (Ongoing)

Z-Component



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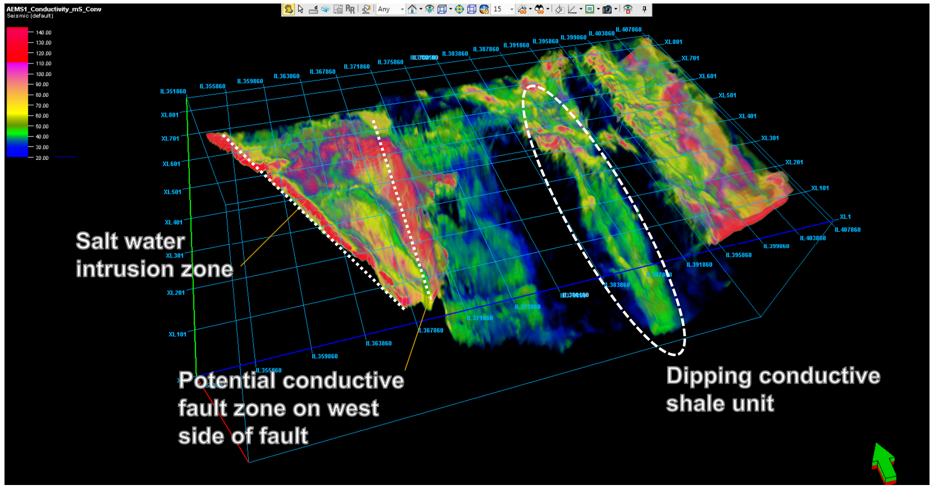
CASE 4 : Curtin University (Ongoing)

3D Volume Rendering



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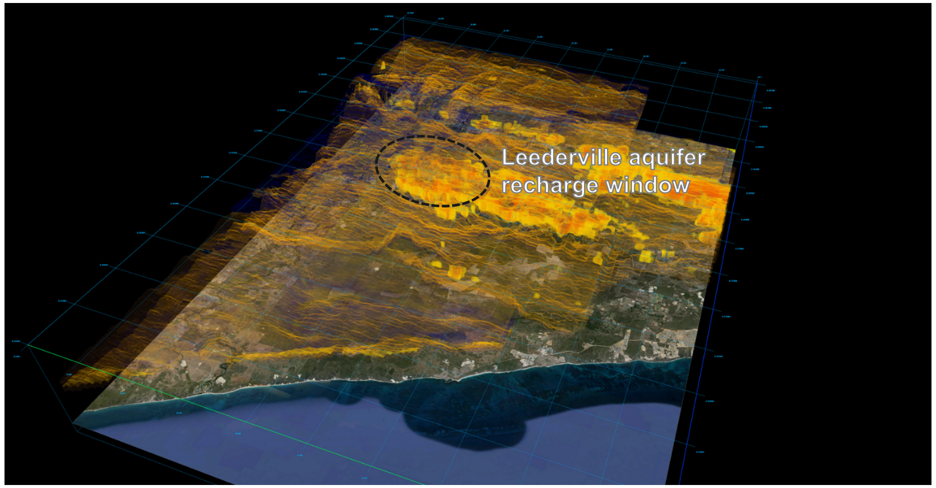
CASE 4 : Curtin University (Ongoing)

3D Volume Rendering



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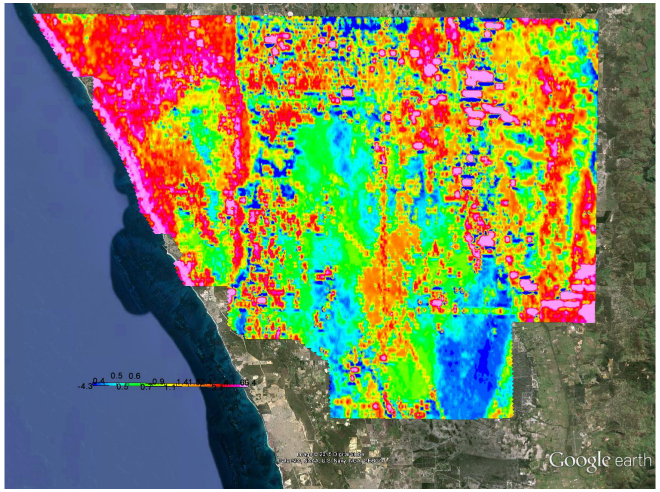
CASE 4 : Curtin University (Ongoing)

RMS Error



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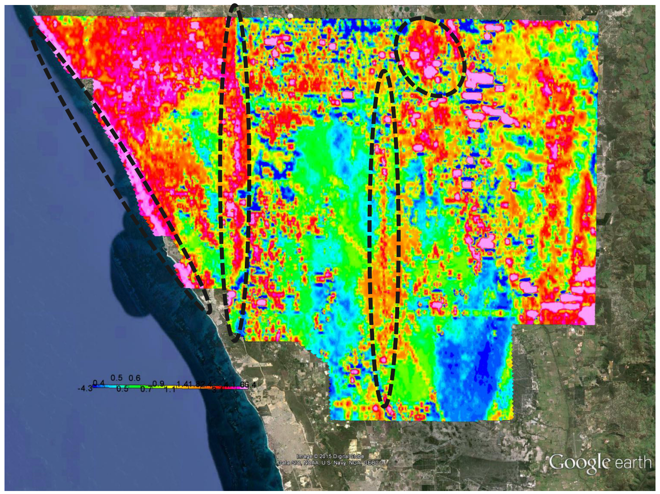
CASE 4 : Curtin University (Ongoing)

RMS Error



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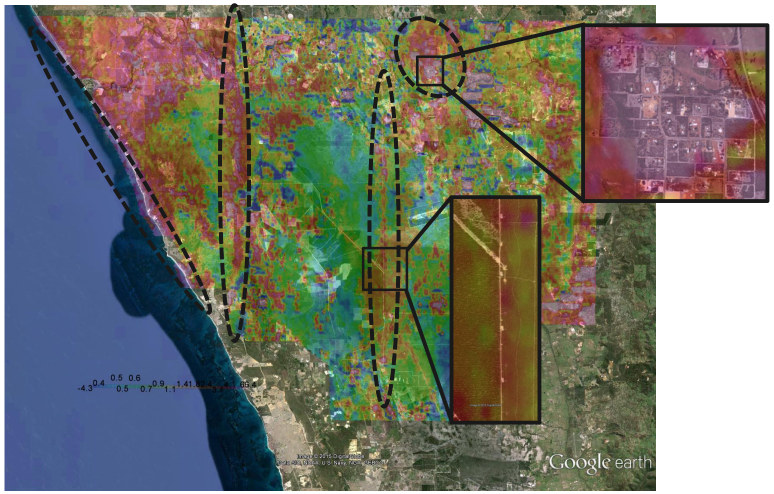
CASE 4 : Curtin University (Ongoing)

RMS Error



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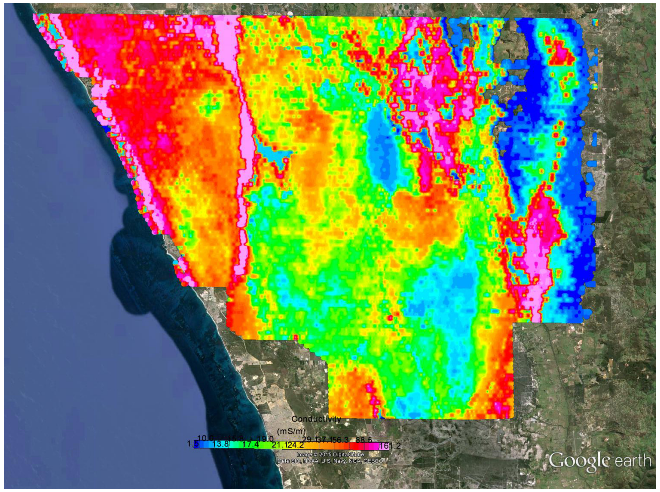
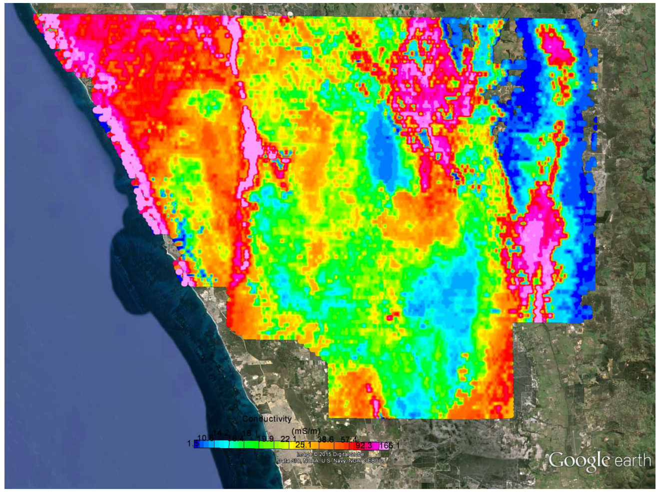
CASE 4 : Curtin University (Ongoing)

60 m depth slice



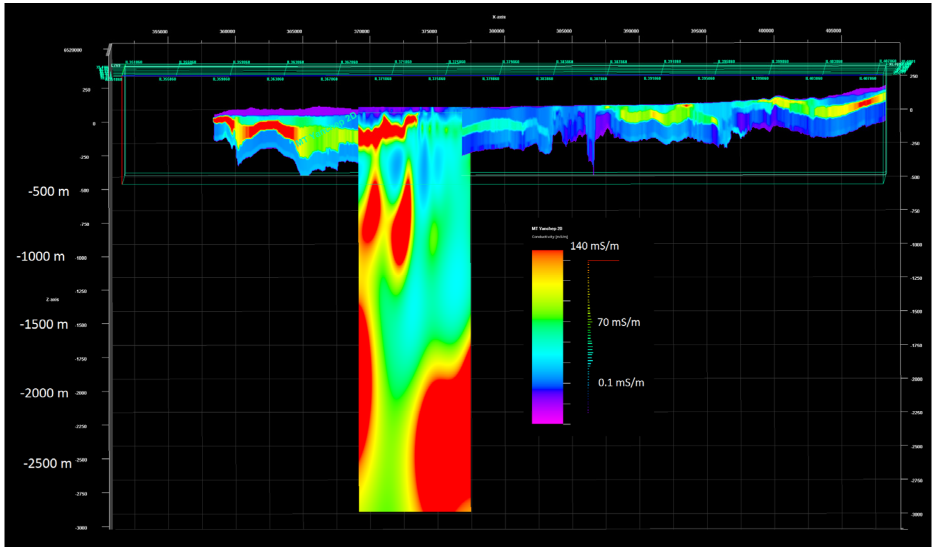
CASE 4 : Curtin University (Ongoing)

Salt water Intrusion Zone – 40 m depth slice



CASE 4 : Curtin University (Ongoing)

MT Versus AEM



CASE 4 : Curtin University (Ongoing)

Results

So what was useful?

The AEM did recover (in great detail):

- electrical properties of both the aquifers and confining clay layers.
- recharge window
- salt water intrusion zone

LECTURE 08

The Magnetotelluric Method S2 2015

- Magnetotelluric Method Principles
- 1D MT Forward Modelling Formulation
- Applications
- CSAMT
- VLF

What is the Magnetotelluric Method?

Natural – Passive Source EM

"A method in which orthogonal components of the horizontal and magnetic fields induced by natural primary sources are measured simultaneously as functions of frequency."

- **Sheriff's Encyclopaedic Dictionary of Applied Geophysics, fourth edition**

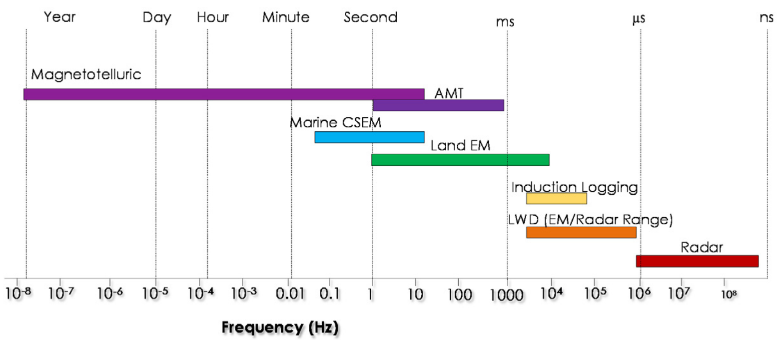
"The magnetotelluric method is a technique for imaging the electrical conductivity and structure of the Earth, from the near surface down to the 410 km transition zone and beyond."

Chave, Alan D., and Alan G. Jones. *The magnetotelluric method: Theory and practice*. Cambridge University Press, 2012.

What is the Magnetotelluric Method?

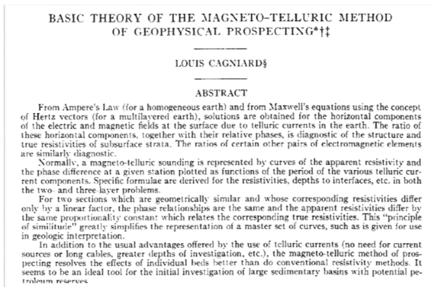
Natural – Passive Source EM

Several variants of the MT method
- Magnetotelluric **(MT)**
- Audio Magnetotelluric **(AMT)**
- Controlled Source Audio Magnetotelluric **(CSAMT)**



History of MT

Russian and French Scientists



BASIC THEORY OF THE MAGNETO-TELLURIC METHOD OF GEOPHYSICAL PROSPECTING*†‡

LOUIS CAGNIARD§

ABSTRACT

From Ampere's Law (for a homogeneous earth) and from Maxwell's equations using the concept of Hertz vectors (for a multilayered earth), solutions are obtained for the horizontal components of the electric and magnetic fields at the surface due to telluric currents in the earth. The ratio of these horizontal components, together with their relative phases, is diagnostic of the structure and true resistivities of subsurface strata. The ratios of certain other pairs of electromagnetic elements are similarly diagnostic.

Normally, a magneto-telluric sounding is represented by curves of the apparent resistivity and the phase difference at a given station plotted as functions of the period of the various telluric current components. Specific formulae are derived for the resistivities, depths to interfaces, etc. in both the two- and three-layer problems.

For two sections which are geometrically similar and whose corresponding resistivities differ only by a linear factor, the phase relationships are the same and the apparent resistivities differ by the same proportionality constant which relates the corresponding true resistivities. This "principle of similitude" greatly simplifies the representation of a master set of curves, such as is given for use in geologic interpretation.

In addition to the usual advantages offered by the use of telluric currents (no need for current sources or long cables, greater depths of investigation, etc.), the magneto-telluric method of prospecting resolves the effects of individual beds better than do conventional resistivity methods. It seems to be an ideal tool for the initial investigation of large sedimentary basins with potential petroleum reserves.

Cagniard, Louis. "Basic theory of the magneto-telluric method of geophysical prospecting." *Geophysics* 18, no. 3 (1953): 605-635.

- It has been known for a long time that currents have been flowing in the ground, that is a potential difference between two points
- Developed by Frenchman Lois Cagniard (1953) and Russian Tikhonov (1950)
- Developed to find electrically conductive targets that do not produce a magnetic or gravity signature
- "In General, petroleum and mining geologists were not satisfied with the ambiguous interpretations which geophysicists could offer them on the basis of equipotential data" (Cagniard, 1953)
- Was adopted because it uses no current source unlike electrical DC or AC methods and can see deeper than a few hundred metres.
- Thought to be useful for oil and gas exploration

MT

Applications

- Mineral exploration
- Geothermal studies
- Environmental
- Hydro-geophysics
- Oil and Gas exploration

Survey Layout

Magnetotelluric Equipment Checklist (For two V8 Receivers)

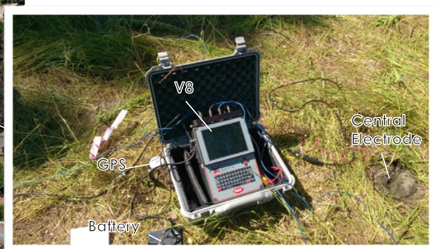
Item	
Phoenix V8 Receivers (Each V8 Should contain)	(x2)□
- Compact Flash Disk	□
- GPS	□
- GPS Cable	□
- Compact Flash Card	□
- Hx/Hy/Hz to V8 cable	□
- Battery Cable	□
- CSEM Tx Antenna	□
Airplane Grounding Connector	□
First Aid Kit	□
Battery 12V Is Charged	(x2)□ (Battery 1) □ (Battery 2) □
E-Field Electrodes	(x10) □
AMT Sensors	(x4) □
MT Sensors	(x4) □
AMT/MT to V8 Cable	(x4) □
Phoenix V8 Field Manual	□
Phoenix Layout Sheets (Field Notes)	□
Pens	□
Phone/Camera (field note recording)	□

Item	
Tarpaulin (To cover V8 on rainy days)	□
Compact Flash Disk Card Reader	□
Field Laptop Is Charged	□ □
Spirit Level(s)	□
Shovel(s)	□
Tape Measure(s) 100m	□
Multi meter(s)	□
Multi meter +/- electrode cables	□
Salt	□
Water Canister (30 L)	□
Water (for canister)	□
Electrical Tape	□
Cables	800 m (E-Field bipoles)
Compass	□
GPS	□
Pliers	□
Wire Cutters/Stripper	□
Food + water + Personal supplies	□
12VAir Compressor (for 4WD)	□

Survey Layout

Magnetotelluric Survey Layout

- Base station
  - 4 channel (minimum) electric and magnetic recorder (i.e., Pheonix V8)
  - GPS (for time synchronization and location)
  - Battery
  - Central Electrode



Survey Layout

Magnetotelluric Survey Layout

- Two Electric Bipole receivers
  - East-West oriented bipole
  - North-South oriented bipole
  - Consists of two electrodes per bipole
  - Typically 50-200 m in length

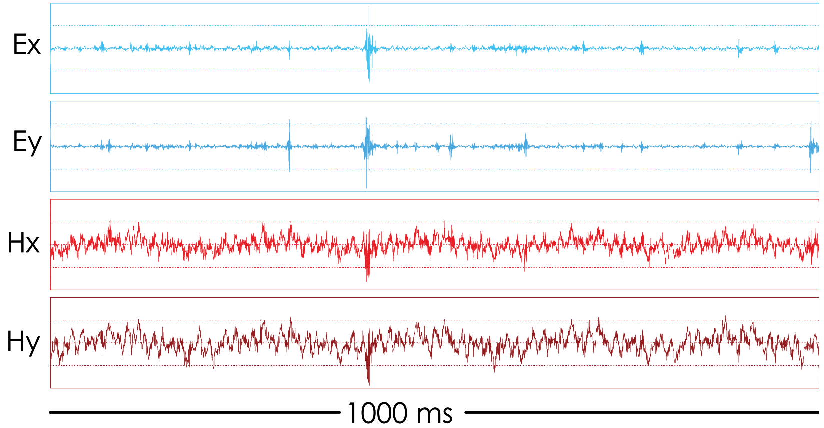
Survey Layout

Magnetotelluric Survey Layout

- Two or Three Magnetic induction receivers (i.e., magnetic coil receivers)
  - East-West oriented magnetic coil (**Hy**)
  - North-South oriented magnetic coil (**Hx**)
  - Vertical magnetic coil (Tipper) (**Hz**)

AMT Time Series

Example AMT Time Series of Electric and Magnetic components (>1 Hz)



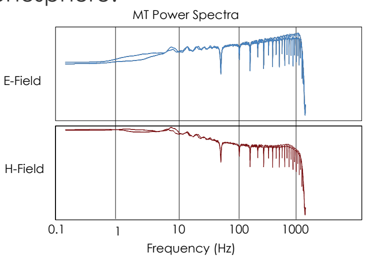
MT/AMT Power Spectra

Where is the signal generated?

There are two main sources of energy

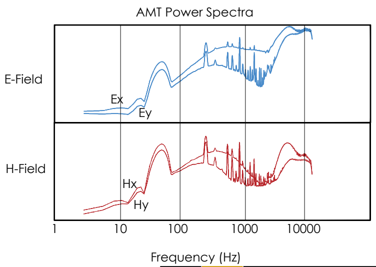
Ionosphere(< 1Hz)

Electromagnetic fields generated by fluctuations of the Earth's magnetic caused by solar radiation interacting with the ionosphere.



Lightning (1-10,000 Hz)

Generated by lightning strikes.



Source of Magnetotelluric Signal

Ionospheric Signal

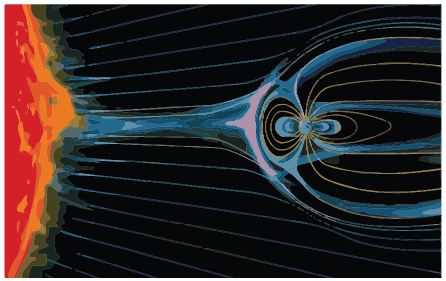
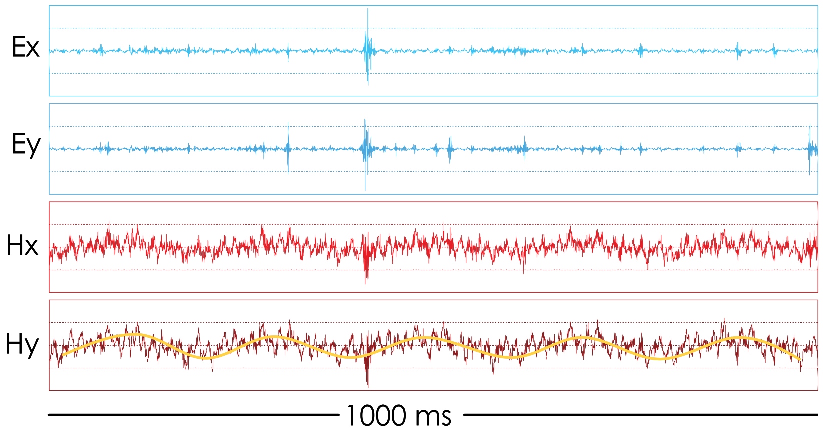


Image modified from, IRIS Project, http://www.propagation.gatech.edu/ECE6390/project/Fall2011/group5/website/ssp/sat/env/radiation.html, Retrieved, Oct 2015

- The ionosphere is a region ranging from 65 km altitude
- Ionization of different molecules occurs at various levels (D, E and F)
- Ions at each level include nitric oxide, oxygen ions , hydrogen and helium
- Ions in within each layer of the ionosphere can be disturbed by:
  - Typical solar radiation/wind (H^+ He^{++})
  - X-Rays caused by solar flares
  - Absoption of high energy protons from solar flares
  - Geo-magnetic storms
  - Lightning (Lightning-induced electron precipitation)
- These interactions will cause net movement of charges within the ionosphere acting as a large electric sheet source

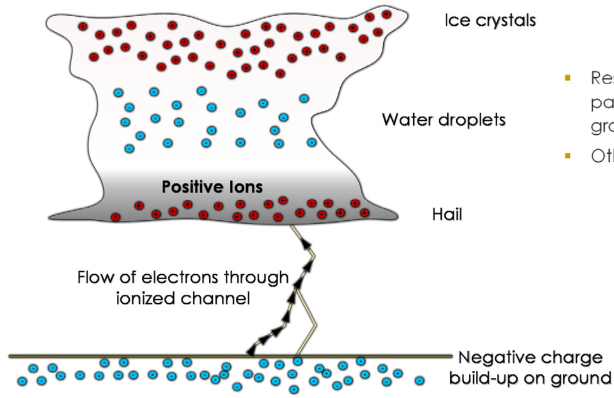
AMT Time Series

Ionospheric Signal



Source of Magnetotelluric Signal

Lightning



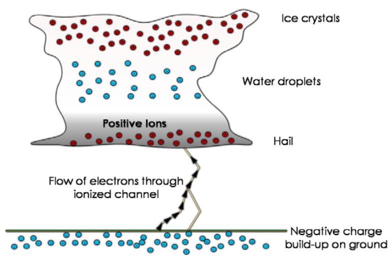
- Results in a rapid flow of charged particles between cloud and ground resulting in lighting
- Other theories include:
  - Positive and negative charge buildups swapped between cloud and ground
  - Triggered by cosmic rays, high energy particles

Source of Magnetotelluric Signal

Lightning

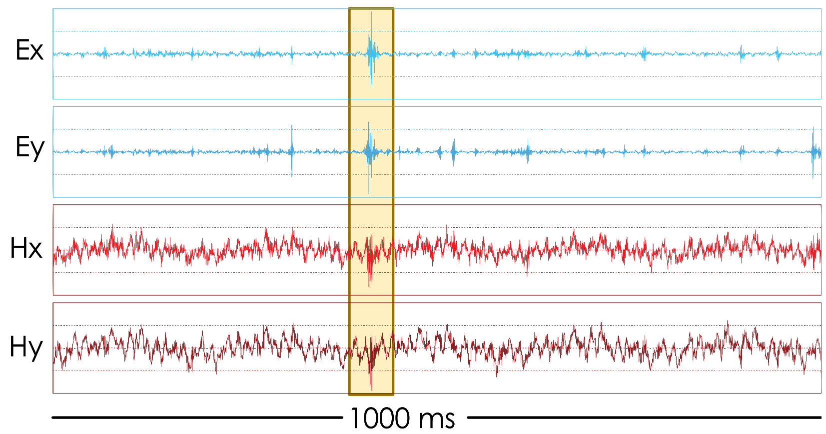
What type of source is Lightning?

A. Electric Bipole transmitter
B. Magnetic Dipole Transmitter



AMT Time Series

Lighting Strikes



Source of Magnetotelluric Signal

Plane Wave

- It is assumed that the signals from the ionosphere and lightning strikes are far away
- The signal is therefore considered to be a plane wave

"Having wavefronts that are planar (with no curvature), as might originate from a very distant source. A common assumption in seismic and electro-magnetic wave analyses that is only rarely true in actual situations."

- **Sheriff's Encyclopaedic Dictionary of Applied Geophysics, fourth edition**

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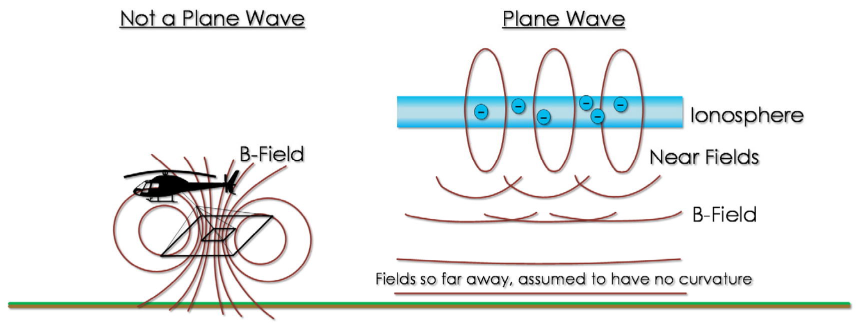
Plane Wave

Plane wave



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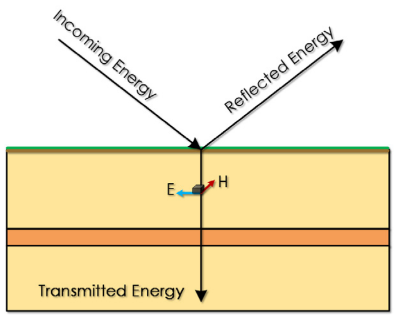
Plane Wave

What is Measured?

- MT methods measure the interaction between the electromagnetic field and the interface of the earth
- Upon interaction of EM energy and the earth, some energy is directed into the earth and some is reflected.
- The transmitted energy refracts in accordance with Snell's law.
- Due to the large contrast in electrical resistivity between air and ground, energy is directed vertically into the ground
- Most energy is lost in the outgoing energy



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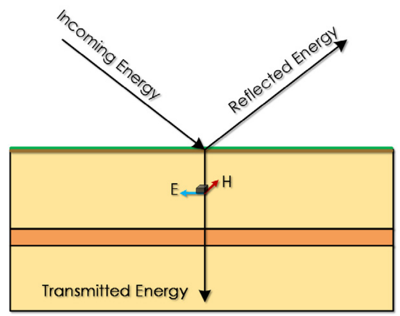
Plane Wave

What is Measured?

"In a uniform or horizontally layered earth all currents, electric fields, and magnetic fields are practically horizontal, regardless of the direction from which these fields enter the earth. This comes about because of the high conductivity of earth relative to air. I t can be thought of in terms of Snell's law in optics, with the velocity in the earth being orders of magnitude smaller than that outside. Furthermore, the currents and electric fields are at right angles to the associated magnetic fields at each point."

Vozoff, Keeva. "The magnetotelluric method in the exploration of sedimentary basins." *Geophysics* 37, no. 1 (1972): 98-141.



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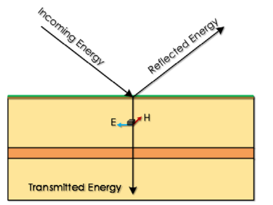
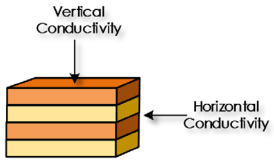
Question

What property is MT sensitive to?





$$\sigma = \begin{bmatrix} \sigma_x & & \\ & \sigma_y & \\ & & \sigma_z \end{bmatrix}$$

1. In a horizontally layered earth, what property of the conductivity tensor is the magnetotelluric method sensitive to?
2. Which is easier to detect using MT?
   A. A thin conductive layer buried at 250 m
   B. A thin resistive layer at 250 m

Impedance

What is Impedance

The wave impedance:

- Also known as Cagniard impedance, field impedance or surface impedance
- Is considered to be the ratio of electric to magnetic component

$$Z_{xy} = \frac{E_x}{H_y} \qquad Z_{yx} = \frac{E_y}{H_x}$$

- The impedance tensor can be written as:

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} \begin{bmatrix} H_x \\ H_y \end{bmatrix}$$

"In the magnetotelluric method, the ratio of the horizontal electric field component in some direction, E_x, to the magnetic field, H_y, in a perpendicular direction. For a horizontally layered earth, it is independent of the choice of x-direction."

- **Sheriff's Encyclopaedic Dictionary of Applied Geophysics, fourth edition**

Apparent Resistivity

Computing Apparent resistivity from Impedance

"The apparent resistivity can be considered an average value of the Earth's resistivity over a hemisphere of radius δ. Thus, by computing apparent resistivity as a function of frequency, the variation of resistivity with depth can be determined."

Gubbins, David, and Emilio Herrero-Bervera, eds. *Encyclopedia of geomagnetism and paleomagnetism*. Springer Science & Business Media, 2007.

$$\rho_{xy} = \frac{1}{2\pi f \mu} |Z_{xy}|^2$$

$$\rho_{yx} = \frac{1}{2\pi f \mu} |Z_{yx}|^2$$

The MT Impedance Tensor

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} \begin{bmatrix} H_x \\ H_y \end{bmatrix}$$

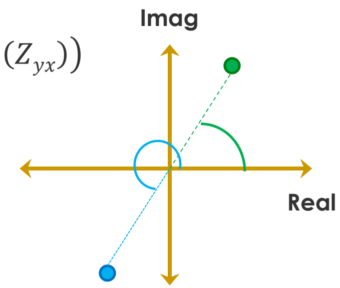
Phase

Computing Phase from Impedance

The phase can similarly be computed from the impedance.

$$\Phi_{xy} = arg(Z_{xy}) = atan2\big(Im(Z_{xy}), Re(Z_{xy})\big)$$

$$\Phi_{yx} = arg(Z_{yx}) = atan2\big(Im(Z_{yx}), Re(Z_{yx})\big)$$



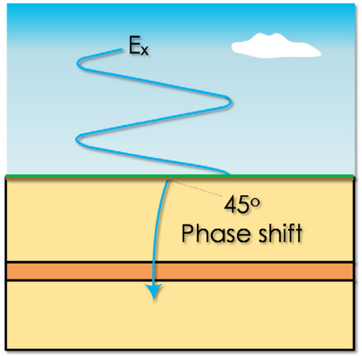
The MT Impedance Tensor

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} \begin{bmatrix} H_x \\ H_y \end{bmatrix}$$

Plane Wave

Phase Change at the Surface

- The large contrast between the air (10^{16} Ω•m) and the earth (approx. 1-10,000 Ω•m) results in a significant phase delay between the electric and magnetic fields at the earth's surface
- Approximately ~45° (~$\pi/4$)change in phase will occur at the surface



Depth of Penetration

Attenuation of the MT signal with Depth

"The depth of penetration of the fields into the earth is inversely related to rock conductivity. In a uniform earth E and H weaken exponentially with depth; the more conductive the earth, the less the penetration. The depth at which the fields have fallen off to e^{-1} of their value at the surface is called the skin depth (δ).

Vozoff, Keeva. "The magnetotelluric method in the exploration of sedimentary basins." *Geophysics* 37, no. 1 (1972): 98-141.

$$\delta = \sqrt{\frac{2}{\sigma\mu\omega}} = 503\sqrt{\frac{\rho}{f}}\ \mathrm{m}$$

Phase Change with Increasing Period

Relationship between phase change and A.Res and Frequency

- For high frequencies, the phase is sensitive to the near surface
- As f becomes much larger than ρ the phase change trends towards 45°

$$\Phi_{xy} = 45\left(1 + \frac{d(\log_{10}\rho_{xy})}{d(\log_{10}f)}\right)$$

$$\Phi_{yx} = 45\left(1 + \frac{d(\log_{10}\rho_{yx})}{d(\log_{10}f)}\right)$$

MT Suffers from Equivalence Issues

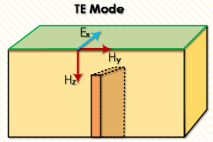
"For a multilayer model, MT data can reliably determine the conductance of a layer. Conductance is the vertically integrated conductivity, and for a uniform layer the conductance is the product of conductivity and thickness. A consequence of the inverse problem of electrical conductivity is that MT data cannot individually determine the conductivity and thickness of a layer. Thus layers with differing values of conductivity and thickness, but the same overall conductance cannot be distinguished with MT"

Gubbins, David, and Emilio Herrero-Bervera, eds. *Encyclopedia of geomagnetism and paleomagnetism*. Springer Science & Business Media, 2007.

Polarization

TE and TM Modes

Transverse Electric
Known as TE Mode



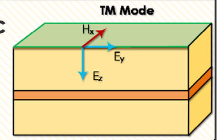
Sensitive to Along Strike Conductors

$$Z_{xy} = \frac{E_x}{H_y}$$

$$\rho_{xy} = \frac{1}{2\pi f\mu}|Z_{xy}|^2$$

$$\Phi_{xy} = arg(Z_{xy})$$

Transverse Magnetic
Known as TM Mode



Sensitive to interfaces with contrasting resistivities

$$Z_{yx} = \frac{E_y}{H_x}$$

$$\rho_{yx} = \frac{1}{2\pi f\mu}|Z_{yx}|^2$$

$$\Phi_{yx} = arg(Z_{yx})$$

In 1D isotropic layered earth TE and TM modes are equivalent.

1D Case

$$\begin{bmatrix}E_x\\E_y\end{bmatrix} = \begin{bmatrix}0 & Z\\ Z & 0\end{bmatrix}\begin{bmatrix}H_x\\H_y\end{bmatrix}$$

2D Case

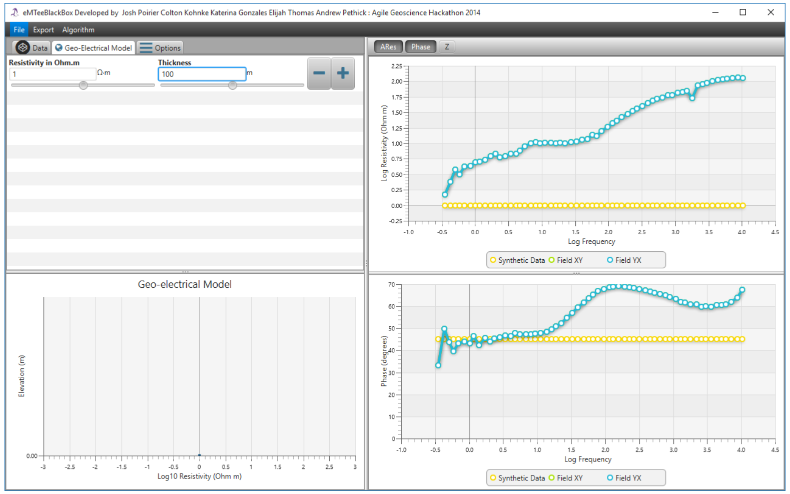
$$\begin{bmatrix}E_x\\E_y\end{bmatrix} = \begin{bmatrix}0 & Z_{xy}\\ Z_{yx} & 0\end{bmatrix}\begin{bmatrix}H_x\\H_y\end{bmatrix}$$

3D Case

$$\begin{bmatrix}E_x\\E_y\end{bmatrix} = \begin{bmatrix}Z_{xx} & Z_{xy}\\ Z_{yx} & Z_{yy}\end{bmatrix}\begin{bmatrix}H_x\\H_y\end{bmatrix}$$

What is Plotted

Log(Apparent Resistivity) and Phase versus Log(Frequency)

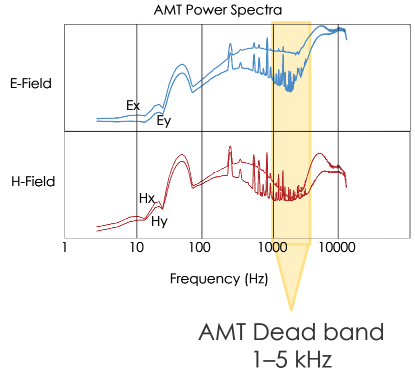


Dead Bands

AMT Dead Band

"The energy sources for magnetotellurics (MT) at frequencies above 8 Hz are electromagnetic waves generated by distant lightning storms propagating globally within the earth-ionosphere waveguide. The nature of the sources and properties of this waveguide display diurnal and seasonal variations that can cause significant signal amplitude attenuation, especially at 1–5 kHz frequencies — the so-called audiomagnetotellurics AMT dead band."

Garcia, Xavier, and Alan G. Jones. "Robust processing of magnetotelluric data in the AMT dead band using the continuous wavelet transform." *Geophysics* 73.6 (2008): F223-F234.

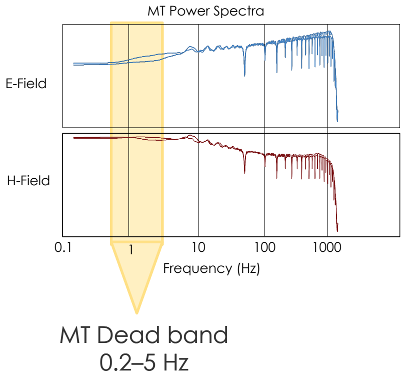


Dead Bands

MT Dead Band

"This peak occurs in the middle of the 0.2-5 Hz 'dead' band in magnetotellurics, where data is usually of the poorest quality. A likely explanation for the poor quality of magnetotelluric data generally obtained in this band is that the natural magnetic field, which is of relatively low strength, is also most contaminated by sensor motion."

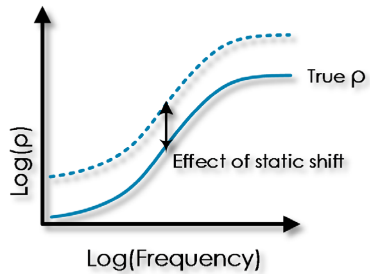
Nichols, E. A., H. F. Morrison, and J. Clarke. "Signals and noise in measurements of low-frequency geomagnetic fields." *Journal of Geophysical Research: Solid Earth (1978–2012)* 93.B11 (1988): 13743-13754.



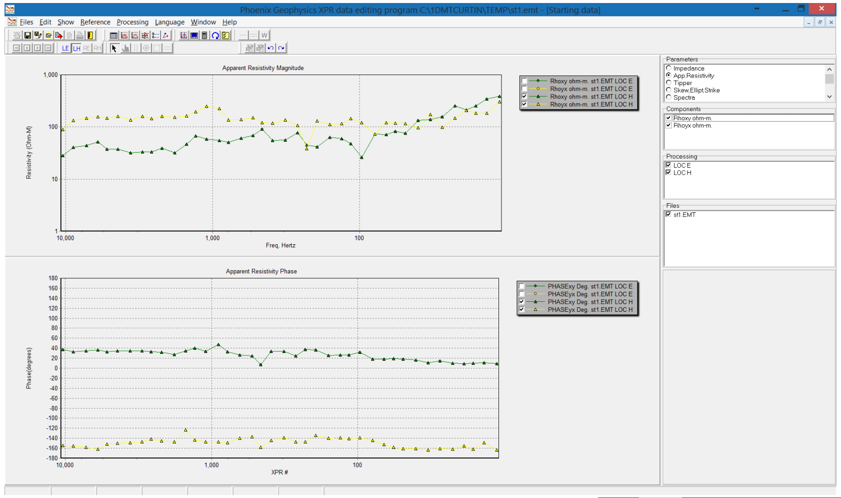
Static Shift

What is it?

- A major issue in MT
- Caused by erroneous measurement of the horizontal E-field
- The measured E-Field component does not reflect the true surface E-field because of local, near surface lateral inhomogeneities
- Similar to current channelling (where current is directed along a conductive pathway)
- Static shift can corrected by using a reference station



Static Shift Example



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Static Shift

Static Shift in Depth by Alan Jones (1988)

"Static shift of an apparent resistivity curve is caused by an erroneous measurement of the pertinent horizontal component of the earth's electric field of regional interest, where the size of the region is given by the appropriate scale length at the period of interest. The erroneous values are due to the potential difference between the electrode pair not truly representing the horizontal electric field component because of the presence of charges on local surficial, or near-surface, lateral inhomogeneities. The effect is closely related to the current channeling problem of MT data; however, it differs from the latter in that even at the highest frequency the potential difference does not give the correct amplitude for the regional electric field, whereas the phase lead of the electric field over the magnetic field is correct..."

"The basic difference between current channeling and static shift is that static shift does not affect the phases of the MT impedance tensor, whereas current channeling does. Thus, static shift is, as implied, a shift of the apparent resistivity curve by the same multiplicative factor at all frequencies such that the shape of the curve is retained when plotted on a log-ordinate scale without any corresponding change in the phase curve...."

"Static shift is due to local surface or near-surface inhomogeneities."

Jones, Alan G. "Static shift of magnetotelluric data and its removal in a sedimentary basin environment." *Geophysics* 53, no. 7 (1988): 967-978.

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Case Study 1

Laboratory 5 – MT sounding next to the ARRC (or what not to do)

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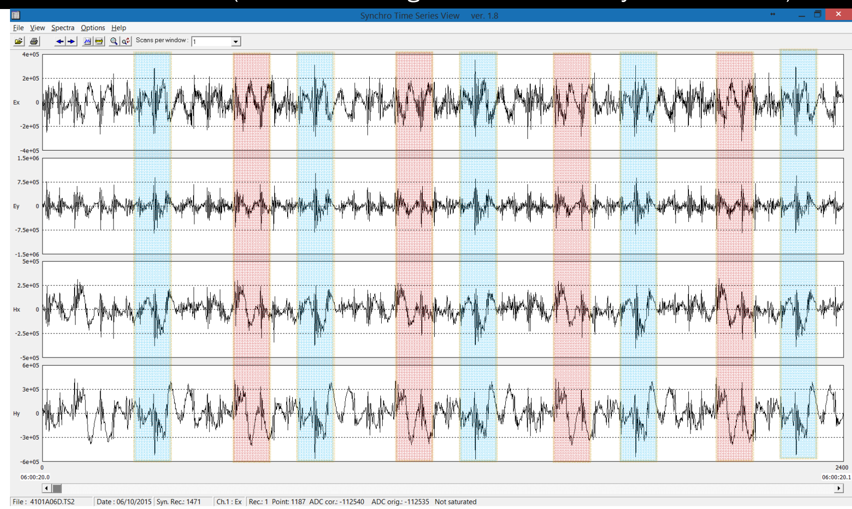
Case Study 1

Raw Time Series (Note how the signal is dominated by cultural noise)



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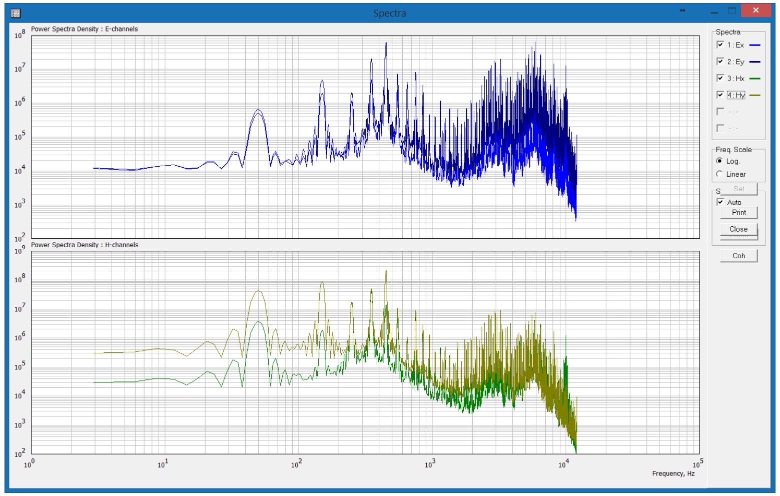
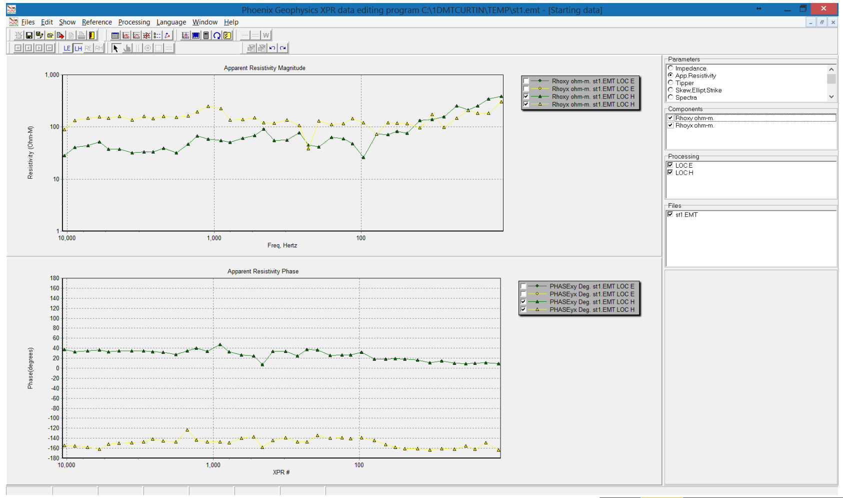
Case Study 1

Power Spectra



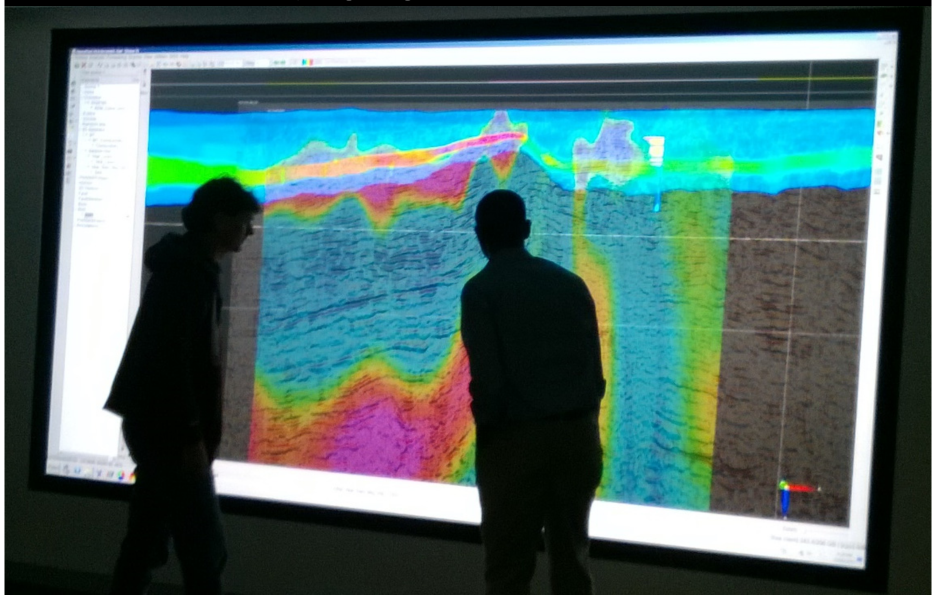
Case Study 1

Apparent Resistivity and Phase Curves (Note the static shift: potential pipes)



Case Study 2

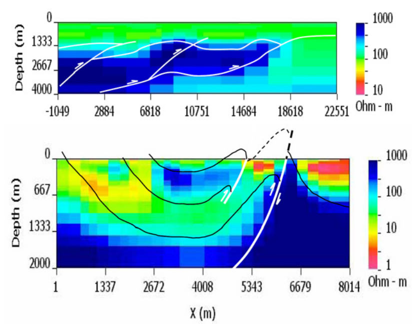
Hydrogeological: North Perth Basin



Case Study: Hydrocarbon Exploration

Can you find hydrocarbon with MT?

- Good to image structures that could host potential hydrocarbon reservoirs
- Not good at directly imaging hydrocarbon
- MT E-Field is driven horizontally so MT is insensitive to vertical resistivity
- Marine MT is performed simultaneously with marine CSEM surveys to determine a good background horizontal resistivity model for use in CSEM inversion

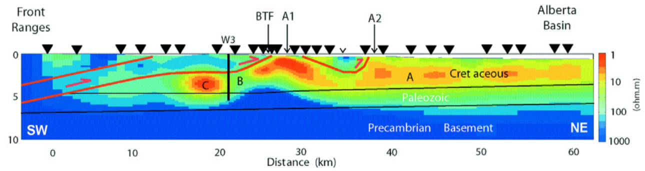


Grandis, H., Widarto, D.S. and Hendro, A., 2004, Magnetotellric (MT) method in hydrocarbon exploration, Department of Geophysics and Meteorology, Bandung.

Other cases

Oil and Gas Exploration: Rocky Mountains

Resistivity model derived from a 2D inversion of land MT data. This dataset is from the Brazea Thrust fault in the Rocky Mountains. MT was performed on a regional scale and shows thrust fault geological features and possible hydrocarbon trap locations.



Unsworth, M., 2005, New developments in conventional hydrocarbon exploration with electromagnetic methods: CSEG Recorder, 34-38.

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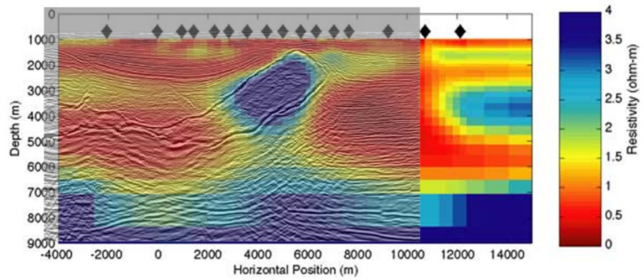
Other cases

Oil and Gas Exploration: Marine MT

The electrical resistivity model from a marine MT survey over Gemini prospect in gulf of Mexico, laid over a seismic section of a salt intrusion



Fischer, P.A., 2005, New EM technology offerings are growing quickly: World Oil, 226, 6.

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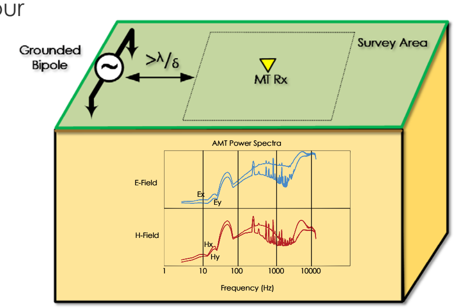
CSAMT

Controlled source audio magnetotelluric

If there signal is lacking in an AMT frequency band, you can generate a synthetic plane wave source to boost your signal.

<u>CSAMT</u> – **C**ontrolled **S**ource **A**udio **MT**

- Transmits between 10Hz and 10kHz
- Generally uses a grounded bipole transmitter
- Uses standard MT receiver sites



"My target depth was in the AMT dead band. Should have gone with CSAMT"

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CSAMT

Problems and Solutions

Problem: CSAMT requires the transmitter to be located further away than the skin depth δ to maintain a plane wave approximation.

Catch 22: The skin depth is dependent upon resistivity and you won't know an approximate resistivity until you perform the survey.

Solution: Assume an approximate skin depth, but keep it conservative (i.e., more resistive)

Another issue: Since the source is polarized, another transmitter is required orthogonally to detect anisotropic structures.

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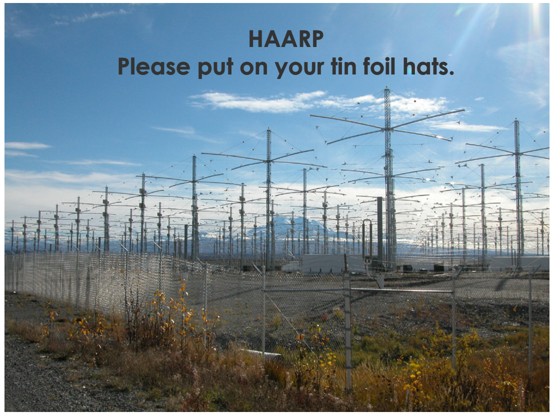
VLF

VLF: Snapshot

Very Low Frequency (VLF)

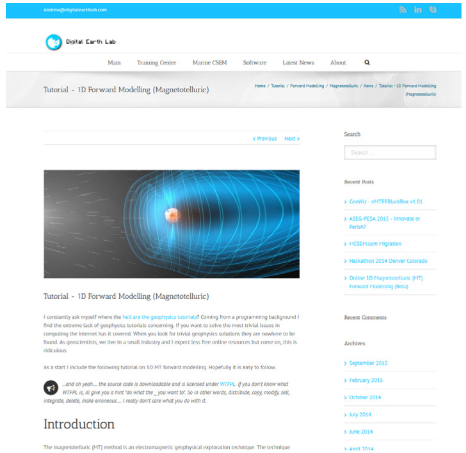
- Operates between 15 and 25kHz
- The source of VLF is mainly large military transmitters
- The skin depth is less than 10m
- Narrow band but useful mapping near surface.



Wikipedia, 2015, HAARP, https://upload.wikimedia.org/wikipedia/commons/7/71/HAARP20l.jpg, Retrieved Oct 2015

1D MT Solution

For a complete 1D Forward MT solution...



The 1D MT problem is rather simple to code. Please visit:
http://www.digitalearthlab.com/tutorial/tutorial-1d-mt-forward/
For a complete overview.

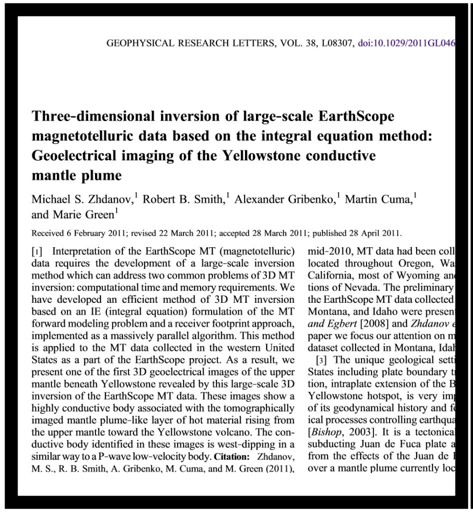
LECTURE 10

Ground Penetrating Radar

S2 2015

- The wave equation revisited
- Dielectric constant
- GPR Basics
- Applications of GPR

Geophysics seen by geophysicists. **Geophysics seen by the media.**



GEOPHYSICAL RESEARCH LETTERS, VOL. 38, L08307, doi:10.1029/2011GL046

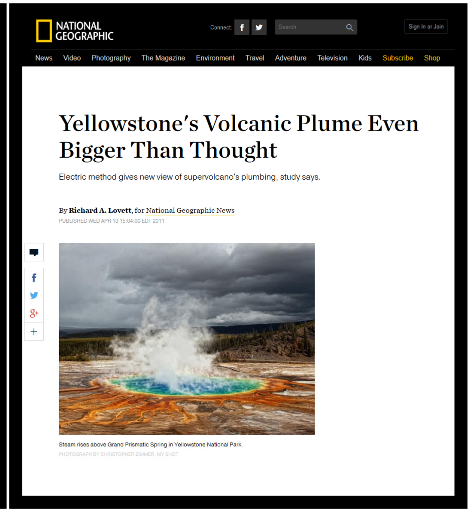
Three-dimensional inversion of large-scale EarthScope magnetotelluric data based on the integral equation method: Geoelectrical imaging of the Yellowstone conductive mantle plume

Michael S. Zhdanov,[1] Robert B. Smith,[1] Alexander Gribenko,[1] Martin Cuma,[1] and Marie Green[1]

Received 6 February 2011; revised 22 March 2011; accepted 28 March 2011; published 28 April 2011.

[1] Interpretation of the EarthScope MT (magnetotelluric) data requires the development of a large-scale inversion method which can address two common problems of 3D MT inversion: computational time and memory requirements. We have developed an efficient method of 3D MT inversion based on an IE (integral equation) formulation of the MT forward modeling problem and a receiver footprint approach, implemented as a massively parallel algorithm. This method is applied to the MT data collected in the western United States as a part of the EarthScope project. As a result, we present one of the first 3D geoelectrical images of the upper mantle beneath Yellowstone revealed by this large-scale 3D inversion of the EarthScope MT data. These images show a highly conductive body associated with the tomographically imaged mantle plume-like layer of hot material rising from the upper mantle toward the Yellowstone volcano. The conductive body identified in these images is west-dipping in a similar way to a P-wave low-velocity body. **Citation:** Zhdanov, M. S., R. B. Smith, A. Gribenko, M. Cuma, and M. Green (2011),

mid-2010, MT data had been coll
located throughout Oregon, Wa
California, most of Wyoming an
tions of Nevada. The preliminary
the EarthScope MT data collected
Montana, and Idaho were presen
and Egbert [2008] and *Zhdanov e*
paper we focus our attention on m
dataset collected in Montana, Idah
[3] The unique geological setti
States including plate boundary t
tion, intraplate extension of the B
Yellowstone hotspot, is very im
of its geodynamical history and f
ical processes controlling earthqua
[*Bishop*, 2003]. It is a tectonica
subducting Juan de Fuca plate a
from the effects of the Juan de I
over a mantle plume currently loc



Recap. Lecture 09

What do you know about noise?

What forms of noise are encountered in TEM?

What techniques can be employed to combat noise?

Does doubling the moment halve the noise?

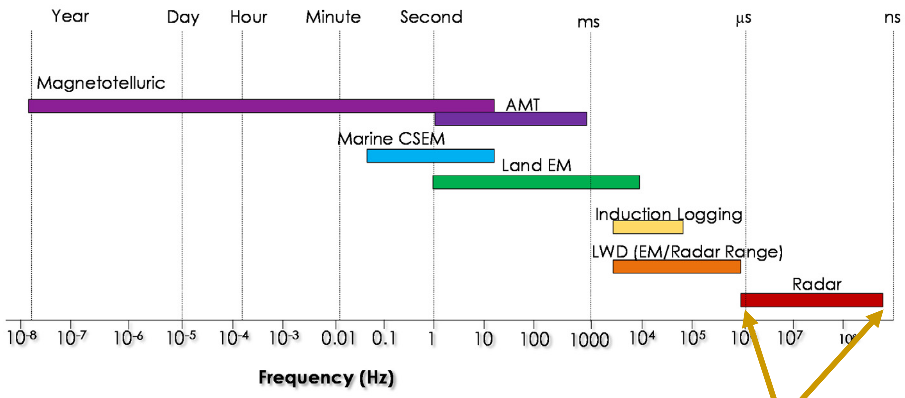
Does doubling the stacks halve the noise?

RA-D-A-R

RAdio-**D**etection-**A**nd-**R**anging

RA-D-A-R

Where does it Lie on the Frequency Spectrum?



RADAR lies within between ~10 MHz to 1GHz

Deriving The Wave Equation

Fundamental equations to EM wave propagation

Start off with Maxwell's equations

$$\nabla \times E = -\frac{\partial B}{dt}$$
$$\nabla \times H = J + \frac{\partial D}{dt}$$

Convert to time harmonic

$$\nabla \times \boldsymbol{E} = -i\omega \boldsymbol{B}$$
$$\nabla \times \boldsymbol{H} = \boldsymbol{J} + i\omega \boldsymbol{D}$$

Substitute constitutive eq.

$$\boldsymbol{J} = \sigma \boldsymbol{E}$$
$$\boldsymbol{B} = \mu \boldsymbol{H}$$
$$\boldsymbol{D} = \varepsilon \boldsymbol{E}$$

$$\nabla \times \boldsymbol{E} = -i\omega\mu \boldsymbol{H}$$
$$\nabla \times \boldsymbol{H} = \sigma \boldsymbol{E} + i\omega\varepsilon \boldsymbol{E}$$

Take curl of both sides

$$\nabla \times \nabla \times \boldsymbol{E} = -\nabla^2 \boldsymbol{E} = -i\omega\mu(\nabla \times \boldsymbol{H})$$
$$\nabla \times \nabla \times \boldsymbol{H} = -\nabla^2 \boldsymbol{H} = \sigma(\nabla \times \boldsymbol{E}) + i\omega\varepsilon(\nabla \times \boldsymbol{E})$$

Sub Amperes and Faradays Law

$$-\nabla^2 \boldsymbol{E} = -i\omega\mu(\sigma \boldsymbol{E} + i\omega\varepsilon \boldsymbol{E})$$
$$-\nabla^2 \boldsymbol{H} = \sigma(-i\omega\mu \boldsymbol{H}) + i\omega\varepsilon(-i\omega\mu \boldsymbol{H})$$

Rearrange

$$\nabla^2 \boldsymbol{E} + (-i\omega\mu\sigma + \omega^2\mu\varepsilon)\, \boldsymbol{E} = 0$$
$$\nabla^2 \boldsymbol{H} + (-i\omega\mu\sigma + \omega^2\mu\varepsilon)\mathbf{H} = 0$$

Deriving The Wave Equation

Fundamental equations to EM wave propagation

So why is the solution to the wave equation so important

$$k^2 = -i\omega\mu\sigma + \omega^2\mu\varepsilon \quad (20)$$
$$\boldsymbol{\nabla}^2 \boldsymbol{E} + k^2 \boldsymbol{E} = \boldsymbol{0} \quad (21)$$
$$\boldsymbol{\nabla}^2 \boldsymbol{H} + k^2 \mathbf{H} = \boldsymbol{0} \quad (22)$$

At frequencies above 100kHz $\omega^2\mu\varepsilon$ >> $\omega\mu\sigma$ the equation is predominantly dominated by the **reflective component**

RADAR is sensitive to conductivity but unlike low frequency EM is also influenced by electric permittivity.

Maxwell's Equations

Medium dependent equations: Physical Constants

$$\mathbf{D} = \varepsilon\mathbf{E} \quad (9)$$

*In many ways the electric displacement field (**D**) and electric field (**E**) are similar but the displacement field is not medium dependent*

Refer to Coulombs law

$$\boldsymbol{E} = \frac{q}{4\pi\varepsilon R^2}$$
$$\boldsymbol{D} = \varepsilon \boldsymbol{E} = \varepsilon \frac{q}{4\pi\varepsilon R^2}$$

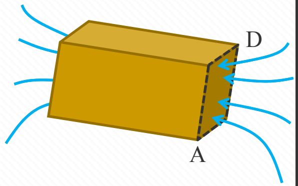
D gives rise to a displacement current

Displacement Field

$\mathbf{D}$

Density of transported charges in a second over a given area.

SI units C/m^2



Electrical Permittivity

ε

Measure of how easily a material stores charge when an electric field is applied

$\varepsilon_0 = 8.854187 \times 10^{-12} F/m$

SI units F/m

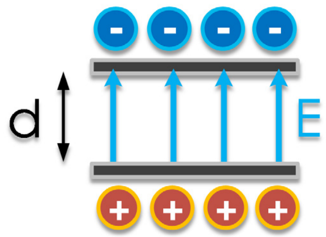
$Relative\ \varepsilon_r = \frac{\varepsilon}{\varepsilon_0}$

Air	1.0
Water	80
Granite	5 – 20

So what is Dielectric Constant ε

Definition

Think Capacitance.



Dielectric Constant (ε)
"A measure of the capacity of a material to store charge when an electric field is applied. It is the dimensionless ratio of the **capacitivity** or **permittivity**, the ratio of the electrical displacement **D** to the electric field strength **E**, of the material to that of free space"

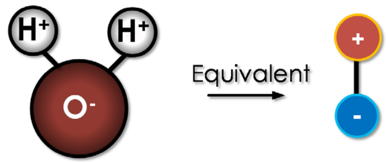
$D = \varepsilon E$

- **Sheriff's Encyclopaedic Dictionary of Applied Geophysics, fourth edition**

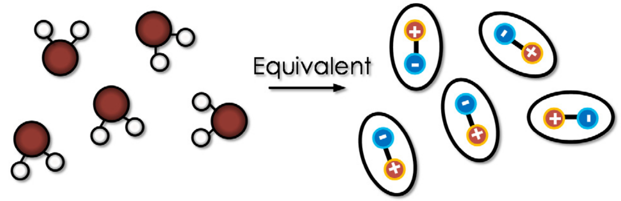
Dielectric Constant - Permittivity ε

Molecules are the collections of atoms. Some create dipoles.

Consider a water molecule **(it does not have to be water)**. The arrangement of molecules essentially forms a dipole.

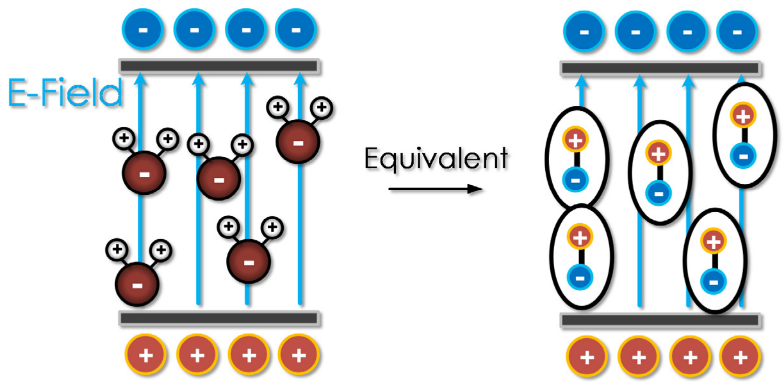


In the absence of an electric field, these water molecules a random orientation.



Dielectric Constant - Permittivity ε

Dipoles aligned by external electric field



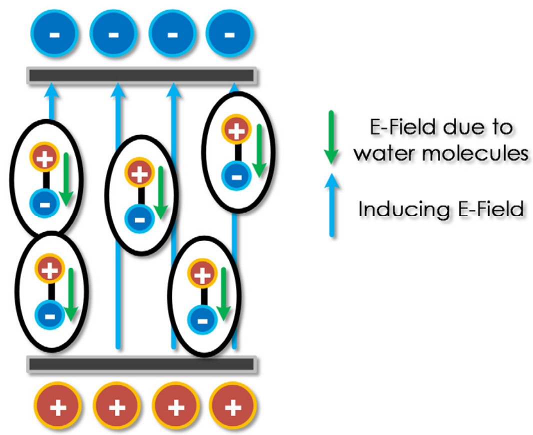
In the presence of an electric field these dipoles/molecules will align with the electric field lines.

Dielectric Constant - Permittivity ε

The alignment will reduce the net electric field.

Note that dipole moment caused by the alignment of the molecules will **oppose** the inducing electric field.

This effect will reduce the total electric field.



How does ε effect the electric field?

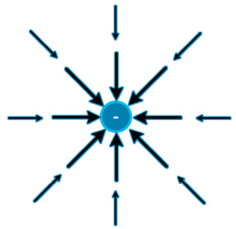
Remember Coulomb's Law

$$E = \frac{q}{4\pi\varepsilon_r\varepsilon_0 R^2}$$

ε_r is always greater than 1.0

So the E-field is always going to be smaller in a medium than in free space.

That is, in a medium, those dipole/molecules will reduce the electric field.



ε_r -Relative Permittivity (%) [also known as κ]
ε_0-Permittivity of Free space (F/m)
ε-Permittivity of medium (F/m)

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GPR

Note of Caution

The nature of high frequency electromagnetism is reflective rather than diffusive, therefore low frequency approximations are invalid for use in GPR.

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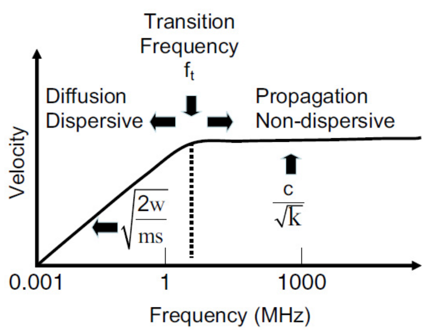
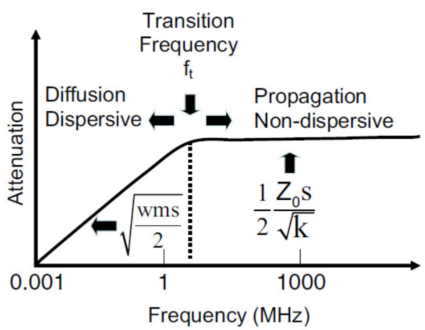
Diffusion or Non Dispersive

Velocity



Attenuation



Annan, A.P. (2005). Ground penetrating radar in near-surface geophysics, In: Near-Surface Geophysics, Investigations in Geophysics, No. 13, Society of Exploration Geophysics, Butler, D.K., pp.357-438, ISBN 1-56080-130-1, Tulsa, OK

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Diffusion or Non Dispersive

Main Equations

Velocity

$$c = \frac{1}{\sqrt{\mu_0\varepsilon_r\varepsilon_0}} = \frac{1}{\sqrt{\mu_0\varepsilon}}$$

Velocity is dependent on:
Electrical permittivity

Annan, A.P. (2005). Ground penetrating radar in near-surface geophysics, In: Near-Surface Geophysics, Investigations in Geophysics, No. 13, Society of Exploration Geophysics, Butler, D.K., pp.357-438, ISBN 1-56080-130-1, Tulsa, OK

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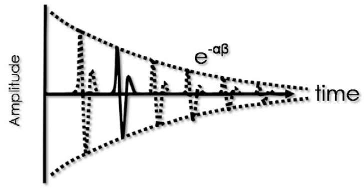
Diffusion or Non Dispersive

Main Equations

Attenuation

$$\alpha = \sqrt{\frac{\mu}{\varepsilon_r}} \cdot \frac{\sigma}{2}$$

Attenuation is dependent on:
Electrical permittivity
Conductivity



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Diffusion or Non Dispersive

Main Equations

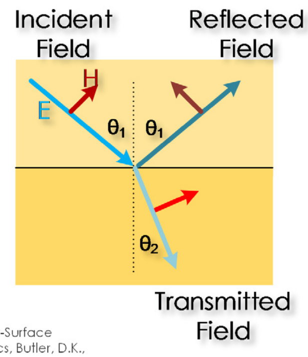
Impedance

$$Z = \sqrt{\frac{\mu_0}{\varepsilon}}$$

Reflectivity

$$R = \frac{\frac{1}{Z_1} - \frac{1}{Z_2}}{\frac{1}{Z_1} + \frac{1}{Z_2}} = \frac{\sqrt{\kappa_1} - \sqrt{\kappa_2}}{\sqrt{\kappa_1} + \sqrt{\kappa_2}}$$

Reflectivity is dependent on:
Electrical permittivity



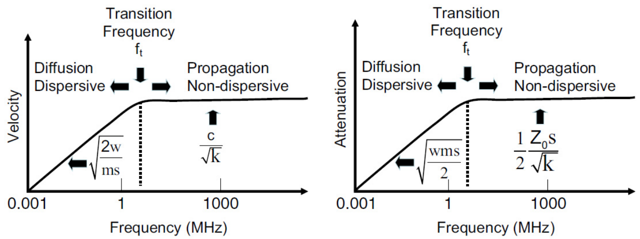
Annan, A.P. (2005). Ground penetrating radar in near-surface geophysics, In: Near-Surface Geophysics, Investigations in Geophysics, No. 13, Society of Exploration Geophysics, Butler, D.K., pp.357-438, ISBN 1-56080-130-1, Tulsa, OK

Frequency Transition

f_t

$$f_t = \frac{\sigma}{2\pi\varepsilon}$$

The frequency transition between diffusion to non-dispersive EM wavefield propagation.



Range of Frequency Transition Zones

Changes in conductivity will influence EM wavefield propogation style

Material	κ	σ	f_t
Dry Soil	4	0.1 1 10	0.45 4.5 45
Wet Soil	25	1 10 100	0.71 7.1 71
Granite	6	0.1	0.3
Limestone	6	1	3
Ice	3.2	0.01	0.06

Annan, A.P. (2005). Ground penetrating radar in near-surface geophysics, In: Near-Surface Geophysics, Investigations in Geophysics, No. 13, Society of Exploration Geophysics, Butler, D.K., pp.357-438, ISBN 1-56080-130-1, Tulsa, OK

Electrical Properties of rock

Medium	Relative dielectric permittivity (ε_r)	Electromagnetic-wave velocity (m ns^{-1})	Conductivity (mS m^{-1})	Attenuation (dB m^{-1})
Air	1	0.3	0	0
Fresh water	80	0.03	0.5	0.1
Seawater	80	0.01	30,000	1000
Unsaturated sand	2.55–7.5	0.1–0.2	0.01	0.01–0.14
Saturated sand	20–31.6	0.05–0.08	0.1–1	0.03–0.5
Unsaturated sand and gravel	3.5–6.5	0.09–0.13	0.007–0.06	0.01–0.1
Saturated sand and gravel	15.5–17.5	0.06	0.7–9	0.03–0.5
Unsaturated silt	2.5–5	0.09–0.12	1–100	1–300[a]
Saturated silt	22–30	0.05–0.07	100	1–300[a]
Unsaturated clay	2.5–5	0.09–0.12	2–20	0.28–300[a]
Saturated clay	15–40	0.05–0.07	20–1000	0.28–300[a]
Unsaturated till	7.4–21.1	0.1–0.12*	2.5–10	[b]
Saturated till	24–34	0.1–0.12*	2–5	[b]
Freshwater peat	57–80	0.03–0.06	<40	0.3
Bedrock	4–6	0.12–0.13	10^{-5}–40	7×10^{-6}–24

From Neal and Roberts (2000).
[a] Unsaturated and saturated values not differentiated (van Heteren et al., 1998).
[b] Values not available.

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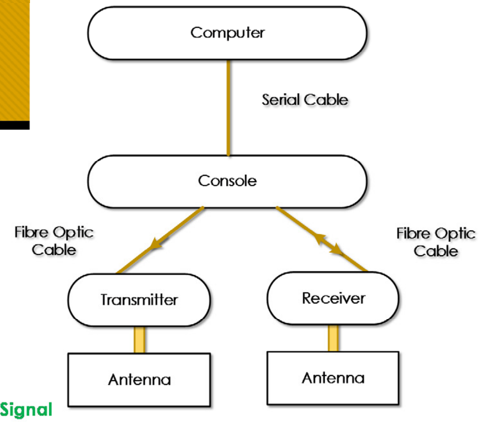
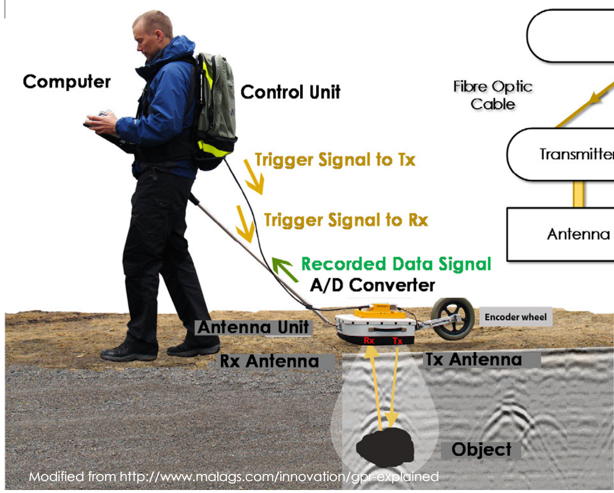
GPR Equipment





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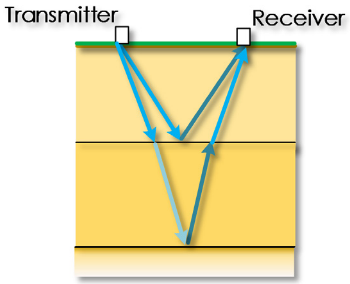
GPR Basics

Overview

1. A radar pulse is emitted by an transmitting antenna
2. The high frequency electromagnetic field interacts with electrical discontinuities (boundaries having contrast in electrical properties)
3. A proportion of the signal is reflected by this interface
4. The returning pulse of electromagnetic energy is then received at the surface

Do you notice the similarities to seismic reflection?



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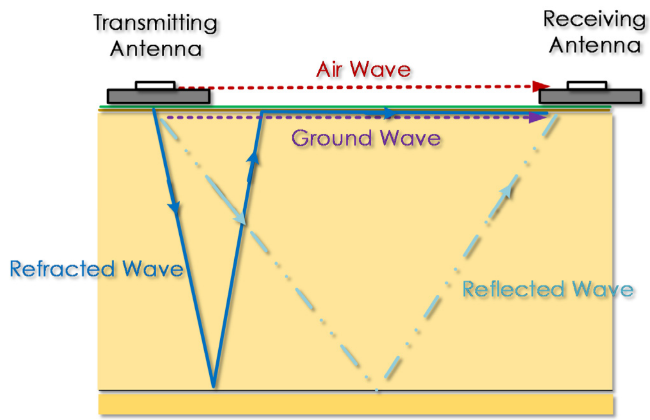
GPR

Wave Propagation



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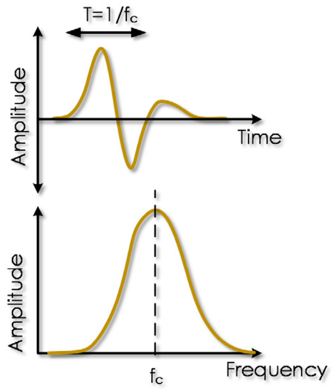
GPR Basics

Waveform

- Does not emit a single pulse
- A succession of repetitive pulses is transmitted
- Repeats 50 to 2 μs
- The power emitted is centred around the pulse frequency f_c
- The frequency content controls the depth of investigation and layer resolution



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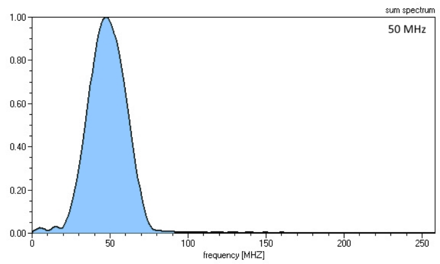
GPR Frequency Spectra

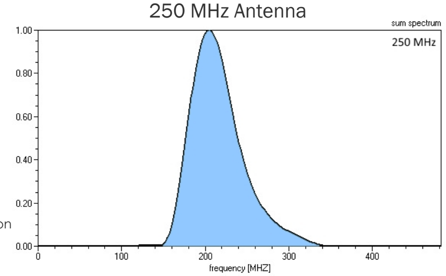
Examples

- The frequency of the transmitted pulse controls the resolution and depth of penetration

50 MHz Antenna



250 MHz Antenna



Costall, A., 2014, Feasibility of Ground Penetrating Radar for Delineation of the Saline Water Interface along Perth's Coastal Margin, Curtin University Exploration Geophysics.

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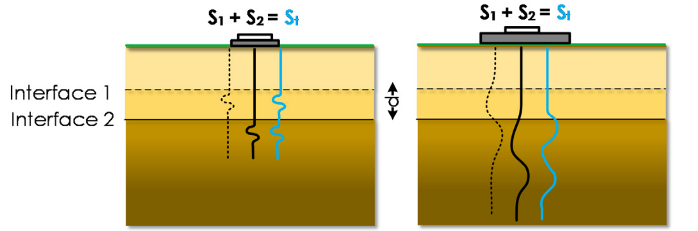
GPR Basics

Waveform

High Frequency Antenna (e.g., 250 MHz)

Low Frequency Antenna (e.g., 50 MHz)



High Frequency Antenna:
- Better Resolution
- Poorer depth of penetration
- Interface 1 is resolved

Low Frequency Antenna:
- Poorer Resolution
- Better depth of penetration
- Interface 1 is not resolved

If the central frequency wavelength (λ) is bigger than layer thickness (d), the layer will not be resolved.

NOTE

DO NOT use electromagnetic skin depth for estimating depth of investigation.

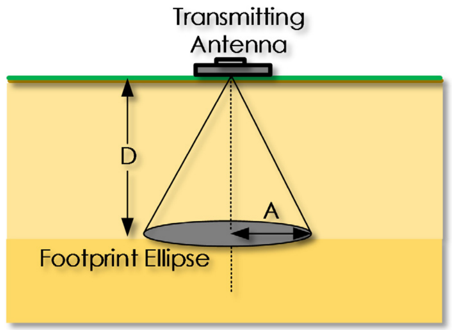
GPR Basics

GPR Footprint

The GPR footprint is important in survey design:

If the line or spatial spacing is less than the radar footprint, a small discrete target may not be illuminated.

$$A = \frac{\lambda}{4} + \frac{D}{\sqrt{\kappa - 1}}$$



A=Approximate radius of footprint (m)
λ=Central frequency wavelength (m)
D=Depth of reflector (m)
κ=Average relative dielectric permittivity (ε_r) (%)

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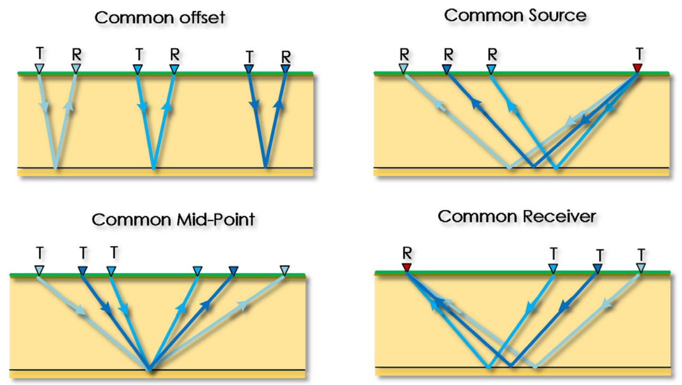
GPR Basics

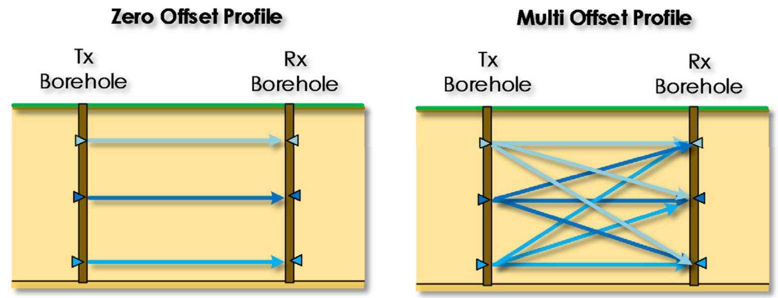
Tx-Rx Geometry



Common offset Tx-Rx geometry is typically used for rapid surveying

GPR Basics

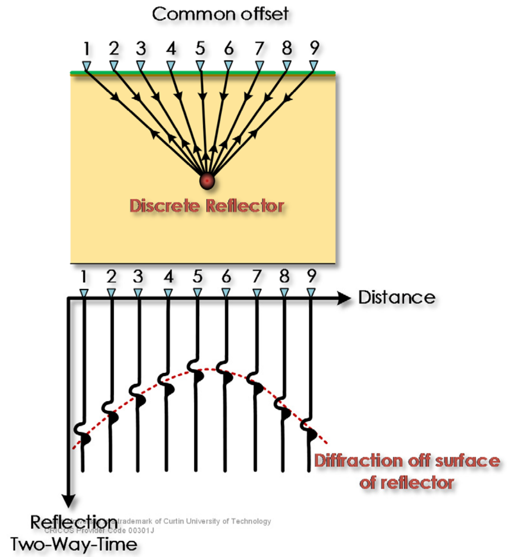
Tx-Rx Geometry

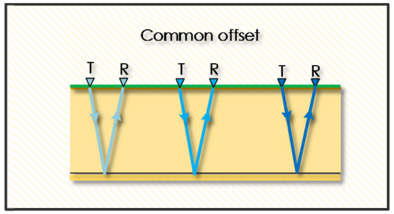


Borehole GPR methods are also possible

GPR Basics

Common Offset Two Way Travel Time of Discrete Reflector



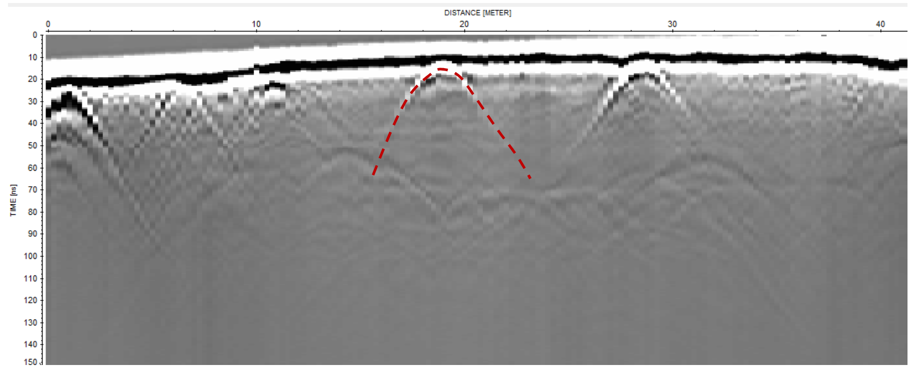


Using a common offset survey, discrete reflectors are identified by diffraction patterns. The shape of these diffractions indicate both the style of the target and velocity of the medium.

Velocities are typically measured in metres per nano second (m/ns)

GPR Basics

Common Offset Two Way Travel Time (TWT) of Discrete Reflector



An example of a TWT diffraction pattern.
In this example it is a diffraction off a sprinkler.

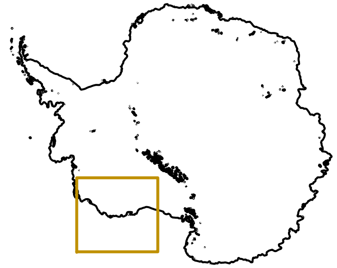
Processing GPR Data

1. Raw data input into **ReflexW**
2. Trace header editing (xyz - coordinates)
3. Spatial down sampling (1 m of traces)
4. Static correction (from airwave arrival)
5. Subtracting mean ("dewow")
6. Gain (energy decay)
7. Topographic correction from z-coordinate, const. velocity
8. Time-depth conversion (const. Velocity)
9. SEGY - export
10. SEGY - Import into **OpendTect**

Taken from Strobach, E., 2012, GPR – Ground Penetrating Radar, GP302 Lecture notes, Curtin University, Department of exploration Geophysics

Applications

Case Study 1 : Accumulation Rates of Snow



Case study taken from: Spikes, Vandy B., Gordon S. Hamilton, Steven A. Arcone, Susan Kaspari, and Paul A. Mayewski. "Variability in accumulation rates from GPR profiling on the West Antarctic plateau." *Annals of Glaciology* 39, no. 1 (2004): 238-244.

Rationale

"Snow accumulation rates on the Antarctic ice sheet are known to be highly variable over short distances…and over short time interval…."

Aim

"Develop a better understanding of the spatial distribution of snow accumulation on the West Antarctic plateau, to investigate how topography and ice flow influence measurements of accumulation rate, and to examine the spatial persistence of temporal variations observed in accumulation record"

Applications

Case Study 1 : Accumulation Rates of Snow

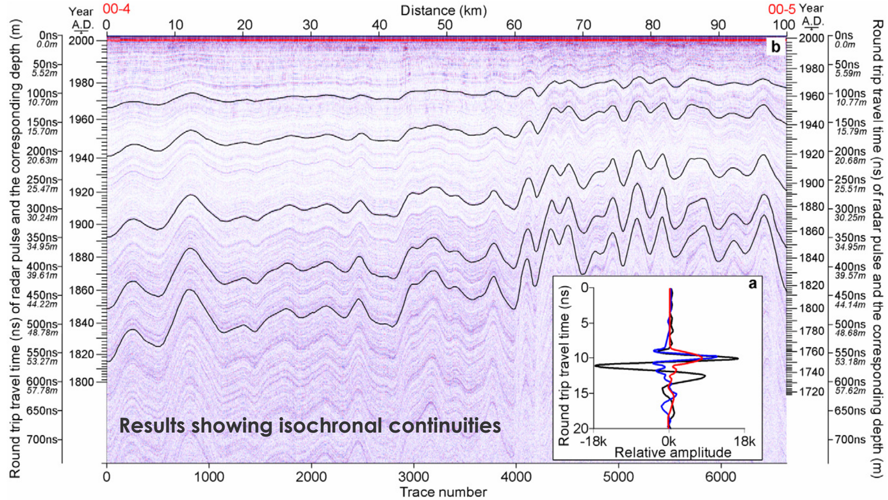
Method

- Common Offset GPR
- Frequency: 400 MHz short radar pulse
- Pulse: 1.5 cycle pulse lasting 3.8 ns
- Survey Length:100 km transect
- Approximate vertical resolution: 35 cm
- Depth of investigation: ~100 m
- Typical dry polar snow dielectric constant (ε) : 2.4
- Other data:
  - GPS
  - Ice core logs and chemistry

Case study taken from: Spikes, Vandy B., Gordon S. Hamilton, Steven A. Arcone, Susan Kaspari, and Paul A. Mayewski. "Variability in accumulation rates from GPR profiling on the West Antarctic plateau." *Annals of Glaciology* 39, no. 1 (2004): 238-244.

Applications

Case Study 1 : Accumulation Rates of Snow



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Applications

Case Study 1 : Accumulation Rates of Snow

Interval (Years A.D.)	Avg. accumulation rate (m a^{-1} w.e.)	Percent difference (%)	Standard Dev (%)
1966-2000	0.141 ± 0.0016	-2.2 ± 1.2	15.6
1941-1966	0.151 ± 0.0008	5.1 ± 0.6	19.1
1893-1941	0.151 ± 0.0004	5.1 ± 0.34	14.1
1848-1893	0.137 ± 0.0003	-4.8 ± 0.2	16.8
1815-1848	0.142 ± 0.0002	-1.7 ± 0.16	21.1

Could determine accumulation rate of snow over the 100 km transect

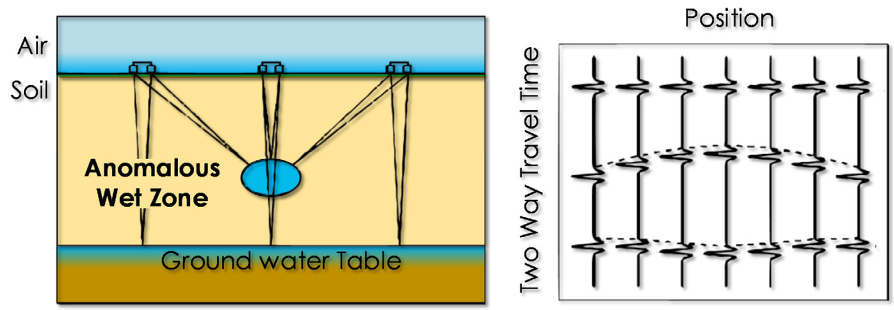
Case study taken from: Spikes, Vandy B., Gordon S. Hamilton, Steven A. Arcone, Susan Kaspari, and Paul A. Mayewski. "Variability in accumulation rates from GPR profiling on the West Antarctic plateau." *Annals of Glaciology* 39, no. 1 (2004): 238-244.

Applications

Case Study 2: Measuring Soil Water Content

Rationale
Soil moisture influences crop irrigation and growth.

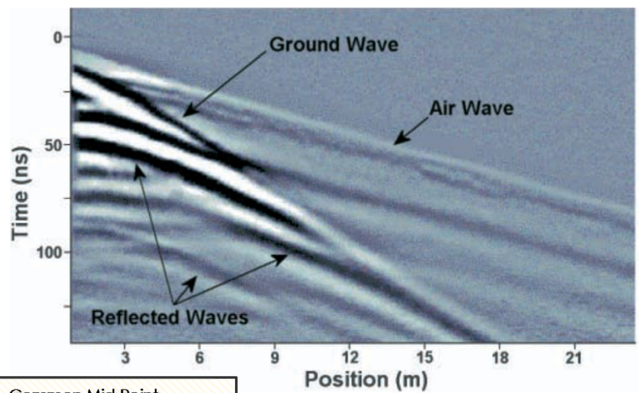
Aim
Overview methods for estimating soil water content

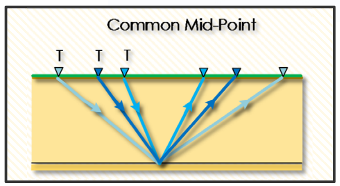


Example taken from Huisman, J. A., S. S. Hubbard, J. D. Redman, and A. P. Annan. "Measuring soil water content with ground penetrating radar." *Vadose zone journal* 2, no. 4 (2003): 476-491.

Applications

Case Study 2: Measuring Soil Water Content





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Applications

Case Study 2: Measuring Soil Water Content

Energy that GPR transmits into the soil will be partly reflected when contrasts in impedance are encountered

$$R = \frac{\frac{1}{Z_1} - \frac{1}{Z_2}}{\frac{1}{Z_1} + \frac{1}{Z_2}} = \frac{\sqrt{\kappa_1} - \sqrt{\kappa_2}}{\sqrt{\kappa_1} + \sqrt{\kappa_2}}$$

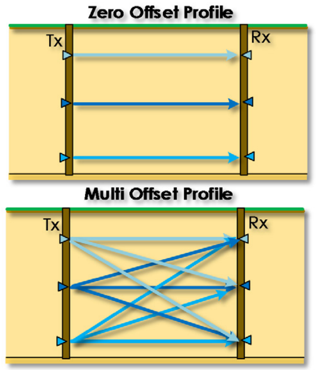
The velocity of wet soil will be slower to that of dry soil. Therefore travel times will be longer.

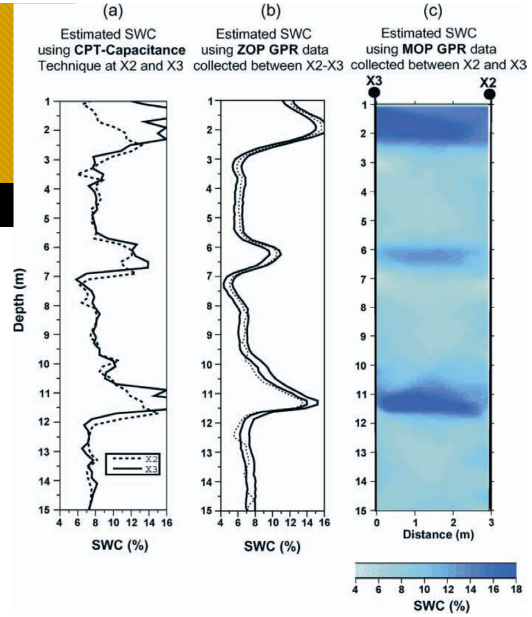
$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_r \varepsilon_0}} = \frac{1}{\sqrt{\mu_0 \varepsilon}}$$

Material	κ	σ	f_t
Dry Soil	4	0.1 1 10	0.45 4.5 45
Wet Soil	25	1 10 100	0.71 7.1 71

Applications

Measuring Soil Water Content





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Applications

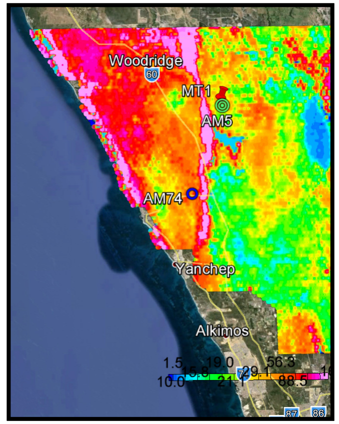
Case Study 3

Rationale

- Perth has a fear of water supply and demand. Pumping and urban use along coastal margins means salt water intrusion.

Objectives

- Evaluate the ground penetrating radar (GPR) method for delineation of the interface between salt and fresh water along Perth's coastal margin.
- Determine the depth to this interface and provide recommendations for the use of GPR for this issue.



Case study taken from Costall, A., 2014, Feasibility of Ground Penetrating Radar for Delineation of the Saline Water Interface along Perth's Coastal Margin, Curtin University Exploration Geophysics.

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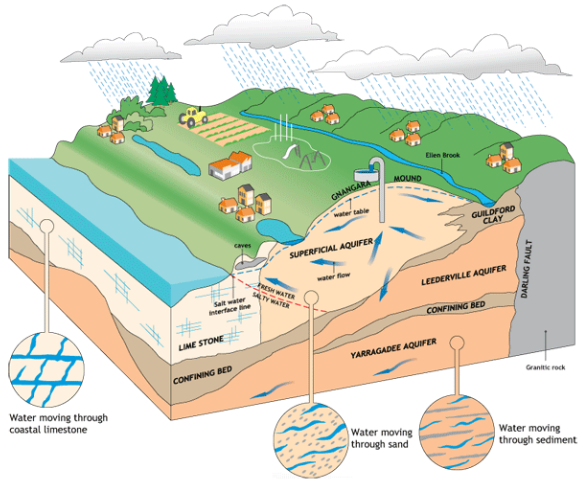
Applications

Case Study 3



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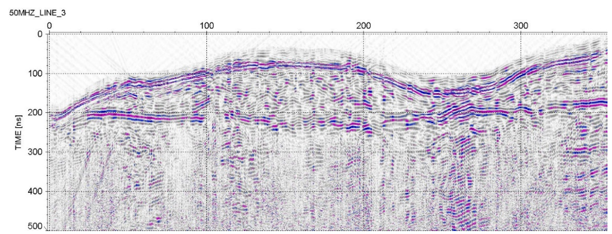
Applications

Case Study 3

Method

- Common offset GPR
- 50 & 250 MHz GPR systems
- MALA ProEx Radar
- Real Time Kinematic Global Positioning System RTK GPS



Case study taken from Costall, A., 2014, Feasibility of Ground Penetrating Radar for Delineation of the Saline Water Interface along Perth's Coastal Margin, Curtin University Exploration Geophysics.

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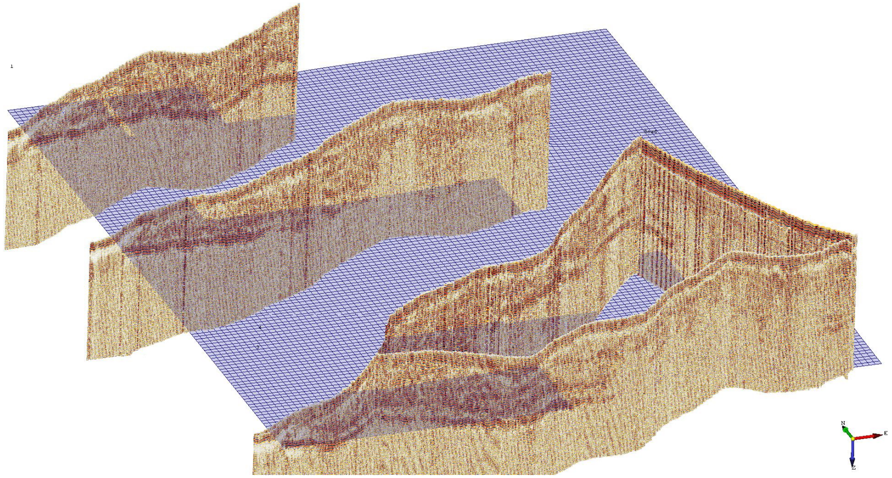
Applications

Case Study 3



Case study taken from Costall, A., 2014, Feasibility of Ground Penetrating Radar for Delineation of the Saline Water Interface along Perth's Coastal Margin, Curtin University Exploration Geophysics.

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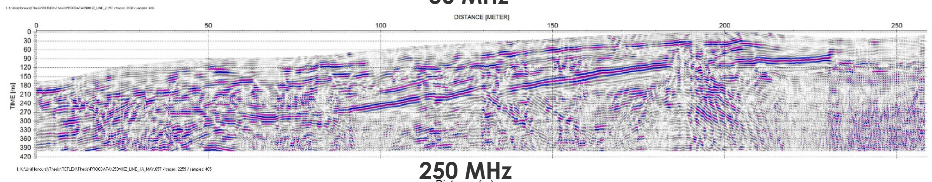
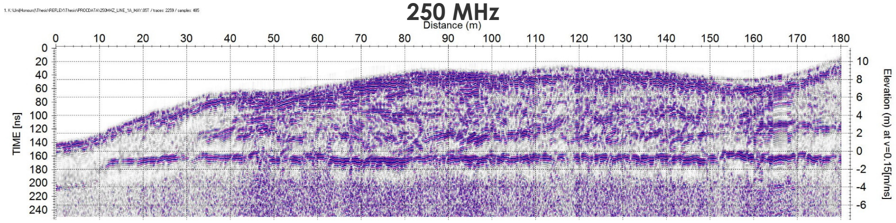
Applications

Case Study 3

50 MHz



250 MHz



"Tamala Limestone inhibits investigation with the 250 MHz antenna as the signal appears to be scattered, while the unshielded nature of the 50 MHz antenna became an issue with overwhelming airwave noise from wire fences along the tracks, additionally, it's inherently lower resolution resulted in hindrances to the technique over this area."

Case study taken from Costall, A., 2014, Feasibility of Ground Penetrating Radar for Delineation of the Saline Water Interface along Perth's Coastal Margin, Curtin University Exploration Geophysics.

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Applications

Case Study 3

Outcomes

"The research concluded that the technique can be applied to the detection and quantitative analysis of the **water table** at coastal boundaries, estimations to the variation in **moisture content**, including variability of **infiltration rates** along profile lines, and **dilution of the saline water interface** have been observed"

Case study taken from Costall, A., 2014, Feasibility of Ground Penetrating Radar for Delineation of the Saline Water Interface along Perth's Coastal Margin, Curtin University Exploration Geophysics.

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Other Applications

Other application of GPR and not limited to…

Civil engineering
- Geotechnical
- Road inspection
- Cavity characterization
- Concrete Inspection Rebar

Archaeology
- Fossil exploration
- Grave detection

Agriculture
- Soil Moisture

Hydrological
- Salt water intrusion
- Estimating porosity and fluid flow
- Contamination

Sedimentology
- Sand dunes
- Paleochannels
- Fracture detection

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Expedition Unknown – GPR in the Media

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LECTURE 12

Recap Lecture

S2 2015

Your time is running out

The Absolute Basics

If you can't answer these questions.... ~~I've failed you.~~ You Failed.

1. What is an Electric field? Units?
2. What is a Magnetic Field? Units?
3. Write down Maxwell's Equations?
4. What are the Medium Dependent Equations?
5. What is the EM Wave equation?
6. EM wavenumber?

Conductivity

Conductivity, what is it?

1. What is Archie's Law?
2. Factors influencing the resistivity of a rock?
3. What is the relationship between conductivity and resistivity?
4. Describe the conductivity tensor?
5. What are the two main types of transmitters?
6. What are the two main types of receivers?

EM Fields Deconstructed

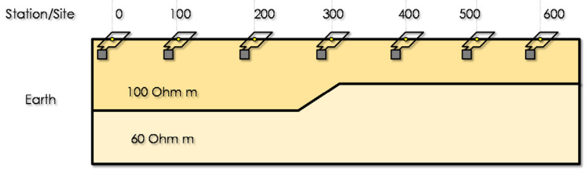
What the hell do we measure in EM?

1. What is the difference between Time Domain EM and Frequency Domain EM. Pro's and Cons of each?
2. What is the relationship between real and imaginary and amplitude and phase?
3. What is mutual inductance?
4. What is the resistive and conductive limit?
5. Define skin depth? What is the skin depth for a 1 Ohm m earth transmitted at 1 Hz
6. What is the diffusion Depth?

Transient EM

OMG! It's getting real in here.

1. What does earth property does TEM detect?
2. What does a standard inloop profile response look like over the following structure?



3. What is a CDI?
4. What is the difference between forward modelling and inversion?
5. What is electrical equivalence? How do we reduce the non-uniqueness of EM inversion

Plates

No. not the thing you eat off.

1. What is the difference between galvanic and inductive current flow?
2. What is null coupling?
3. Draw the inloop profile response over a vertical condutive plate in a resistive host overlaid by conductive overburden?
4. Draw the slingram profile response over a vertical conductive plate in a resistive host overlaid by resistive overburden?

Decay Curves

Don't let your enthusiasm decay like a bounded conductor.

1. Draw a decay curve for a coil sensor that contains the following feature (please note type of decay and decay factors)
   - SPM
   - Halfspace
   - Thin Conductive Layer
   - Bounded Conductor
2. What is current channeling and how does it impact data
3. What causes an IP effect and how does it present in data?

Mag-ne-to-tel-lur-ic

Don't just sit passively by.

1. How do you conduct an MT survey?
2. What are the TE and TM modes in the magnetotelluric method?
3. What is static shift? How do you reduce it's impact?
4. What is CSAMT? How is it different to MT?
5. What are the steps to process MT data?
6. How does the skin depth equation relate to MT's depth of investigation?

Noise and Anomalous Signal

Stop stacking on the signal.

1. List as many types of noise are found in TEM data?
2. How to you remove/limit noise?
3. How does increasing moment influence noise?
4. How does increasing number of stacks influence noise?
5. How does binning influence noise?

Radar

No you Die(electric).

1. What does RADAR stand for?
2. How do you conduct a radar survey? What instrumentation is required?
3. How does the wavenumber relate to the propogation of high frequency EM fields?
4. What properties of the earth are recorded?
5. What earth property(s) controls reflectivity?
6. What earth property(s) control attenuation?
7. List some applications of GPR?

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Radiometrics

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Tips

Don't freak out.

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