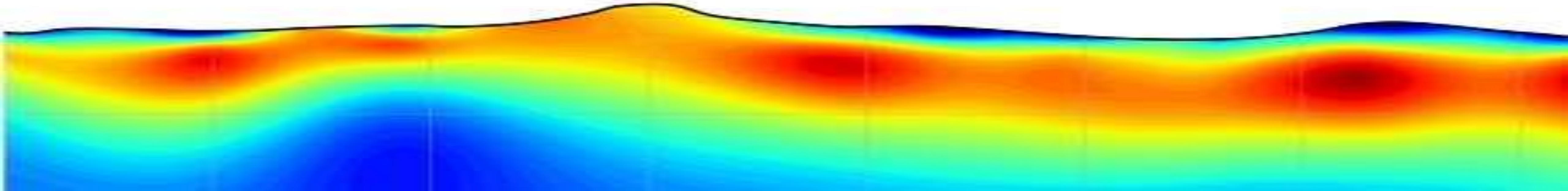
# ESS302 Applied Geophysics II

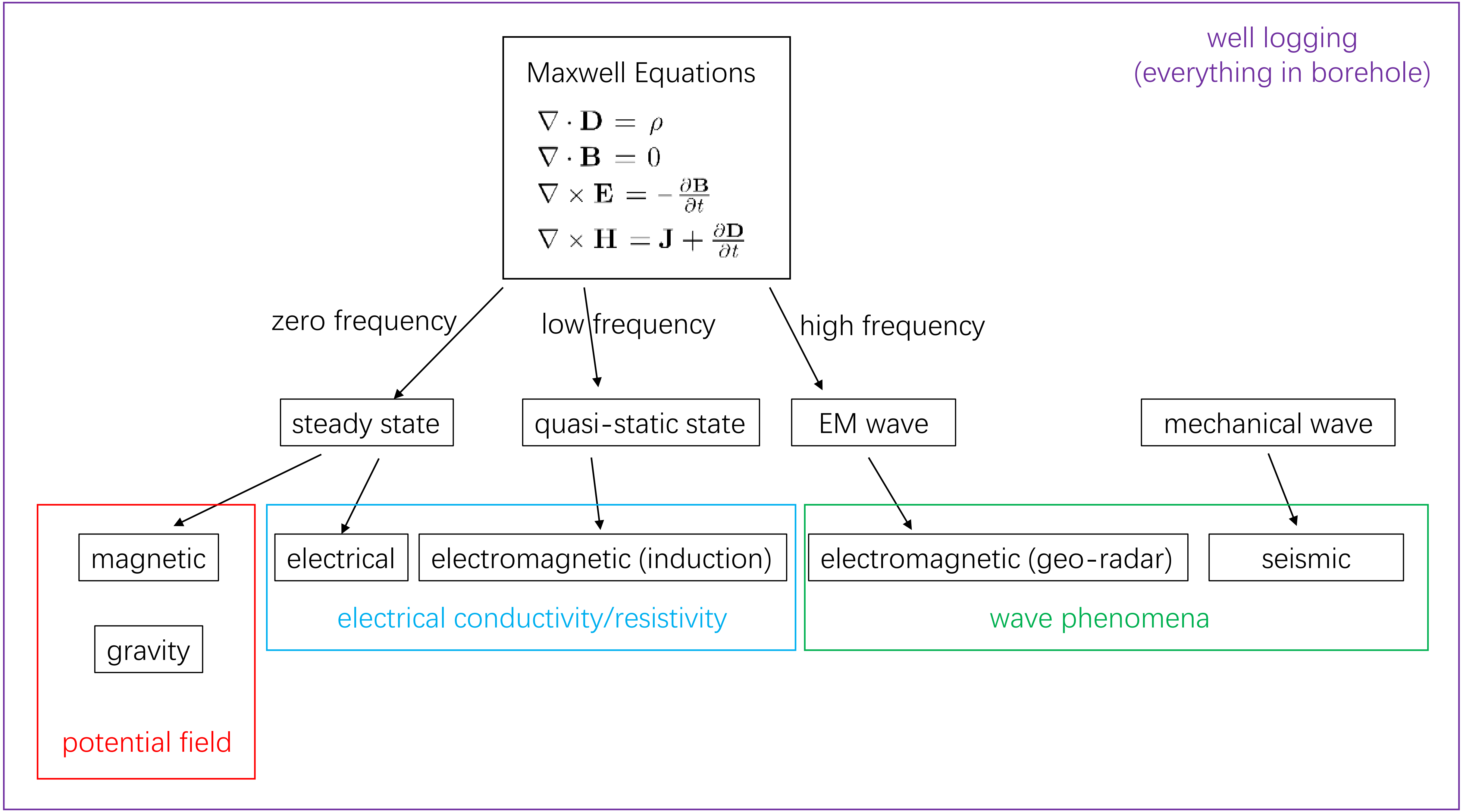
Gravity, Magnetic, Electrical, Electromagnetic and Well Logging

## EM Wrap-up

Instructor: Dikun Yang

Feb – May, 2020





well logging
(everything in borehole)
Maxwell Equations
$\nabla \cdot \mathbf{D} = \rho$
$\nabla \cdot \mathbf{B} = 0$
$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$
$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$
zero frequency
low frequency
high frequency
steady state
quasi-static state
EM wave
mechanical wave
magnetic
gravity
potential field
electrical
electromagnetic (induction)
electrical conductivity/resistivity
electromagnetic (geo-radar)
seismic
wave phenomena

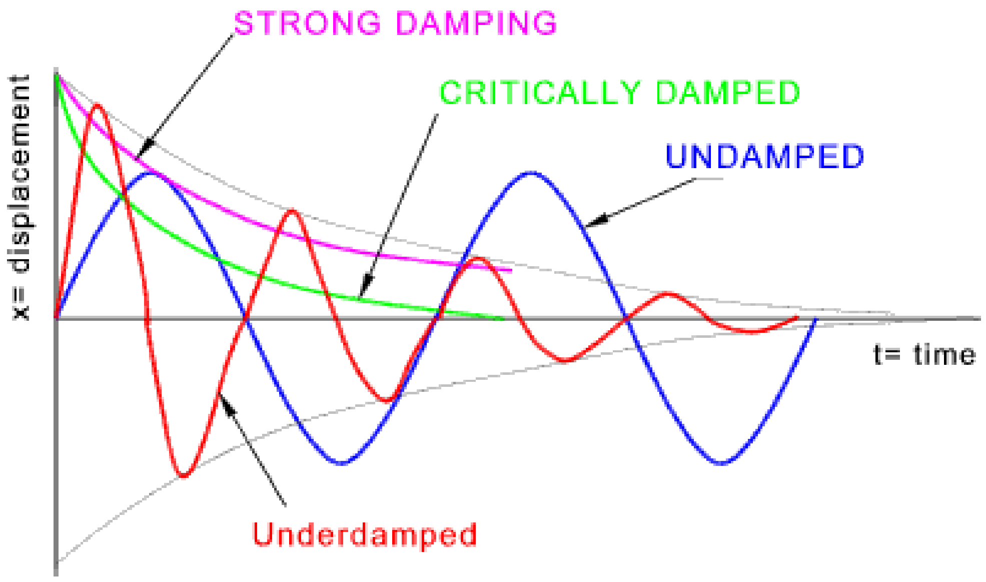
# Quasi-static Maxwell's Equations

$$\nabla \times E = -\mu \frac{\partial H}{\partial t}$$

$$\nabla \times H = \sigma E + \cancel{\epsilon \frac{\partial E}{\partial t}}$$

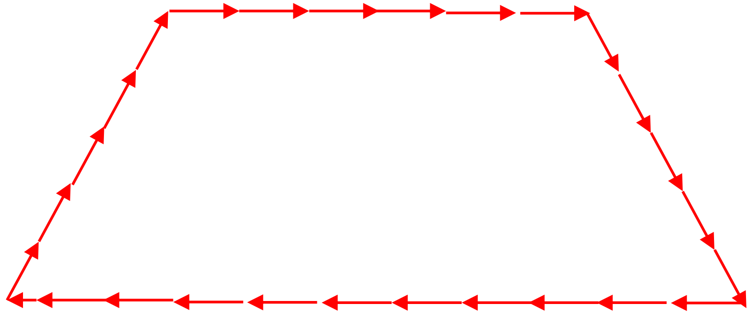
$$\nabla \times E = -i\omega\mu H$$

$$\nabla \times H = \sigma E + \cancel{i\omega\epsilon E}$$

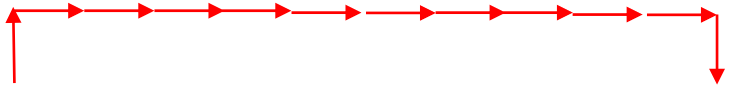


# Wires and Loops

Electrical dipole
(a *small* piece of wire)



Closed loop
- Magnetic field (dB/dt)
- Non-contact (divergence free)
- Inductive coupling

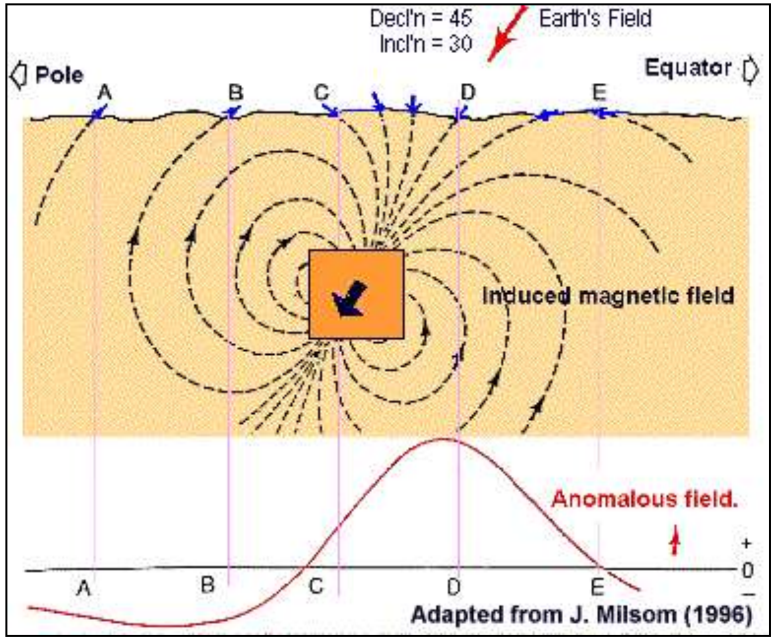


Grounded wire
- Electrical field (E)
- End points in contact with ground
- Galvanic and inductive coupling

# Loop-loop System in Frequency Domain

# EM =

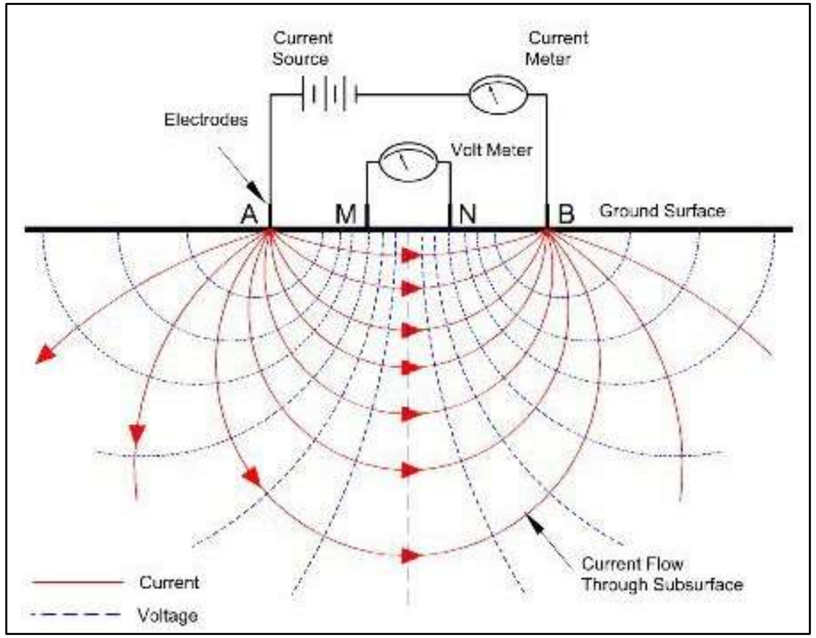
## Magnetics




- Magnetic dipole
- Magnetic flux (B)

+

## Electric Resistivity

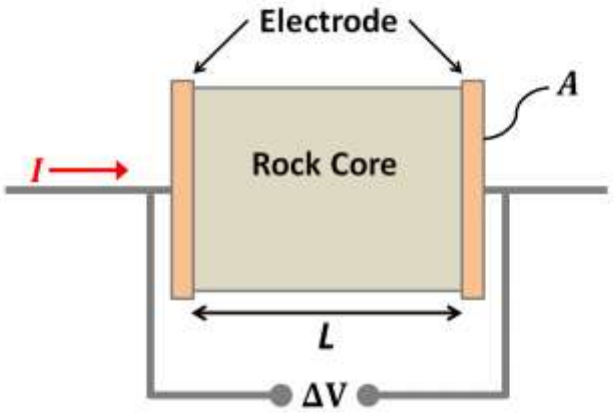



- Electric dipole
- Electric current (J)

# Electrical energy transmission

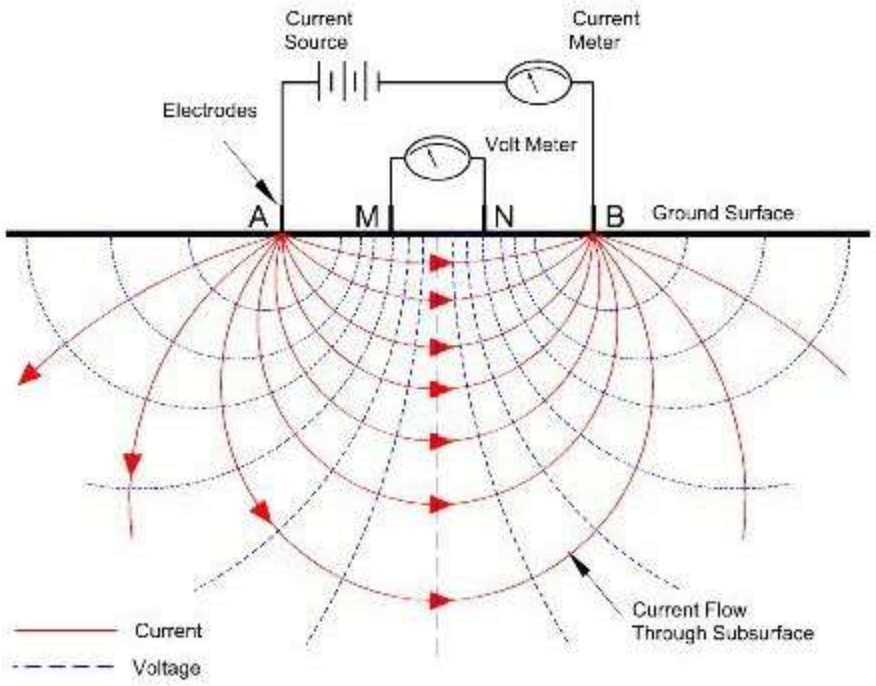
- Galvanic (electric current)

Ohm's law



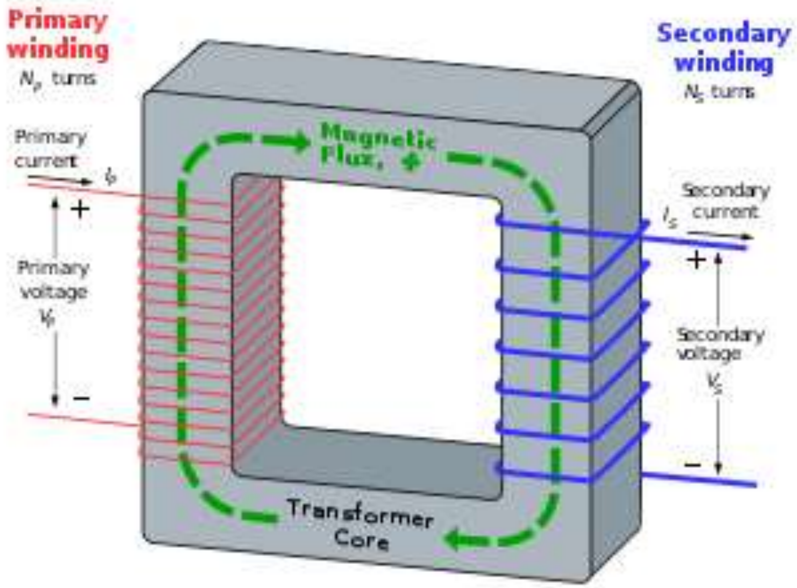

$$R = \frac{\Delta V}{I}$$

DC resistivity
(electric resistivity tomography)



# Electrical energy transmission

- Inductive (magnetic flux B)



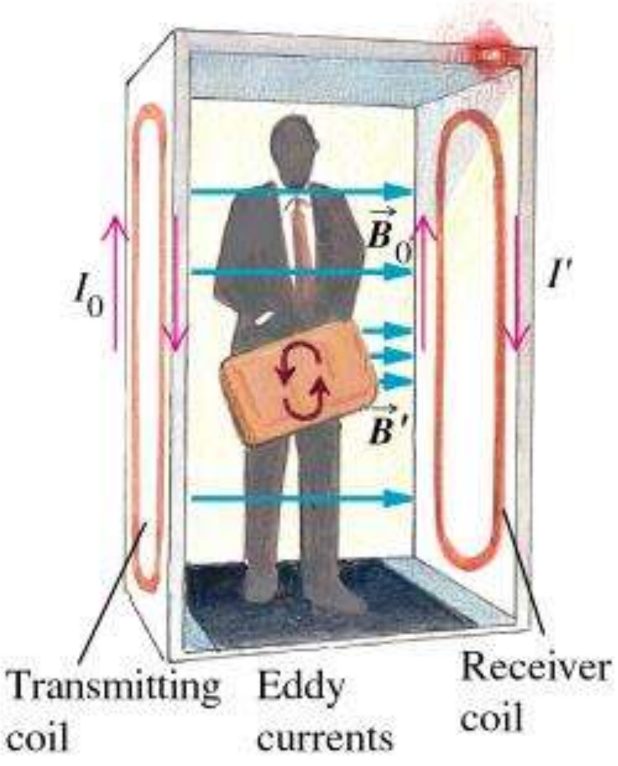

1. Change of current in the primary
2. Change of magnetic flux in the core
3. Induced current in the secondary

A transformer:

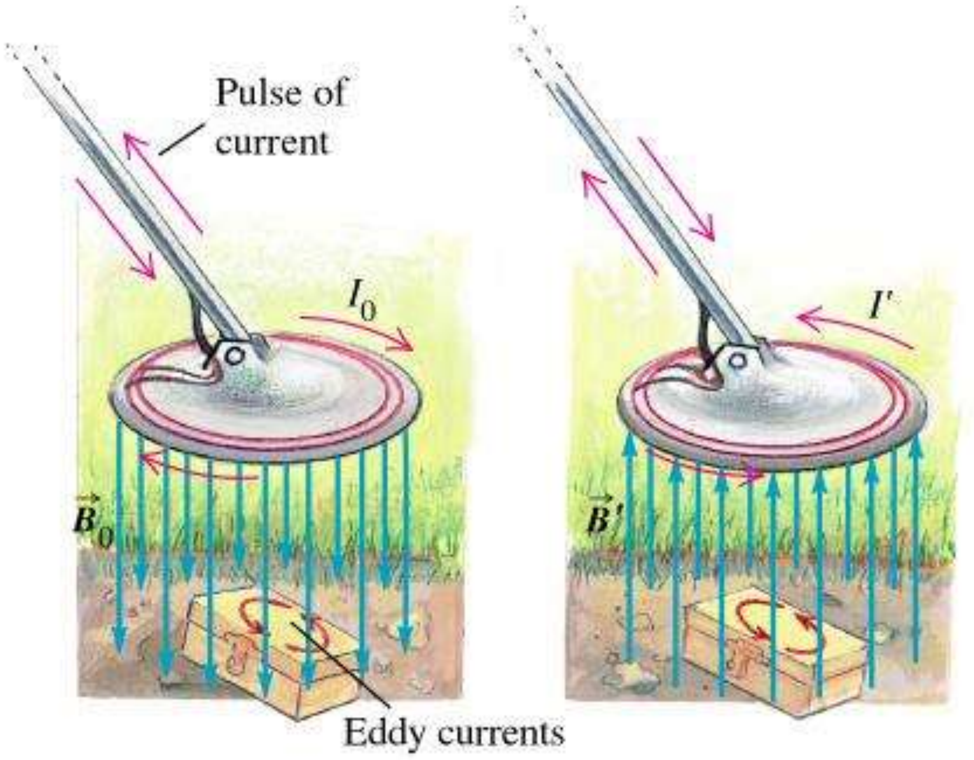
- No direct connection between primary and secondary windings
- Energy goes through in the forms of electric, magnetic then electric
- Magnetic flux linkage only in AC (requires non-stationary current)

# Electrical energy transmission

- Inductive (magnetic flux B)




Security scan



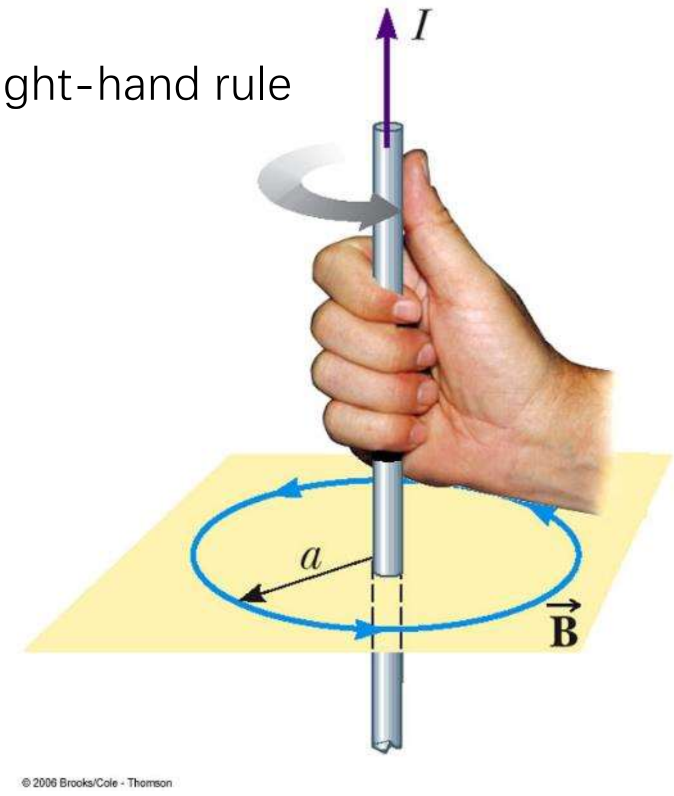

Metal detector

# Ampere's law

J generates B $$\nabla \times \mu^{-1}\mathbf{B} = \mathbf{J} = \sigma\mathbf{E}$$

Current in wire causes a magnetic field to surround it (iron filings).

Right-hand rule



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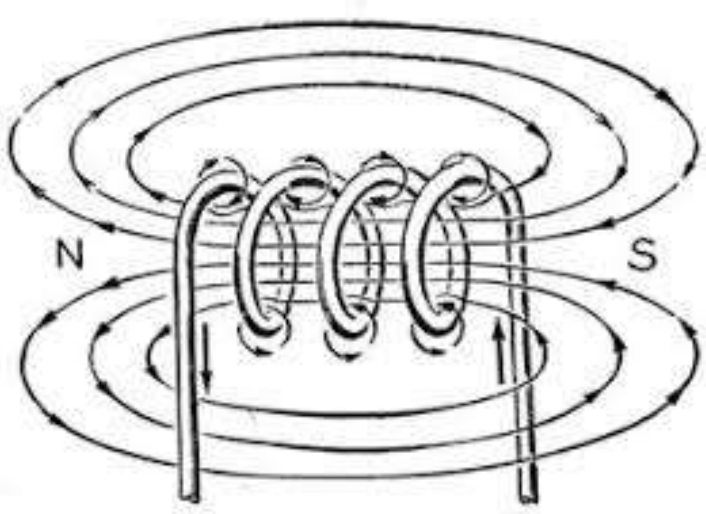
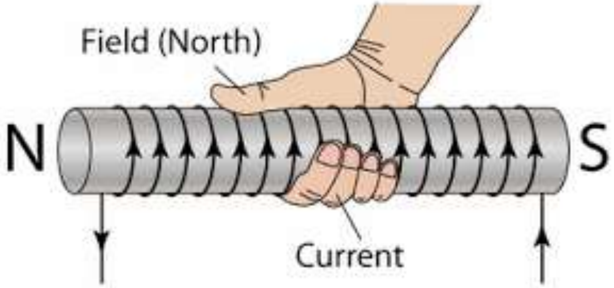
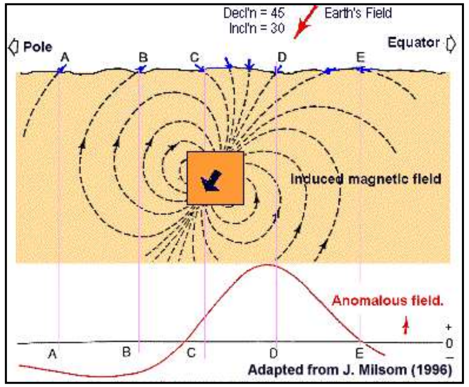



A small solenoid generates a magnetic field that can be approximated by a magnetic dipole (or a small bar magnet)

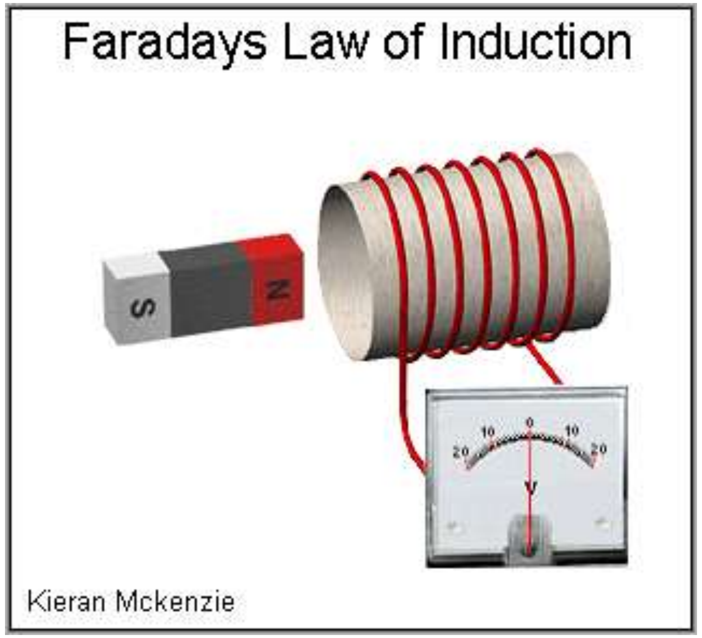



Still remember the magnetic dipole?

# Faraday’s law

Change of B generates J

$$\nabla \times \sigma^{-1}\mathbf{J} = \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

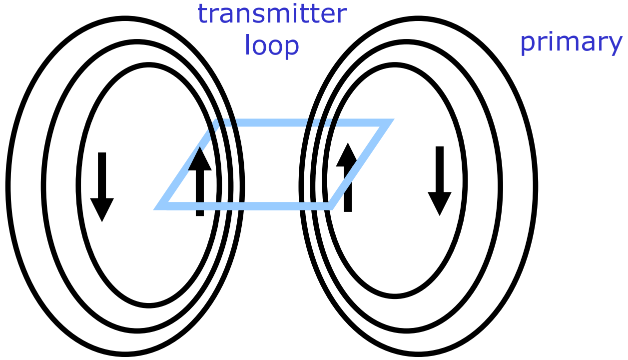



**Induced current depends on**

- How fast B changes
- How many B-field lines go through
- How conductive the object is

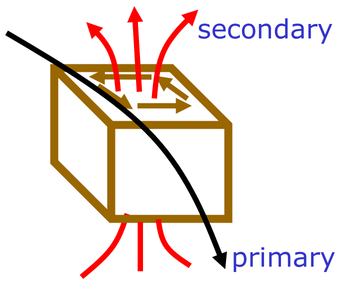
# Communicate with the Earth without Contact

**Transmitter loop**



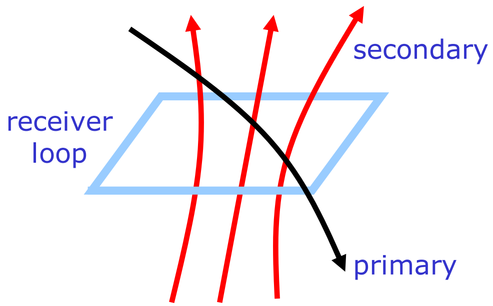

**Ampere**: time-varying current and changing primary magnetic field

**Target/Ground**




**Faraday**: current induced by the changing primary field;
**Ampere**: induced current generates a secondary magnetic field

**Receiver loop**

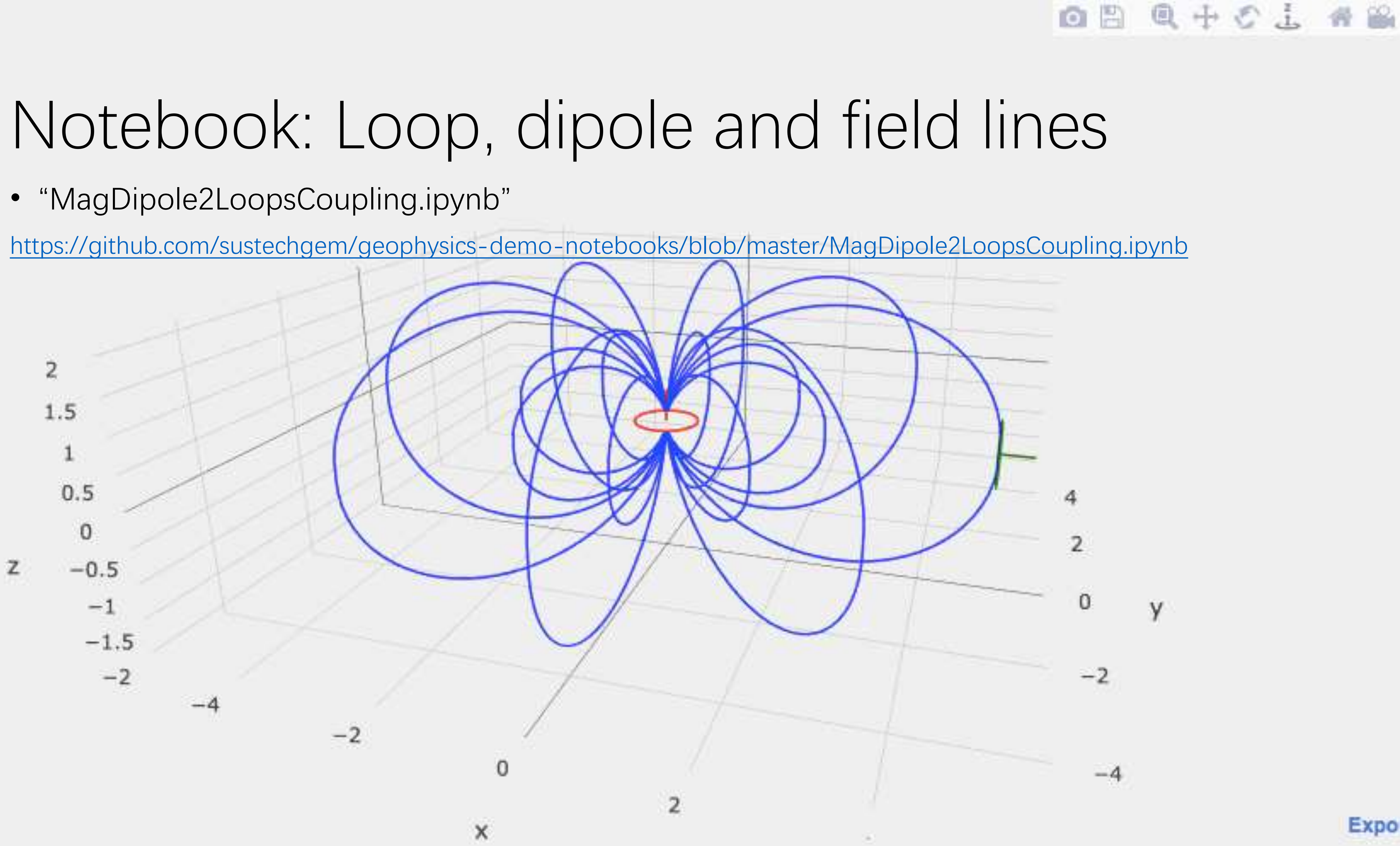



**Faraday**: measurable current induced in the loop by the changing secondary field

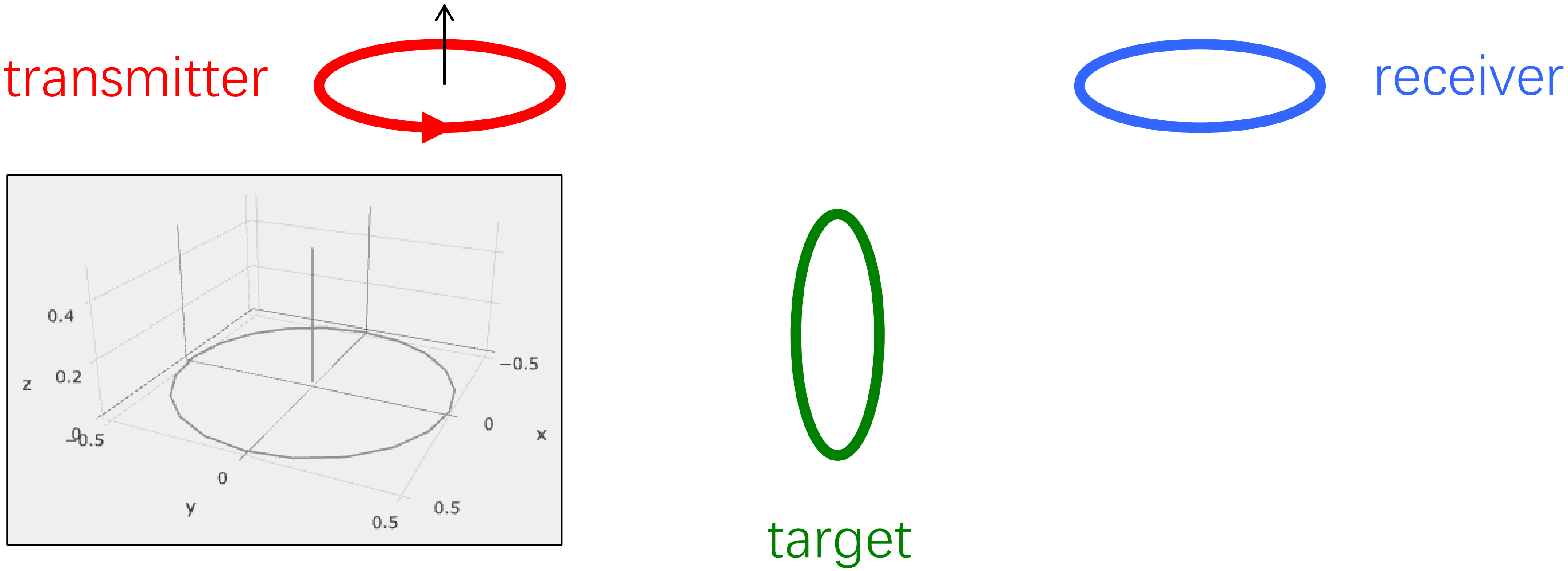
# Notebook: Loop, dipole and field lines

- "MagDipole2LoopsCoupling.ipynb"

https://github.com/sustechgem/geophysics-demo-notebooks/blob/master/MagDipole2LoopsCoupling.ipynb

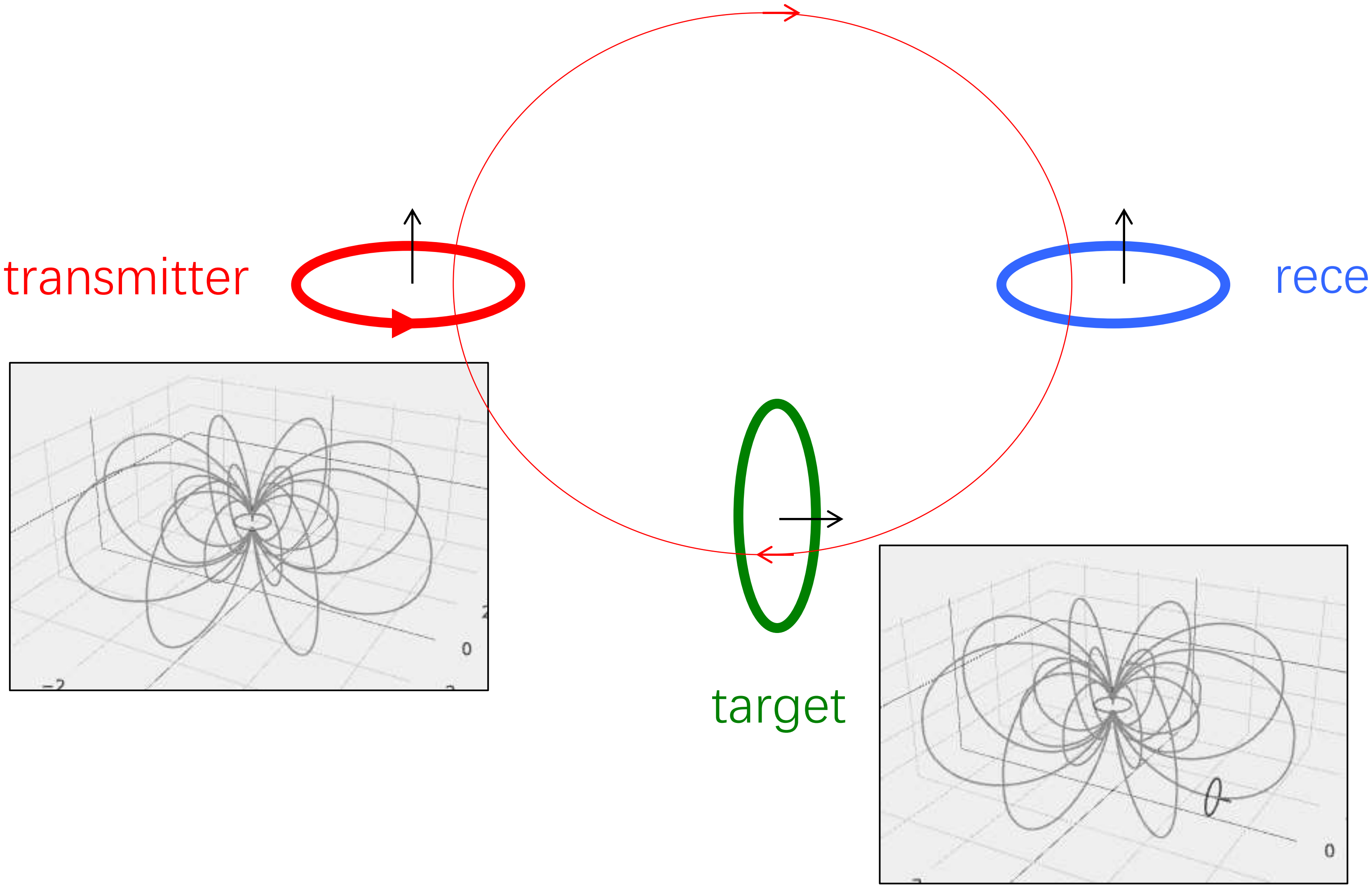


# 3-loop Model

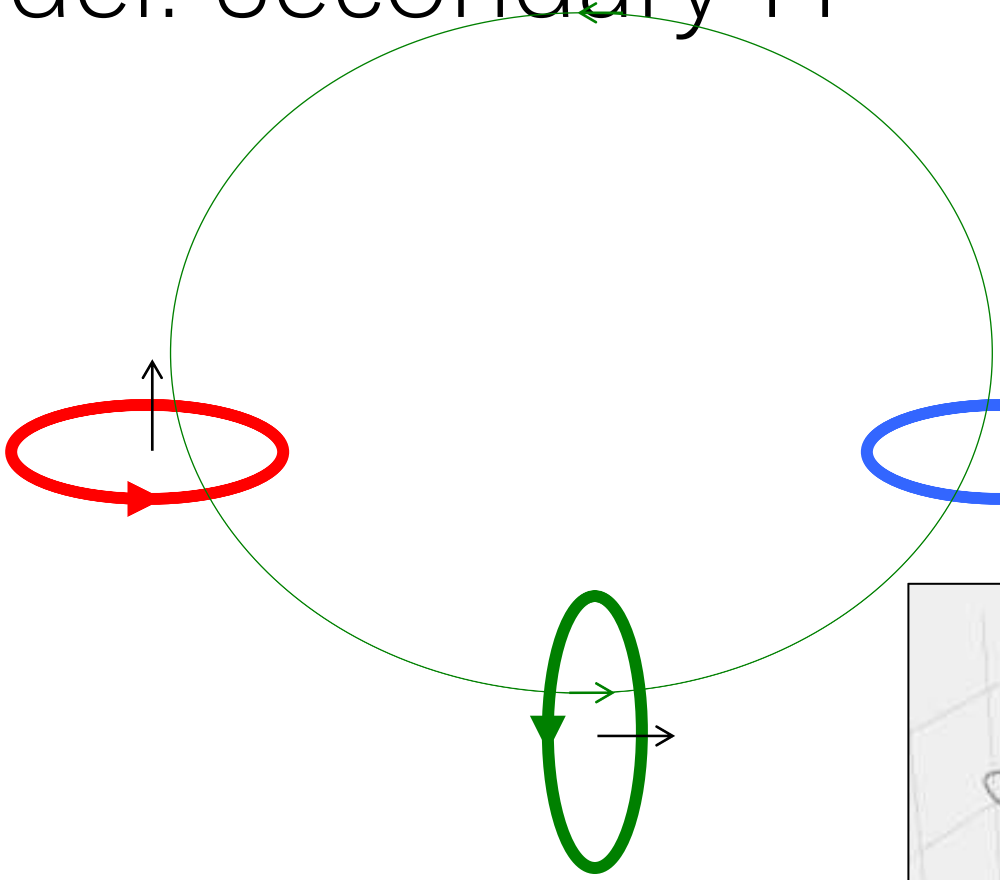


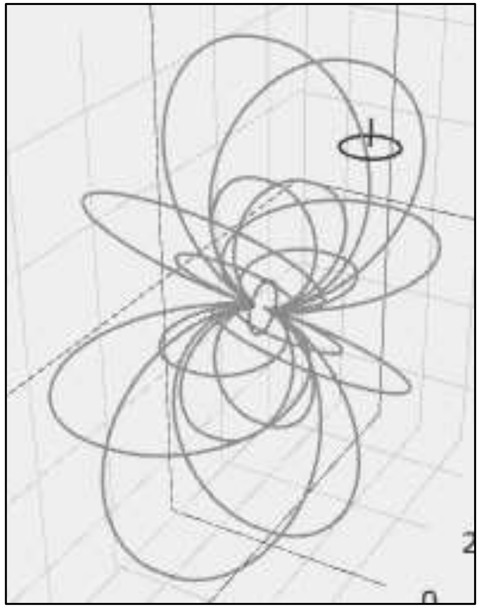

Interactive 3D visualization in “MagDipoleLoops3D.ipynb”

# 3-loop Model: Primary $H^p$

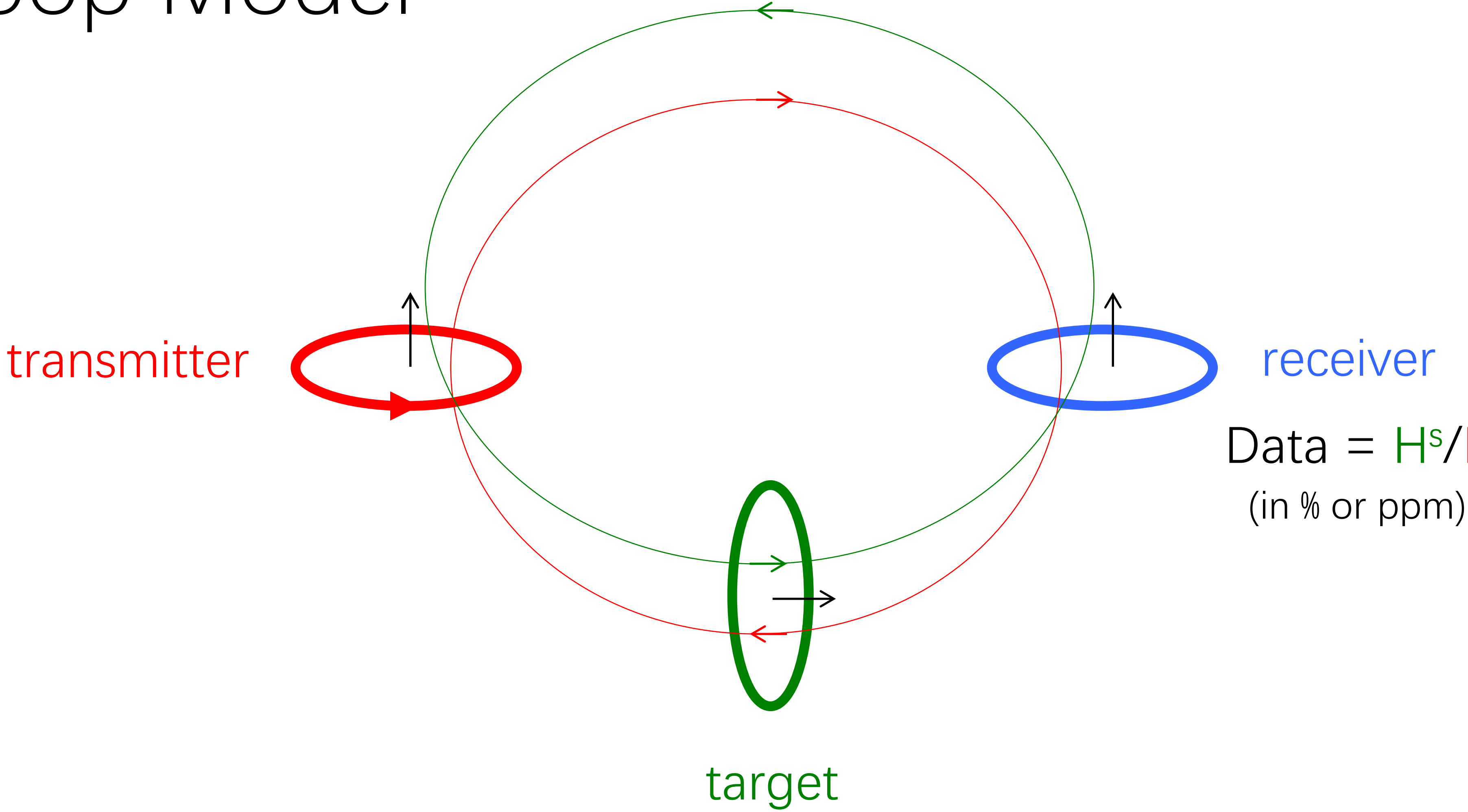


# 3-loop Model: Secondary $H^s$



# 3-loop Model




Data = $H^s/H^p$
(in % or ppm)

**Question**: Is the data positive or negative for the scenario on this page?
Hint: Think about the positive and negative anomalies in total field magnetics.

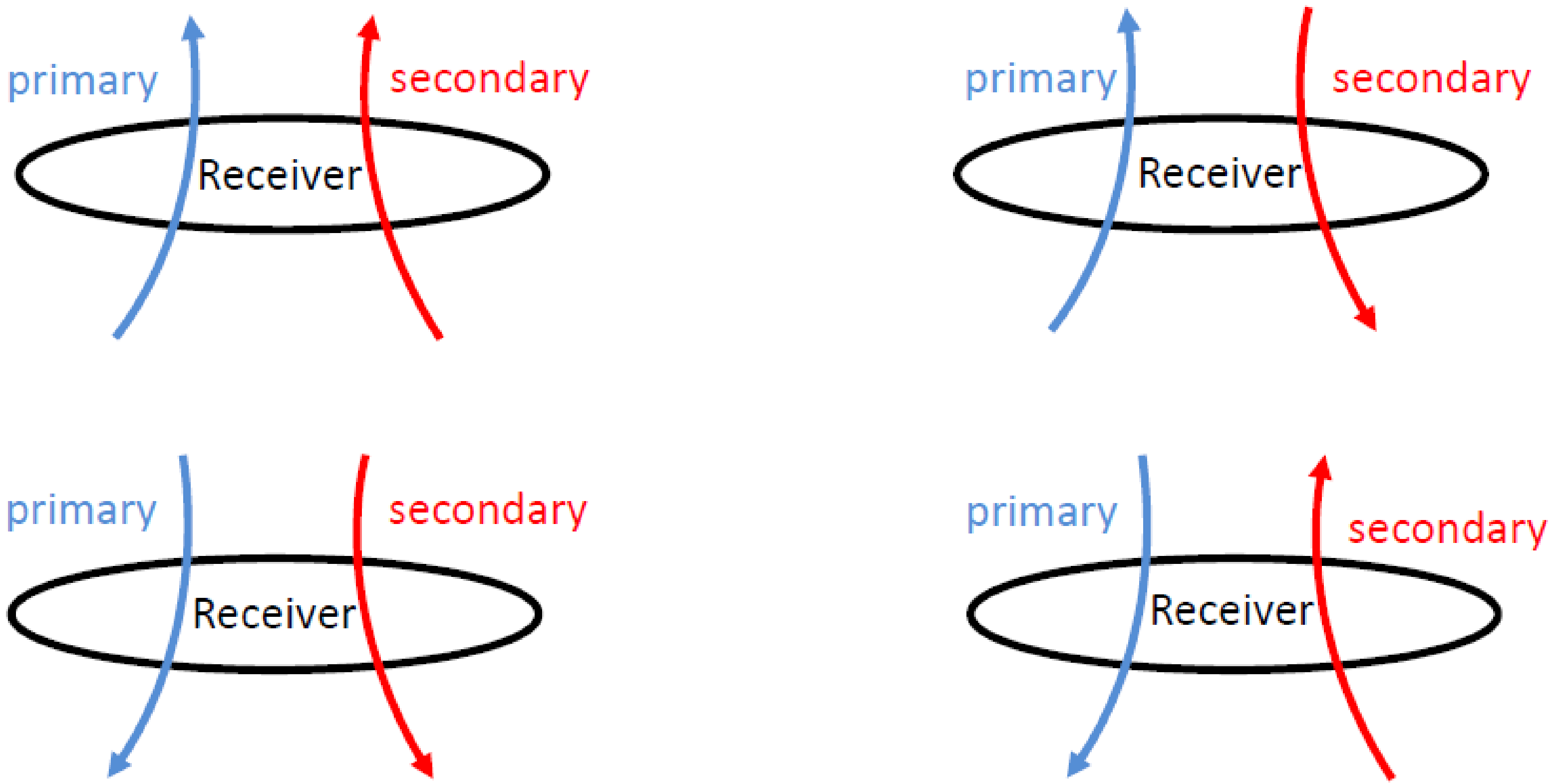
# Data (Hs/Hp) Sign Convention

Positive

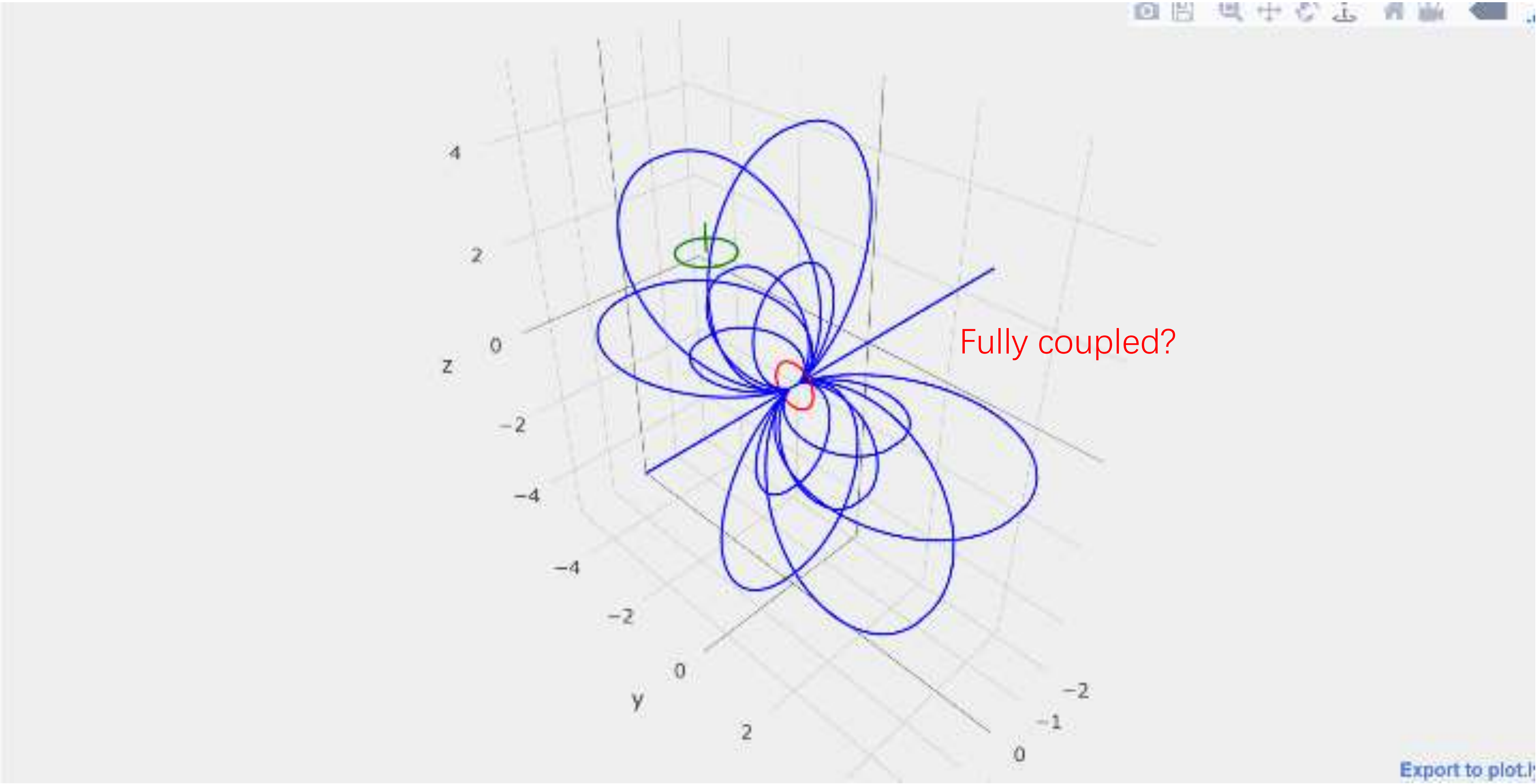
primary and secondary in same direction

Negative

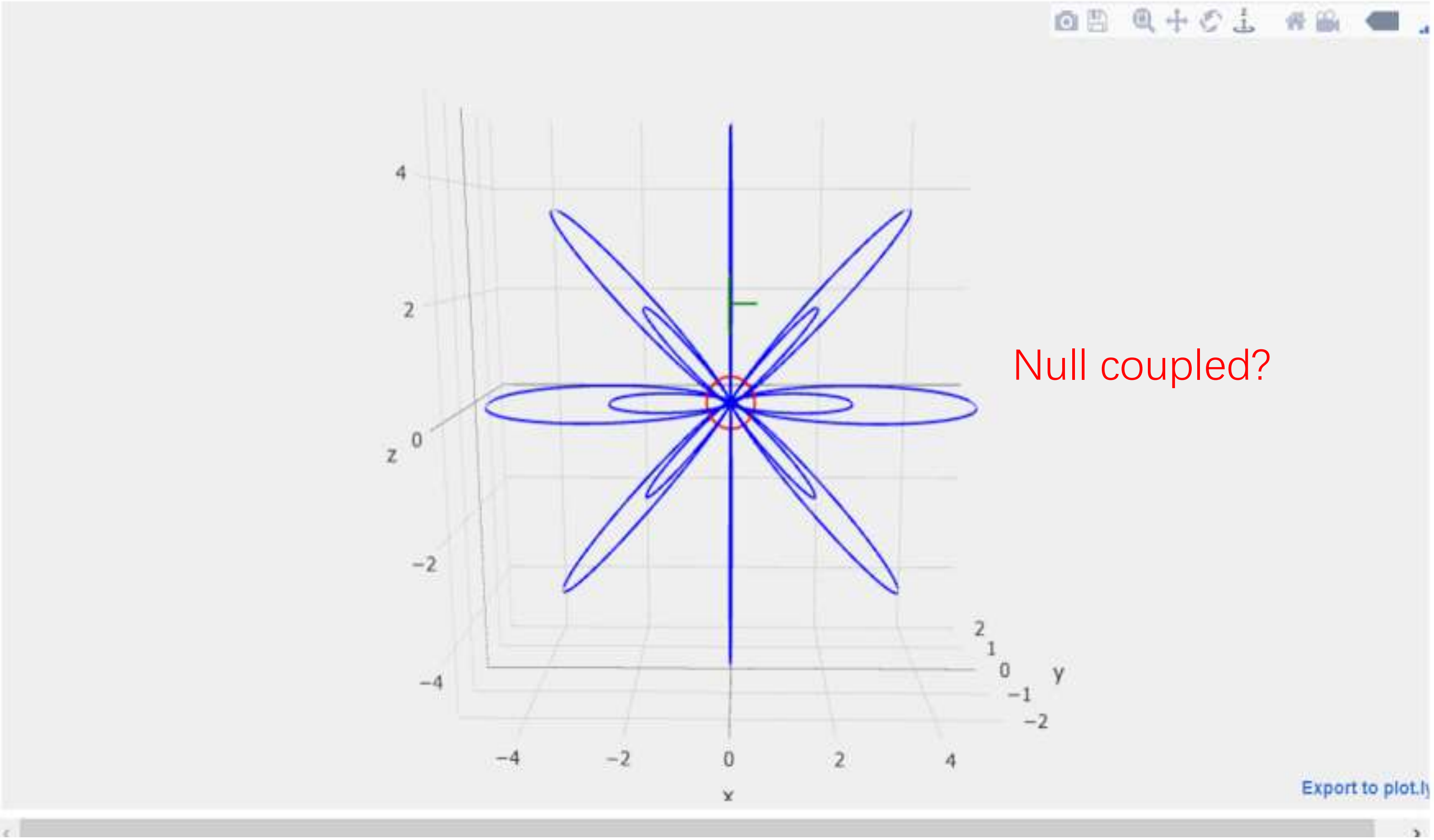
primary and secondary in opposite directions



# Coupling between Two Loops Through Magnetic Flux Linkage

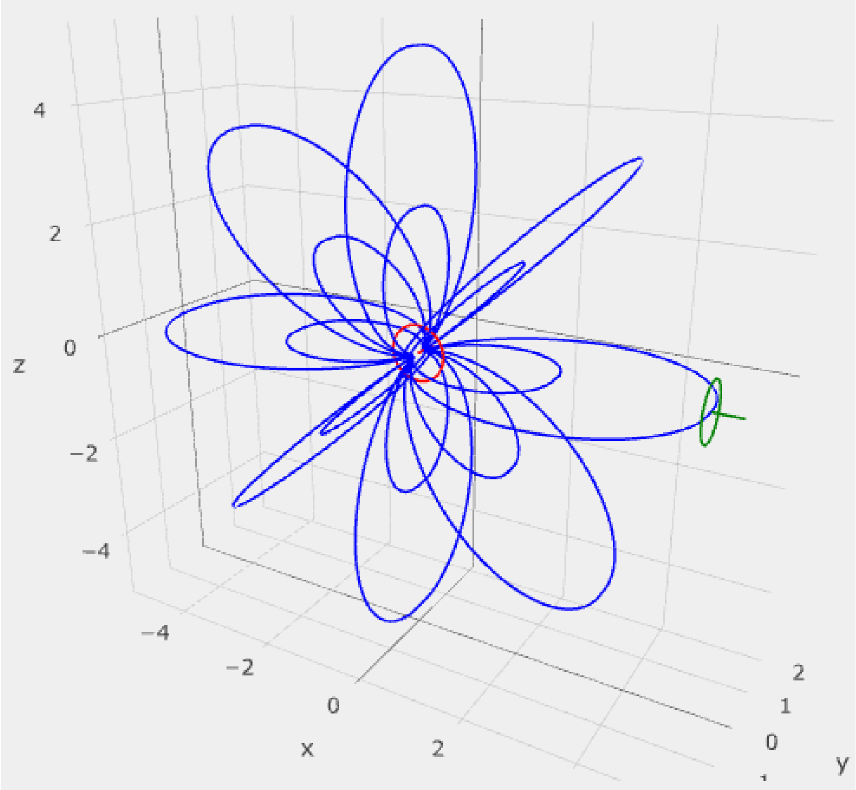


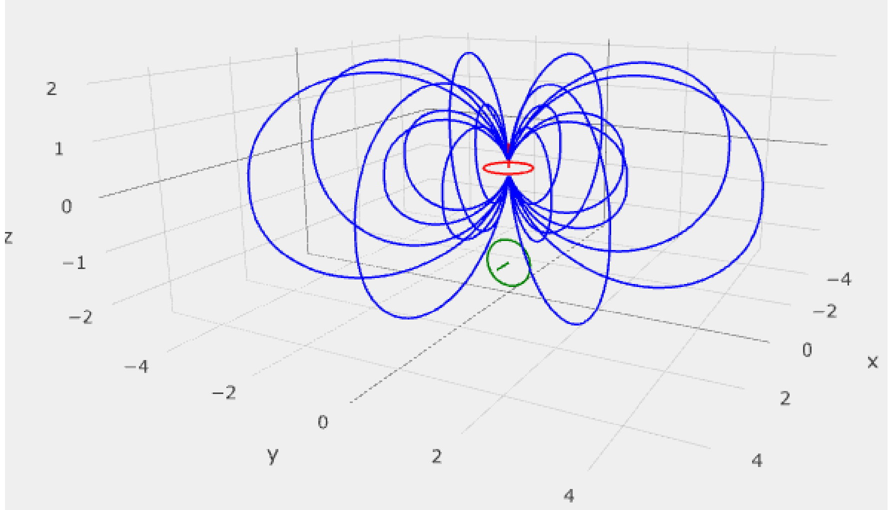
# Coupling between Two Loops Through Magnetic Flux Linkage

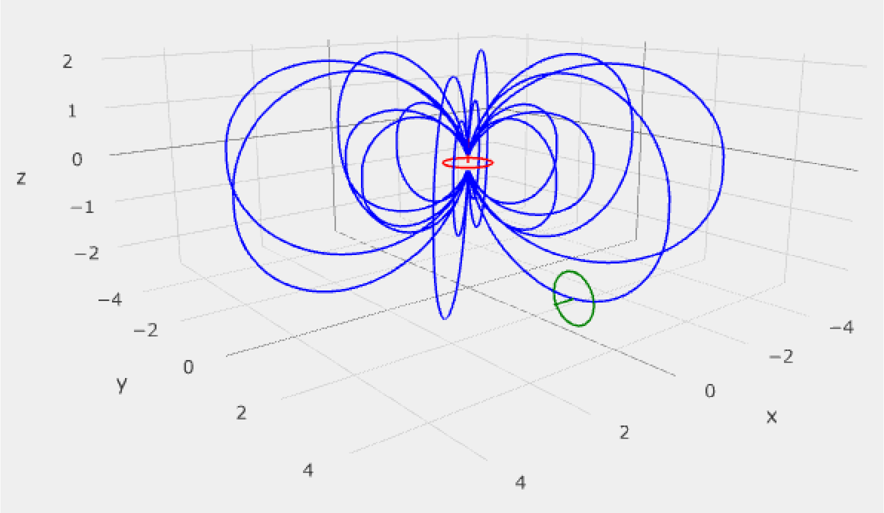



Null coupled?

# Coupling between Two Loops Through Magnetic Flux Linkage

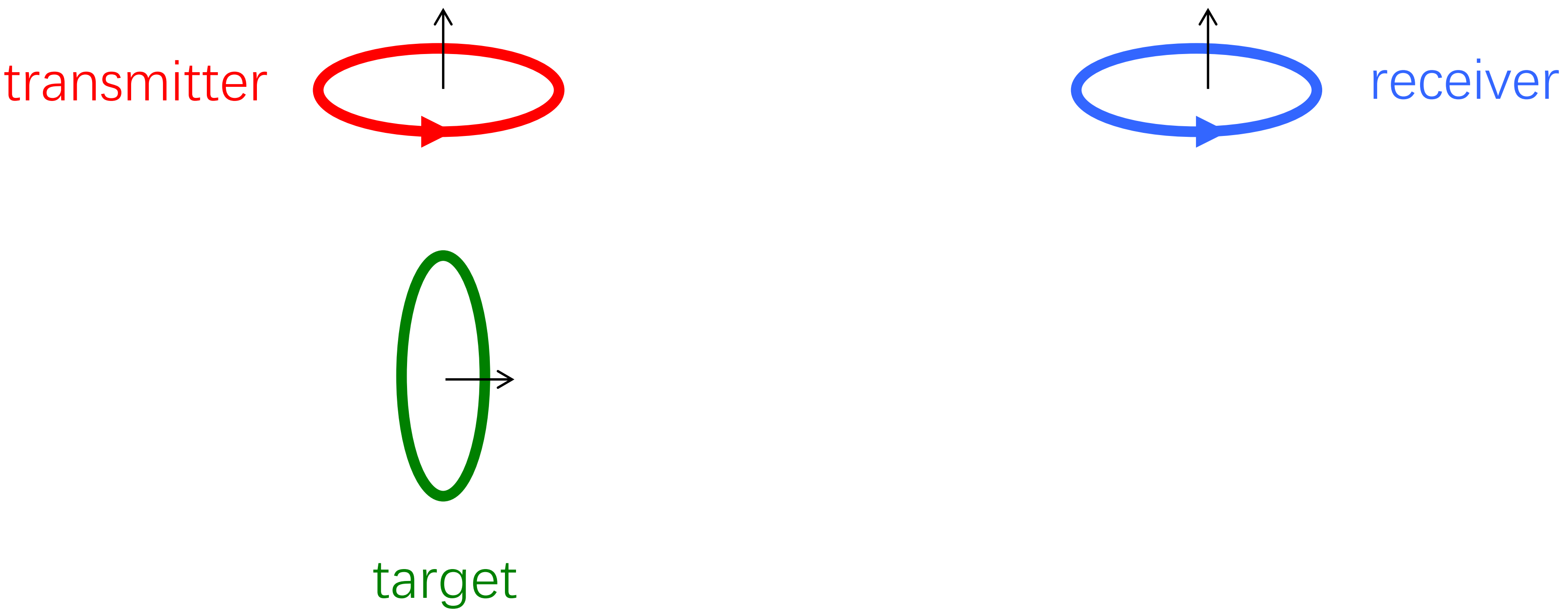


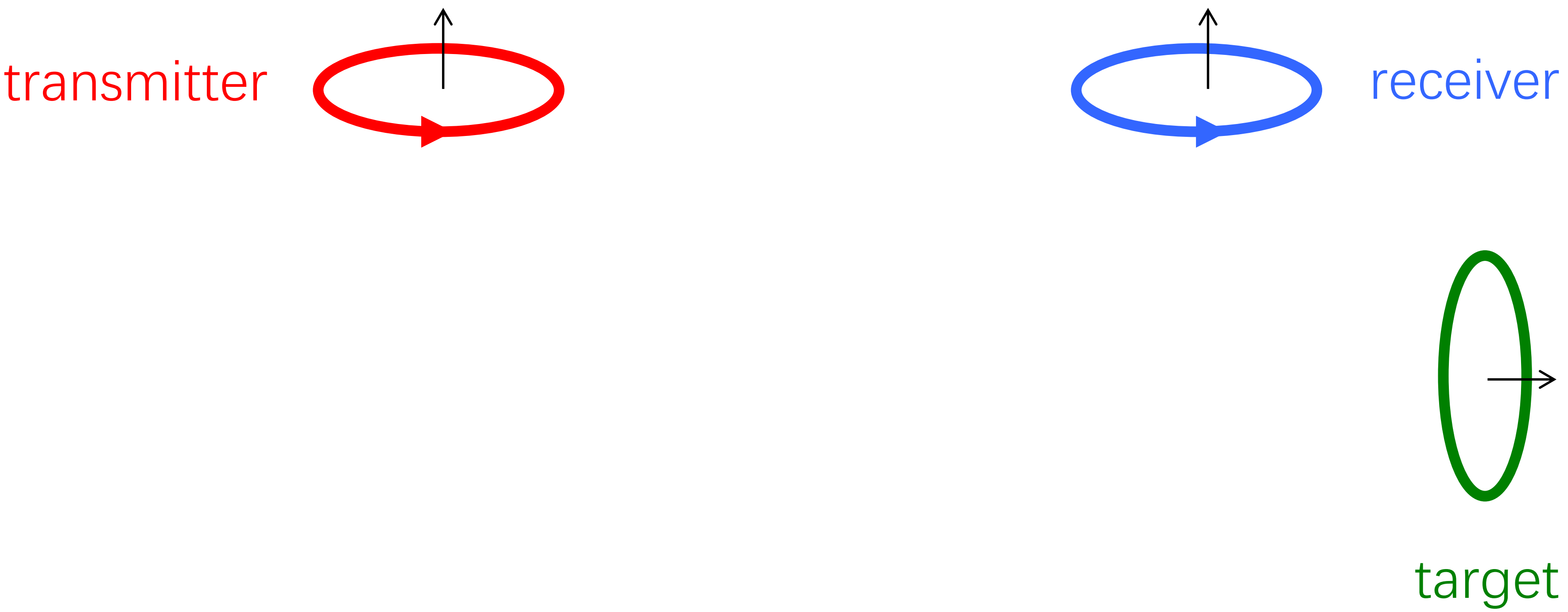




Null coupled

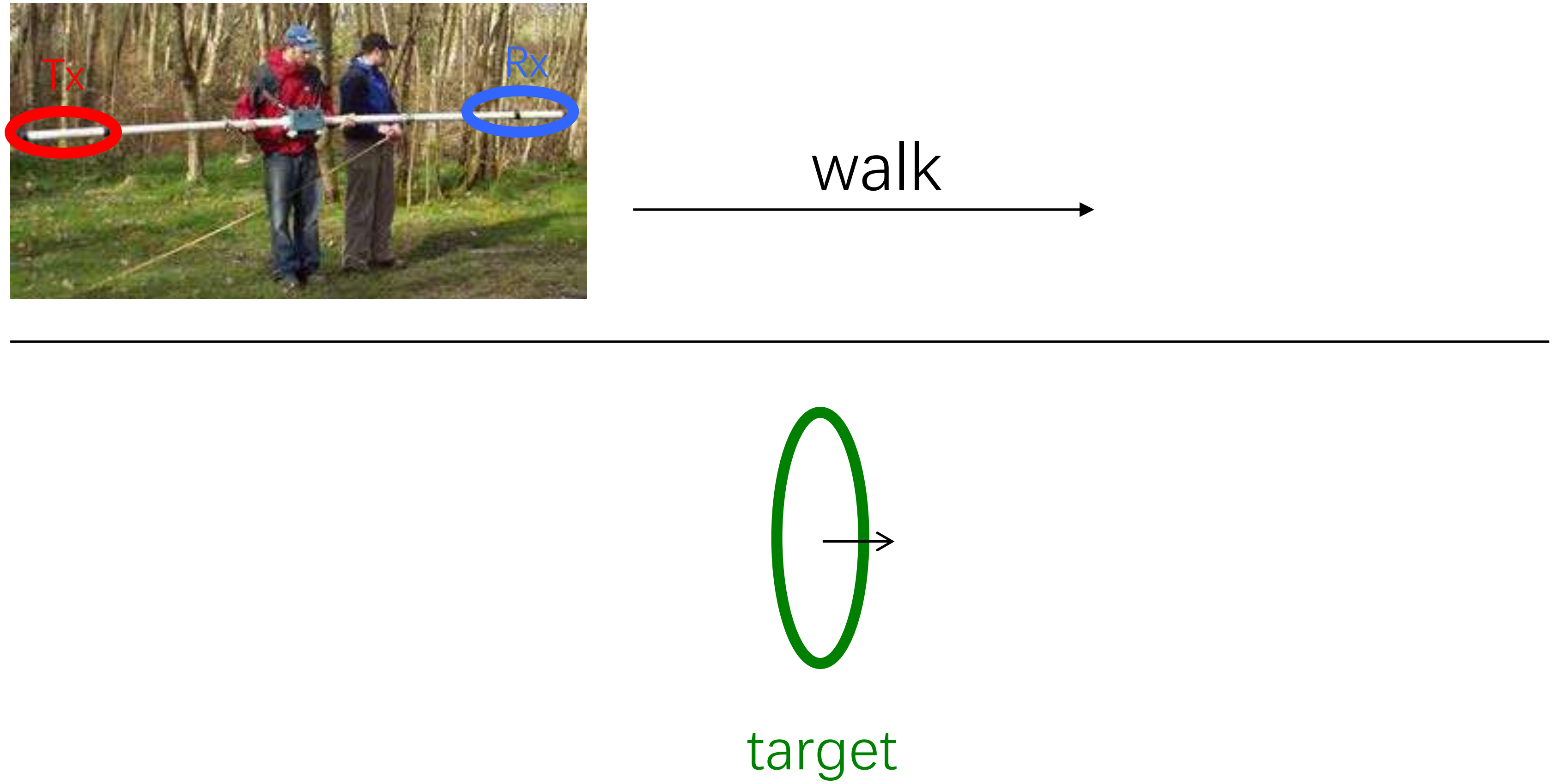
# $H^s/H^p$: Positive or Negative?



# $H^s/H^p$: Positive or Negative?



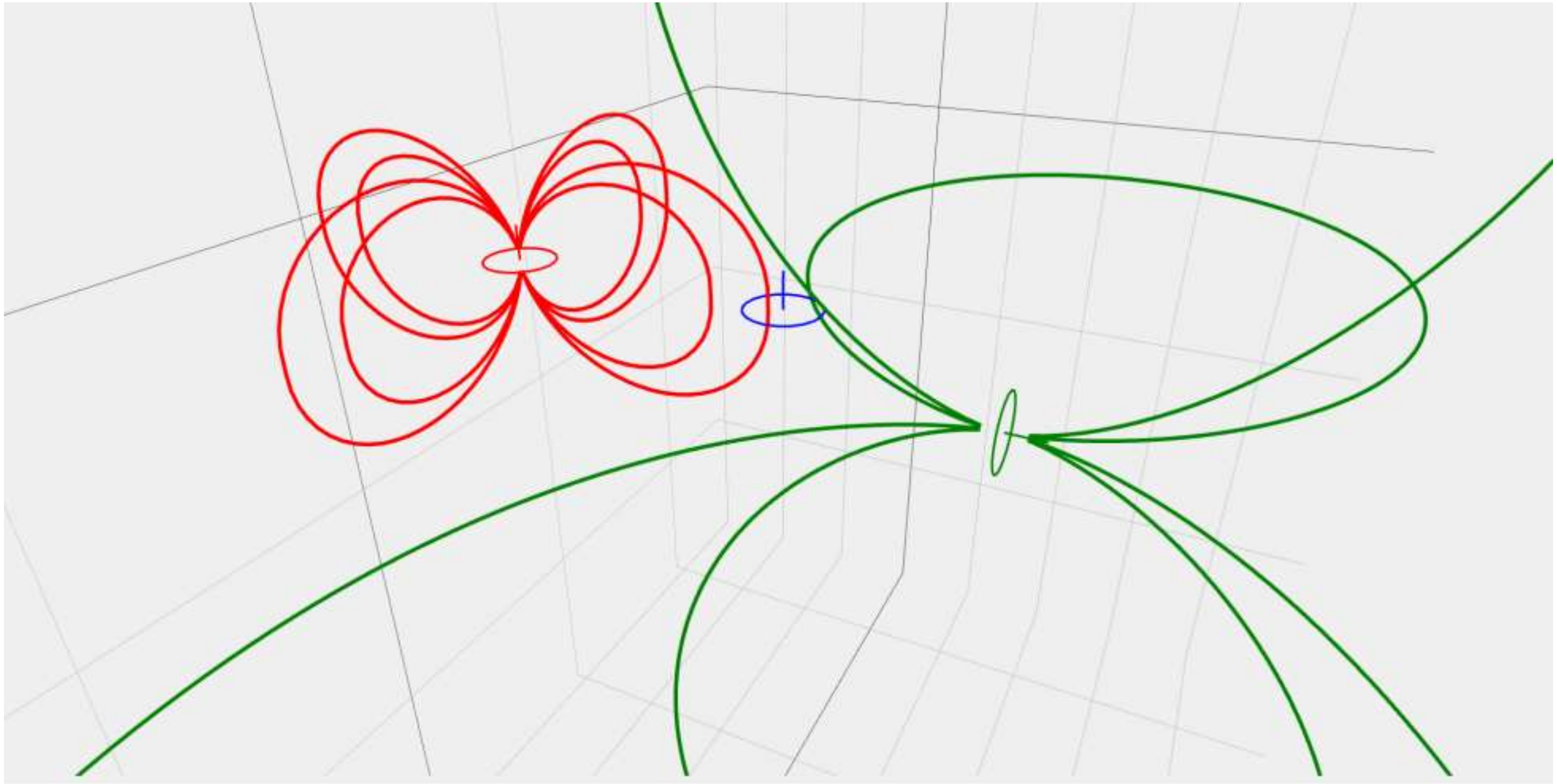
# Hs/Hp Profile



# Verify using Demo Notebook

- “MagDipole3LoopsCoupling.ipynb”

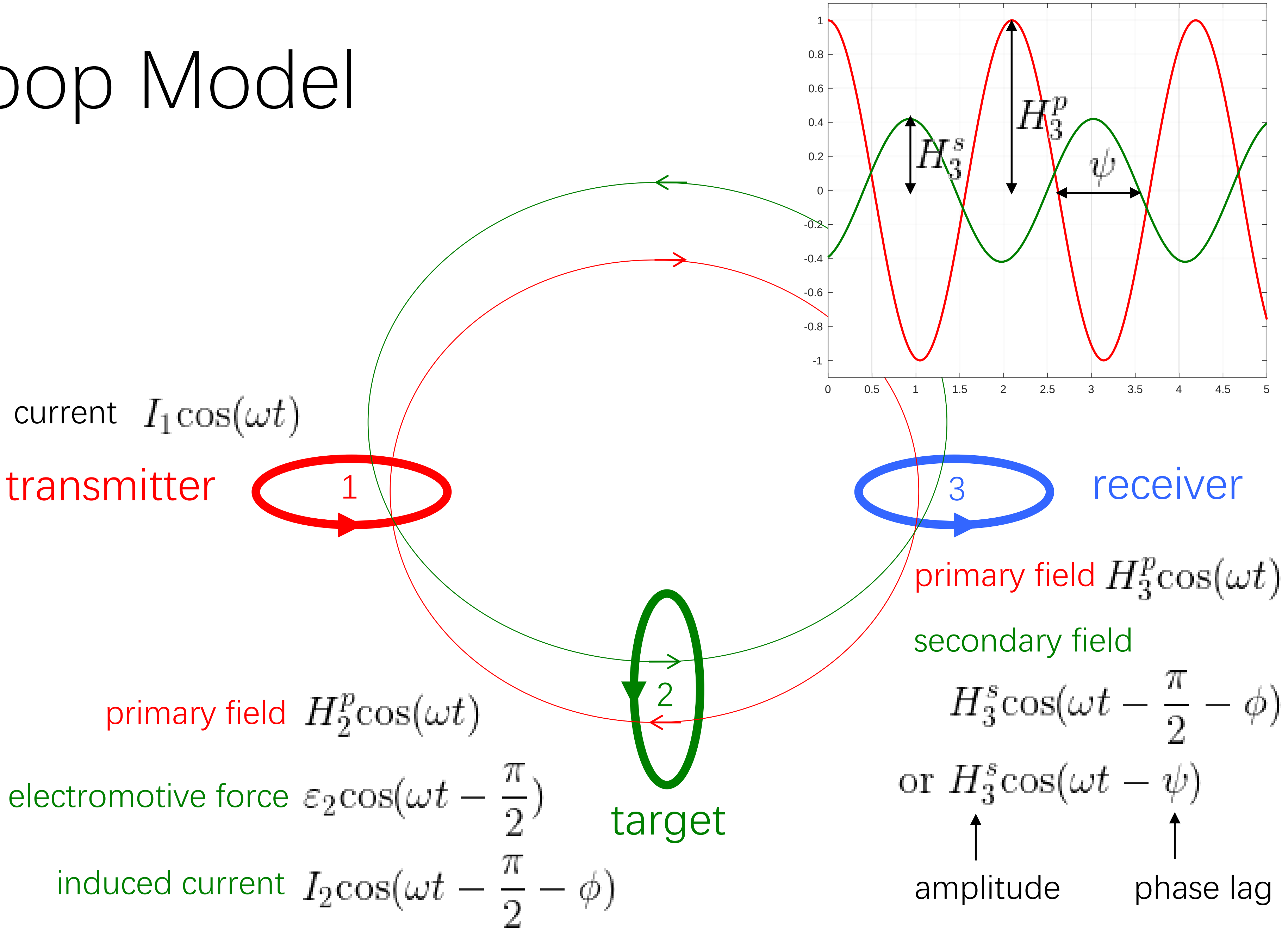
https://github.com/sustechgem/geophysics-demo-notebooks/blob/master/MagDipole3LoopsCoupling.ipynb



Drawing lines only helps qualitative understanding.

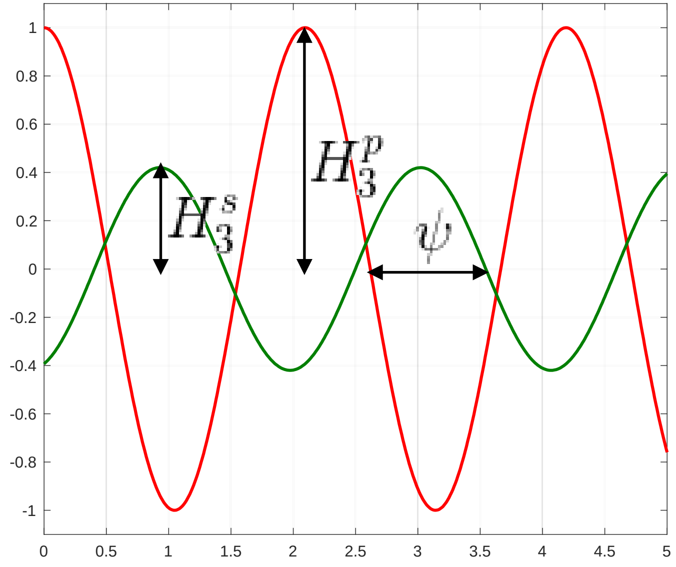
We need more math to do a quantitative interpretation.

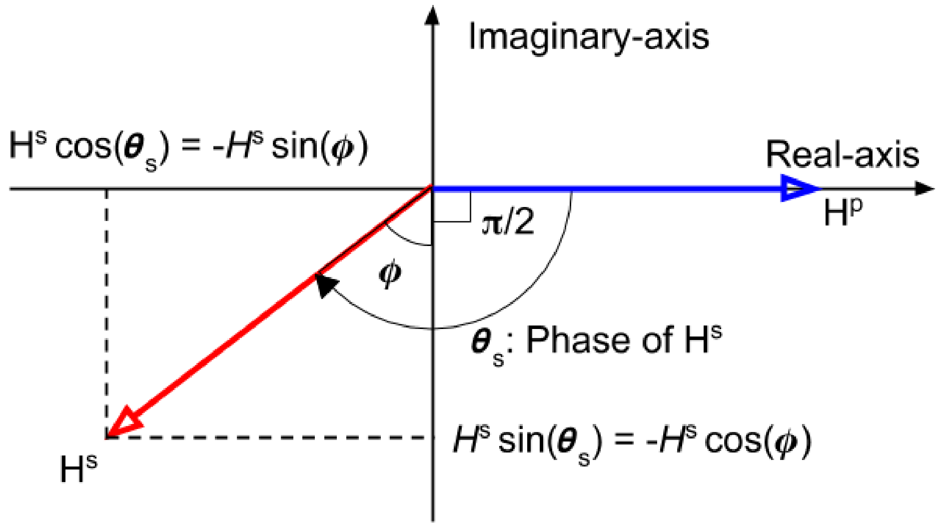
# 3-loop Model



$H_3^s$
$H_3^p$
$\psi$
current $I_1\cos(\omega t)$
transmitter
1
3
receiver
2
target
primary field $H_3^p\cos(\omega t)$
secondary field
$H_3^s\cos(\omega t - \frac{\pi}{2} - \phi)$
or $H_3^s\cos(\omega t - \psi)$
amplitude
phase lag
primary field $H_2^p\cos(\omega t)$
electromotive force $\varepsilon_2\cos(\omega t - \frac{\pi}{2})$
induced current $I_2\cos(\omega t - \frac{\pi}{2} - \phi)$

# Decompose Secondary Field




primary field $H_3^p \cos(\omega t)$

secondary field

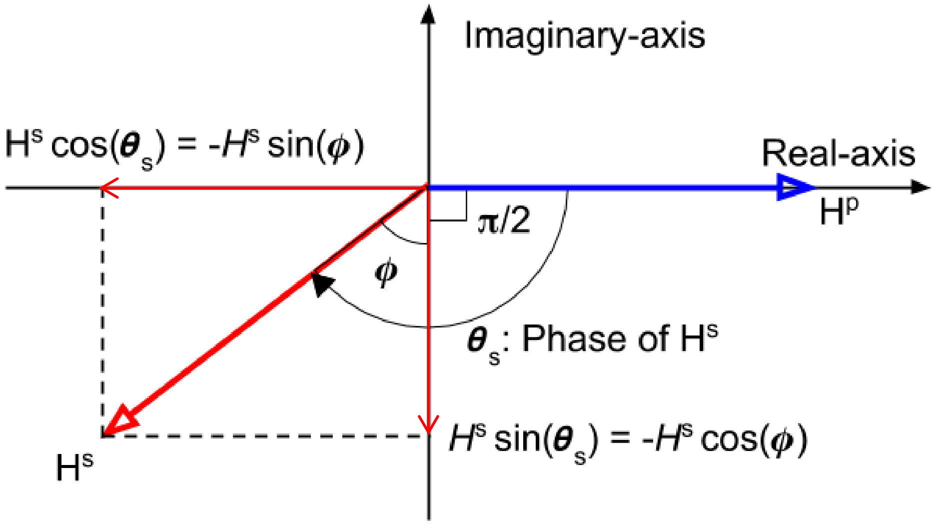
$$H_3^s \cos(\omega t - \frac{\pi}{2} - \phi)$$

$$\text{or } H_3^s \cos(\omega t - \psi)$$

$$\phi = tan^{-1}(\frac{\omega L}{R}) = tan^{-1}(\alpha)$$

- $H^s$ swings in the third quadrant: 0 < φ < 90°
- φ depends on the induction number **α**
- **α** is a function of frequency **ω**, self inductance **L** and resistance **R** of Loop 2

# Decompose Secondary Field




$$\phi = tan^{-1}(\frac{\omega L}{R}) = tan^{-1}(\alpha)$$

**Question**: What happens to the $H^s$ (red arrow) for a very conductive or very resistive target?

Decompose $H^s$ to two orthogonal components then normalize by $H^p$:

90° phase lag: called "out-of-phase", "quadrature", "imaginary"

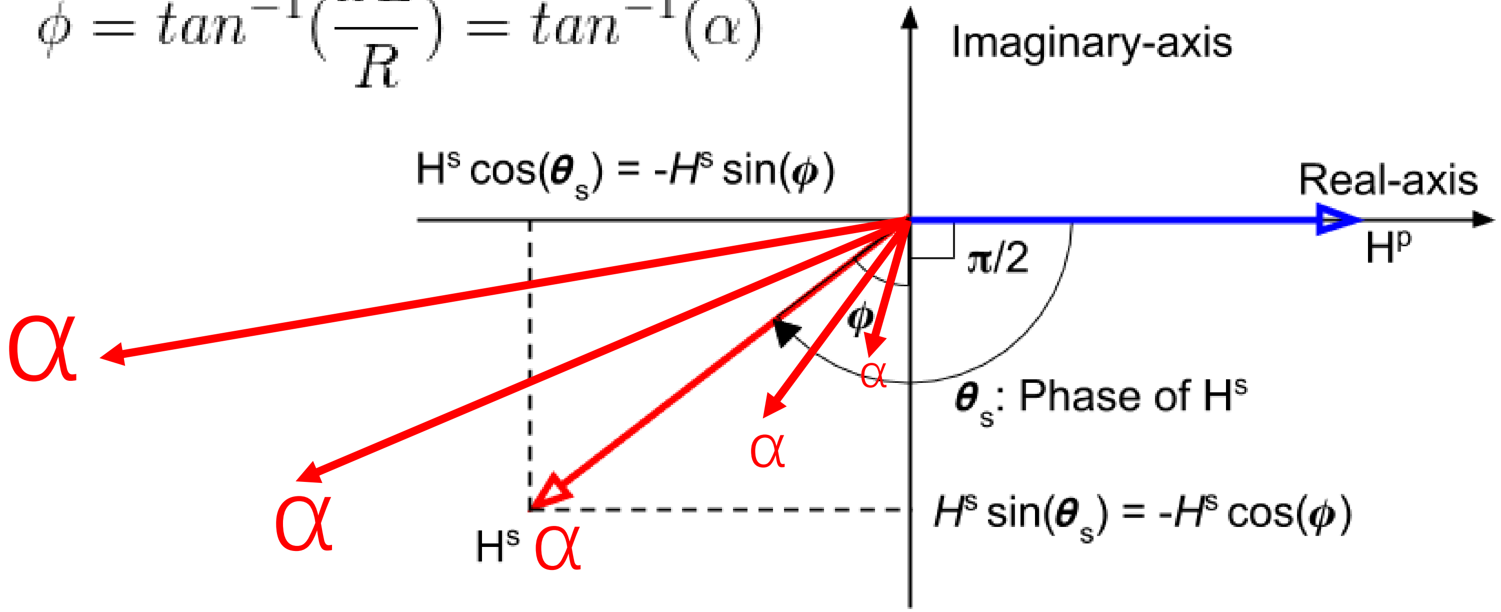
$$\frac{H^s \cos(\phi)}{H^p}$$

180° phase lag: called "in-phase", "real"

$$\frac{H^s \sin(\phi)}{H^p}$$

# Response Function

$$\phi = tan^{-1}(\frac{\omega L}{R}) = tan^{-1}(\alpha)$$



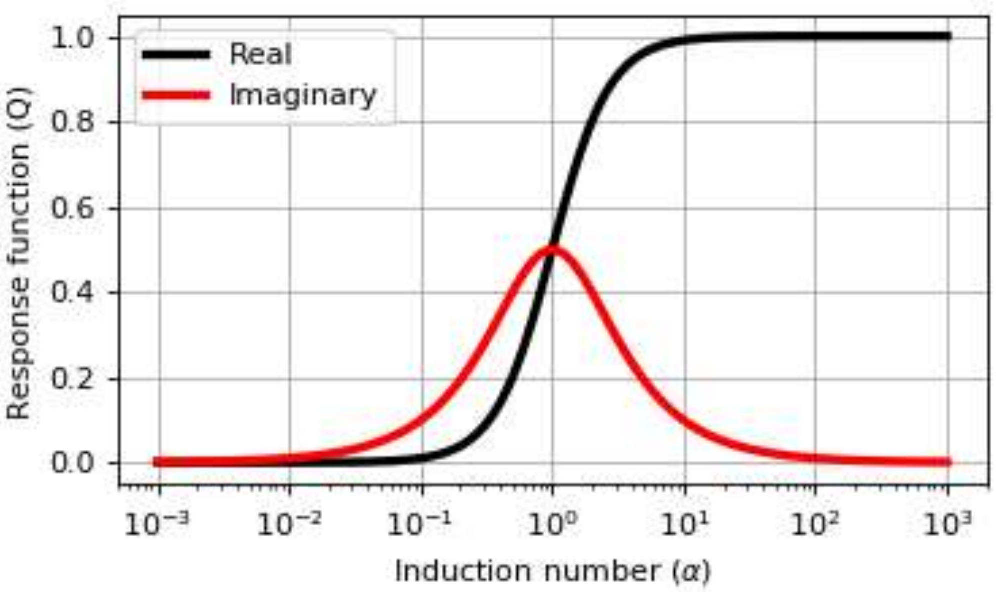

**Question**: How would the real and imaginary data change with the induction number α?

# Response Function

$$Q(\alpha) = \frac{i\alpha}{1 + i\alpha} = \frac{\alpha^2 + i\alpha}{1 + \alpha^2} \qquad \alpha = \frac{\omega L}{R}$$

Resistive limit:

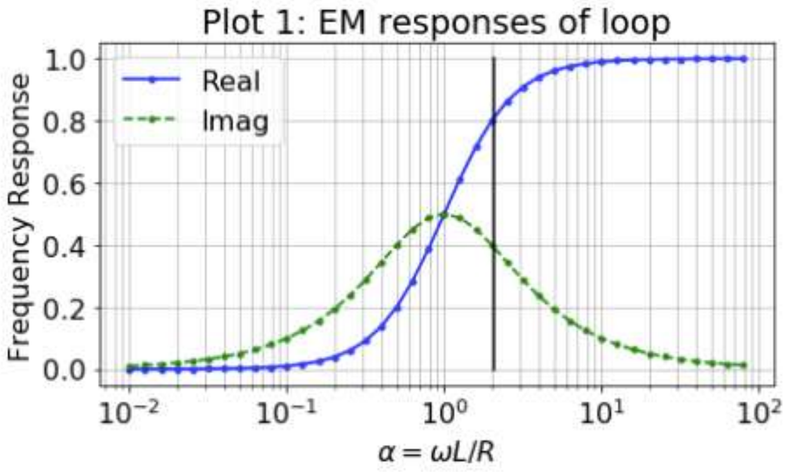
- low frequency
- low conductivity

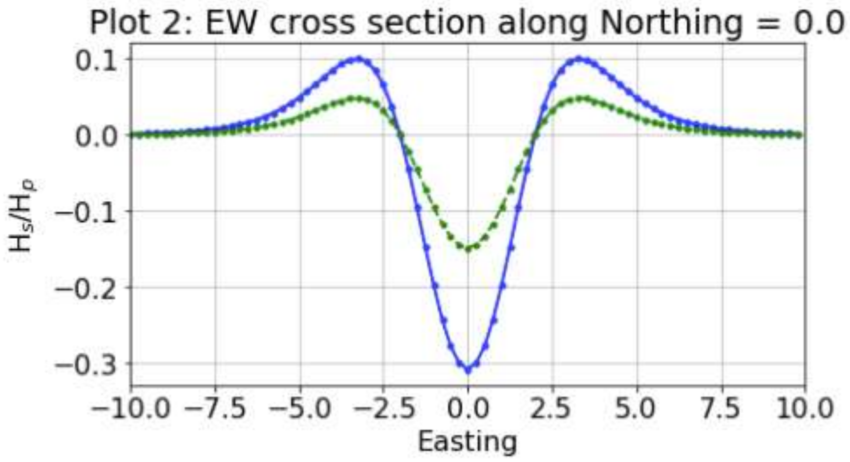



Inductive limit:

- high frequency
- high conductivity

# Expected Data From a Loop Target

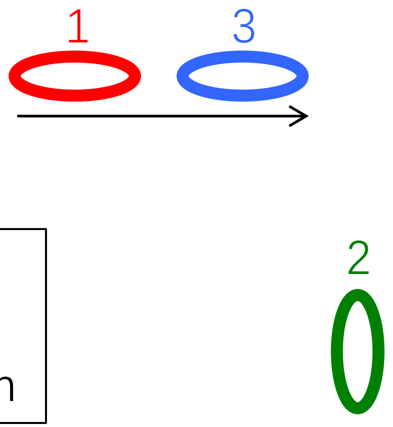



$$\frac{H_3^s}{H_3^p} = -\frac{M_{12}M_{23}}{M_{13}L}\left[\frac{\alpha^2 + i\alpha}{1+\alpha^2}\right]$$

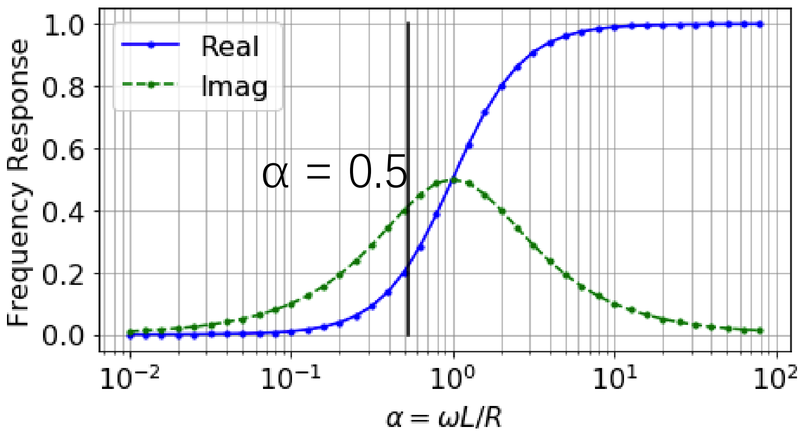
Coupling
- location, orientation
- overall magnitude

Induction
- properties of loop 2
- how much in Re & Im

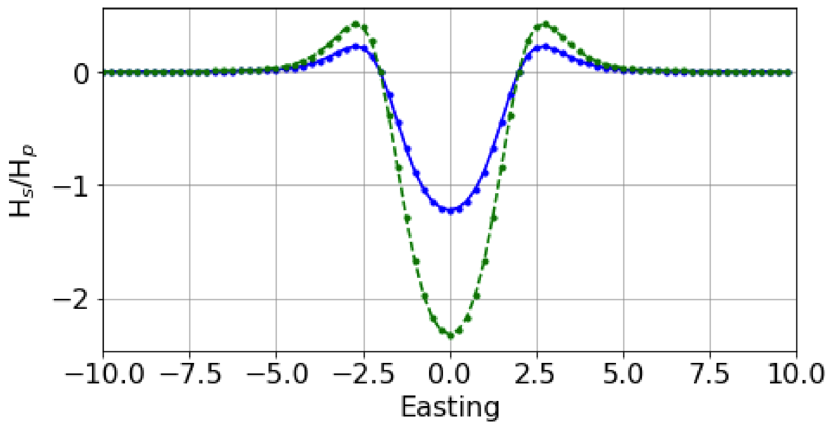


# A Smaller Induction Number

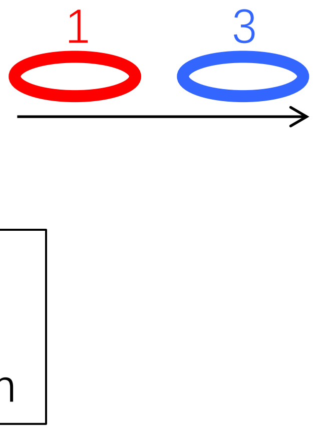
Response function of different α




Data along a profile for α = 0.5




$$\frac{H_3^s}{H_3^p} = -\frac{M_{12}M_{23}}{M_{13}L}\left[\frac{\alpha^2 + i\alpha}{1+\alpha^2}\right]$$

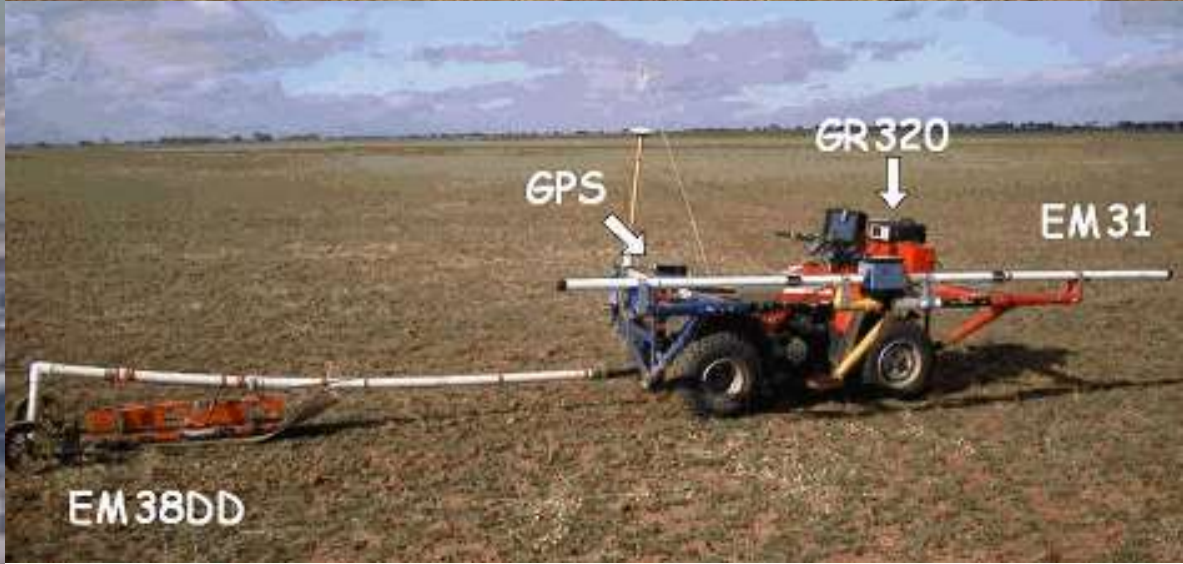



Coupling
- location, orientation
- overall magnitude

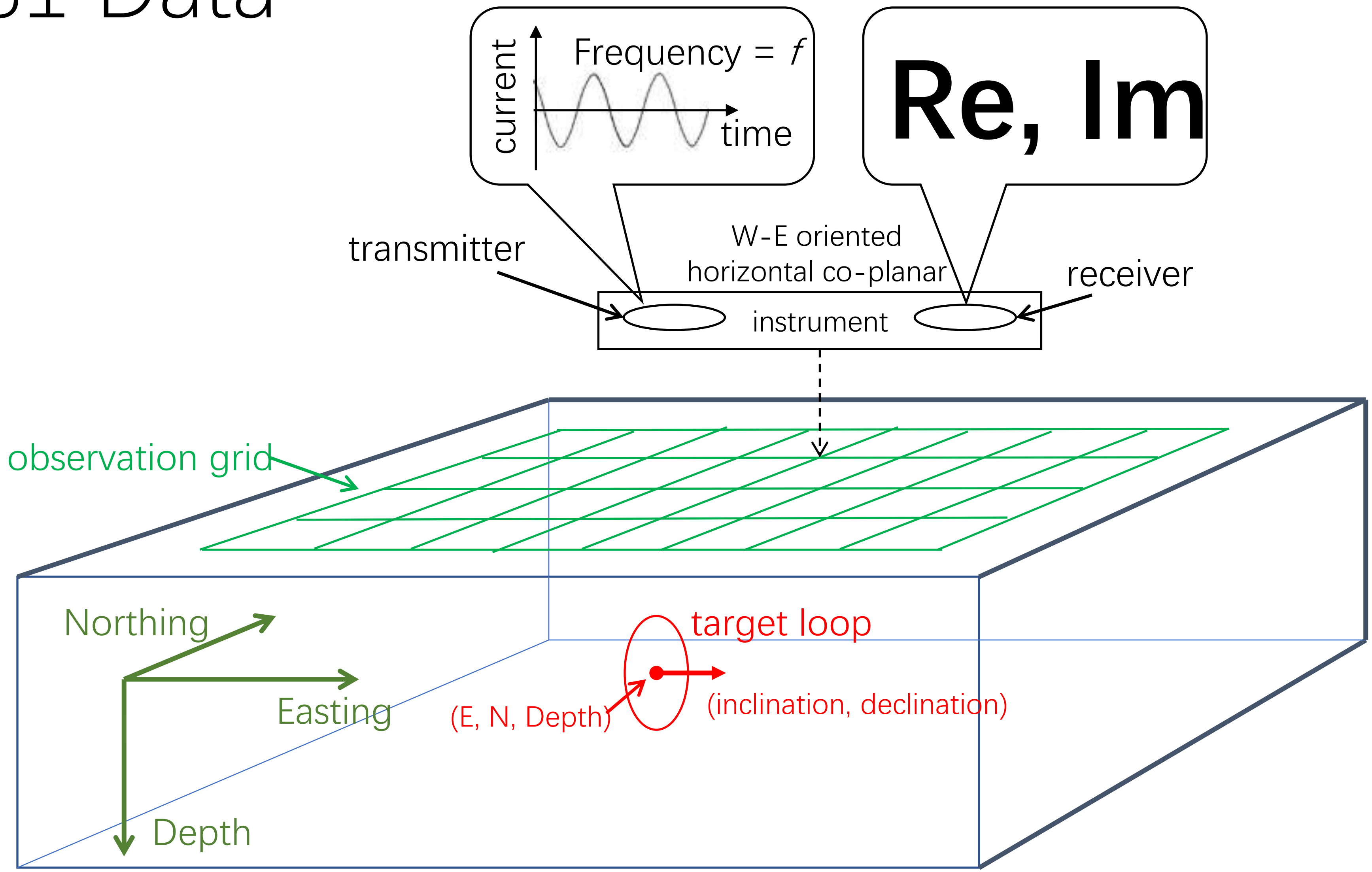
Induction
- properties of loop 2
- how much in Re & Im

# EM-31

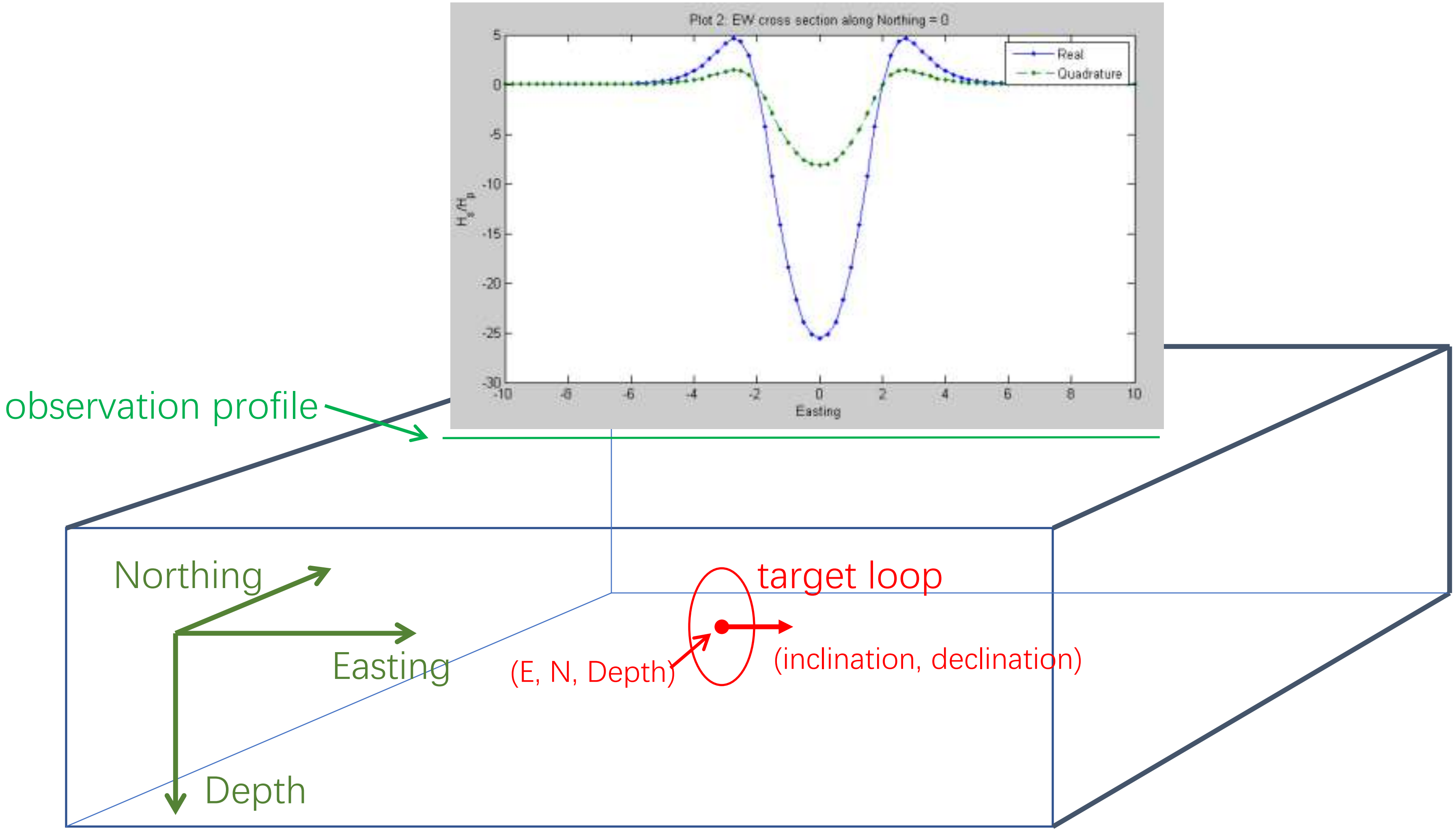
- Frequency = 9.8 kHz
- Tx-Rx spacing = 3.66 m
- Horizontal or vertical coplanar
- “Ground conductivity meter”

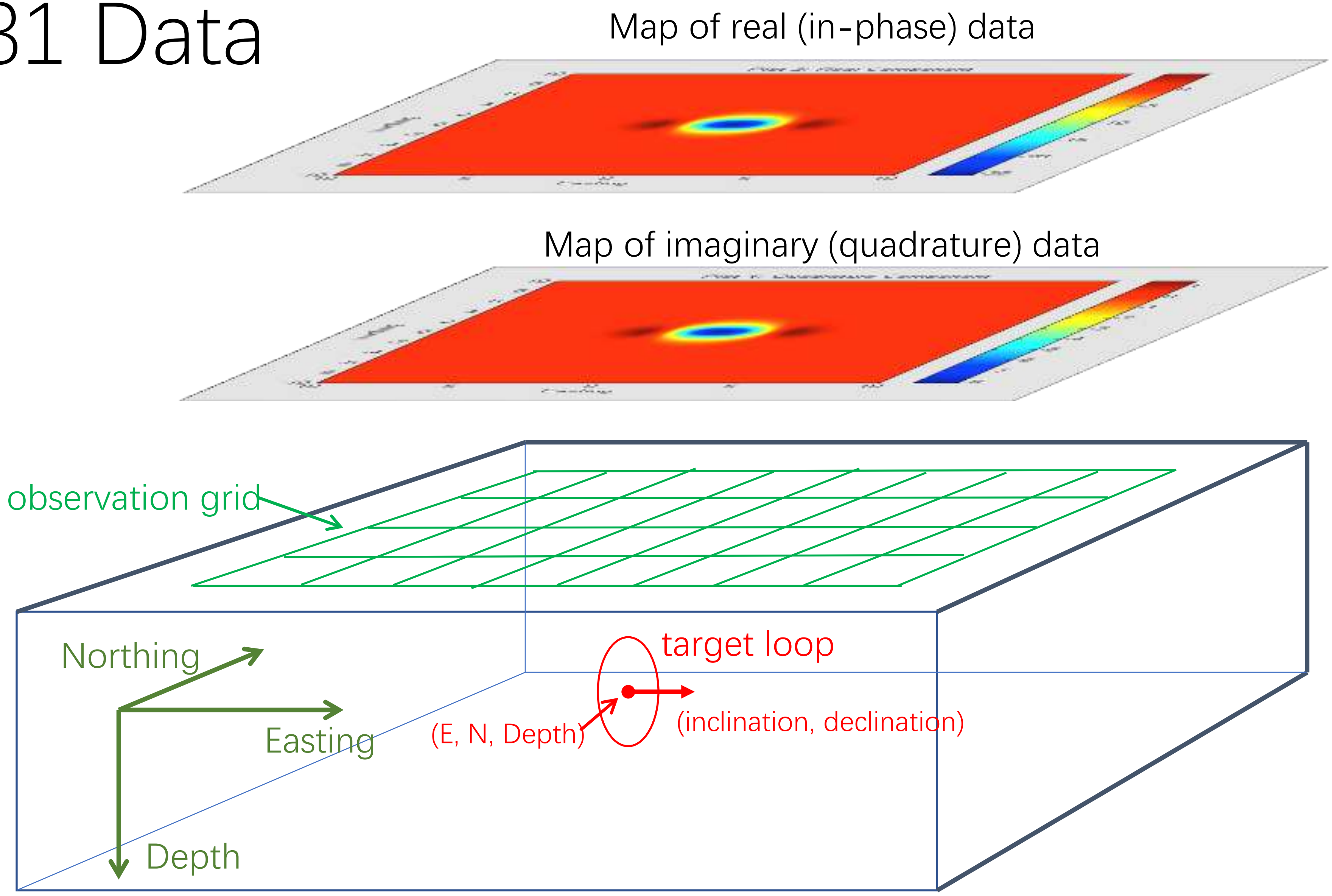
# EM-31 Data


current
Frequency = f
time
Re, Im
transmitter
W-E oriented
horizontal co-planar
receiver
instrument
observation grid
Northing
Easting
Depth
target loop
(E, N, Depth)
(inclination, declination)

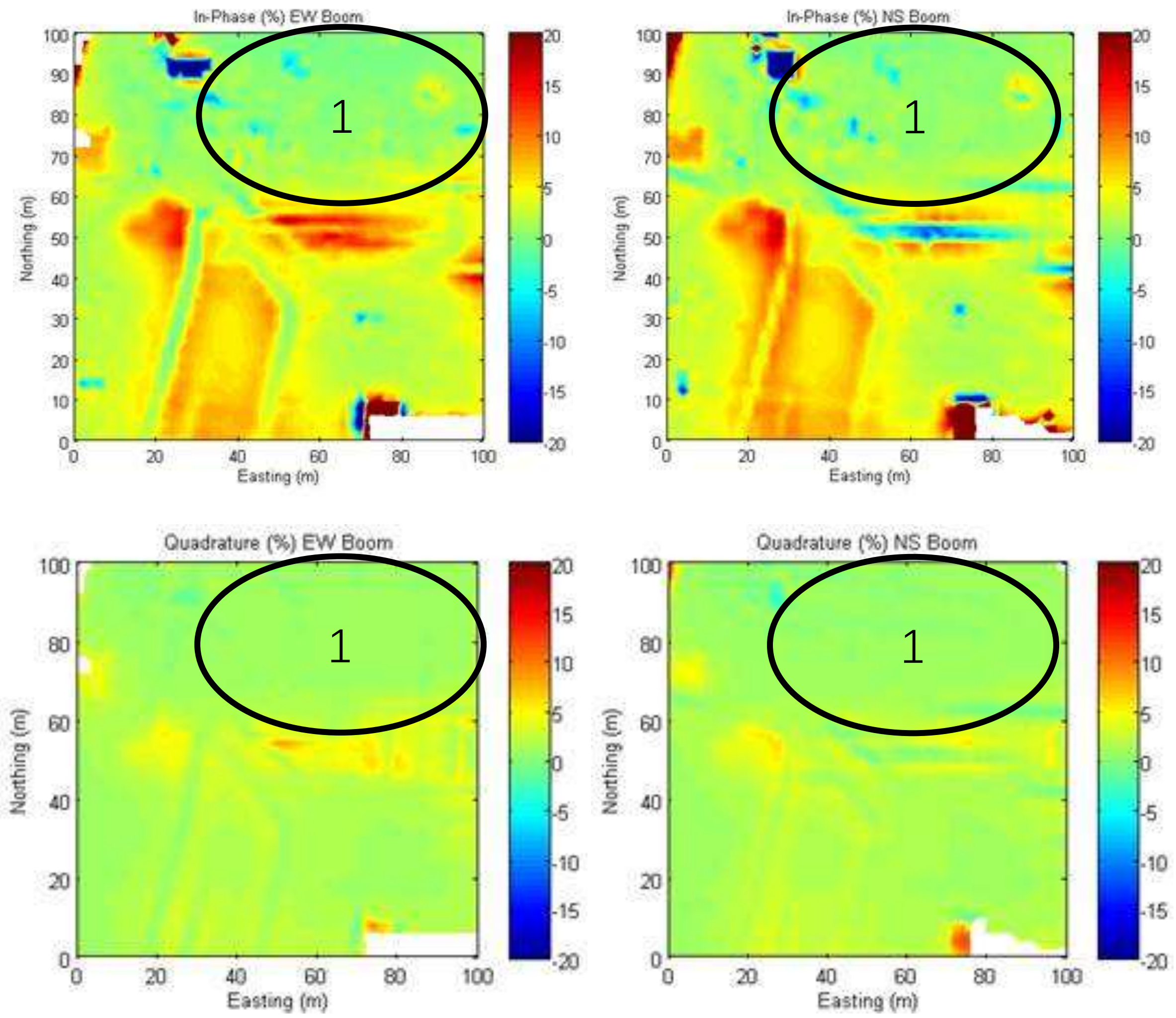
# EM-31 Data


Plot 2: EW cross section along Northing = 0
Real
Quadrature
$H_s/H_p$
Easting
observation profile
Northing
Easting
Depth
target loop
(E, N, Depth)
(inclination, declination)

# EM-31 Data

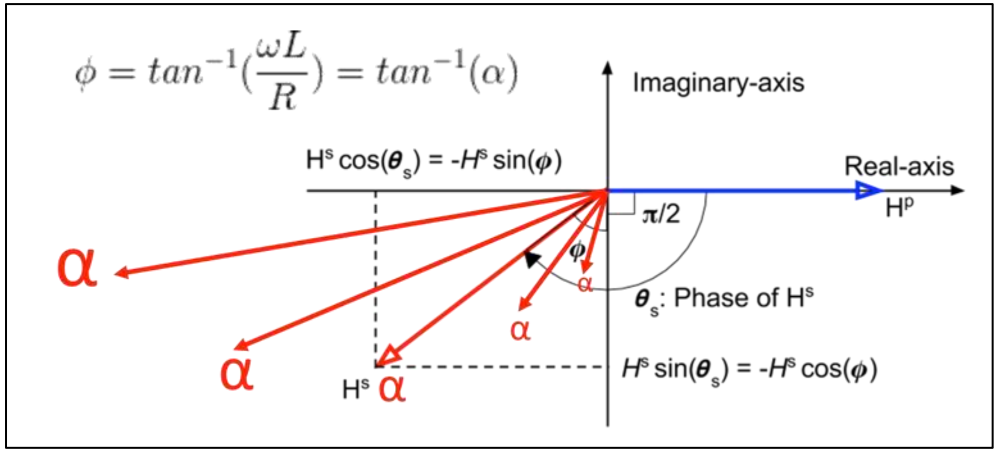

Map of real (in-phase) data
Map of imaginary (quadrature) data
observation grid
Northing
Easting
Depth
target loop
(E, N, Depth)
(inclination, declination)

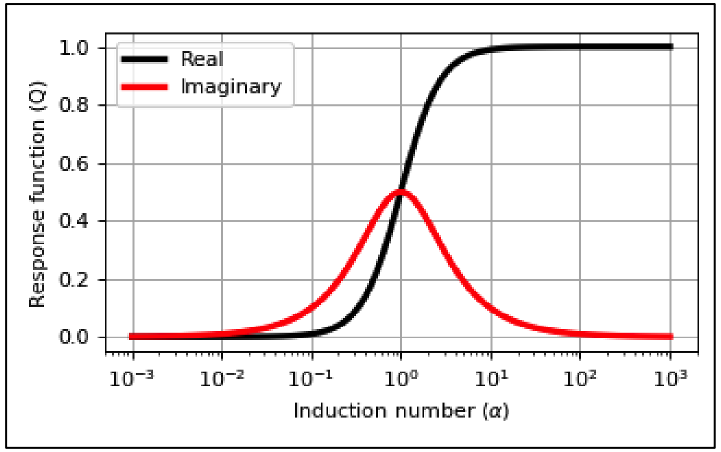
# EM-31 Field Data




**Data Feature 1**:
Uniform, smooth and small

# EM-31 Data at Low Induction



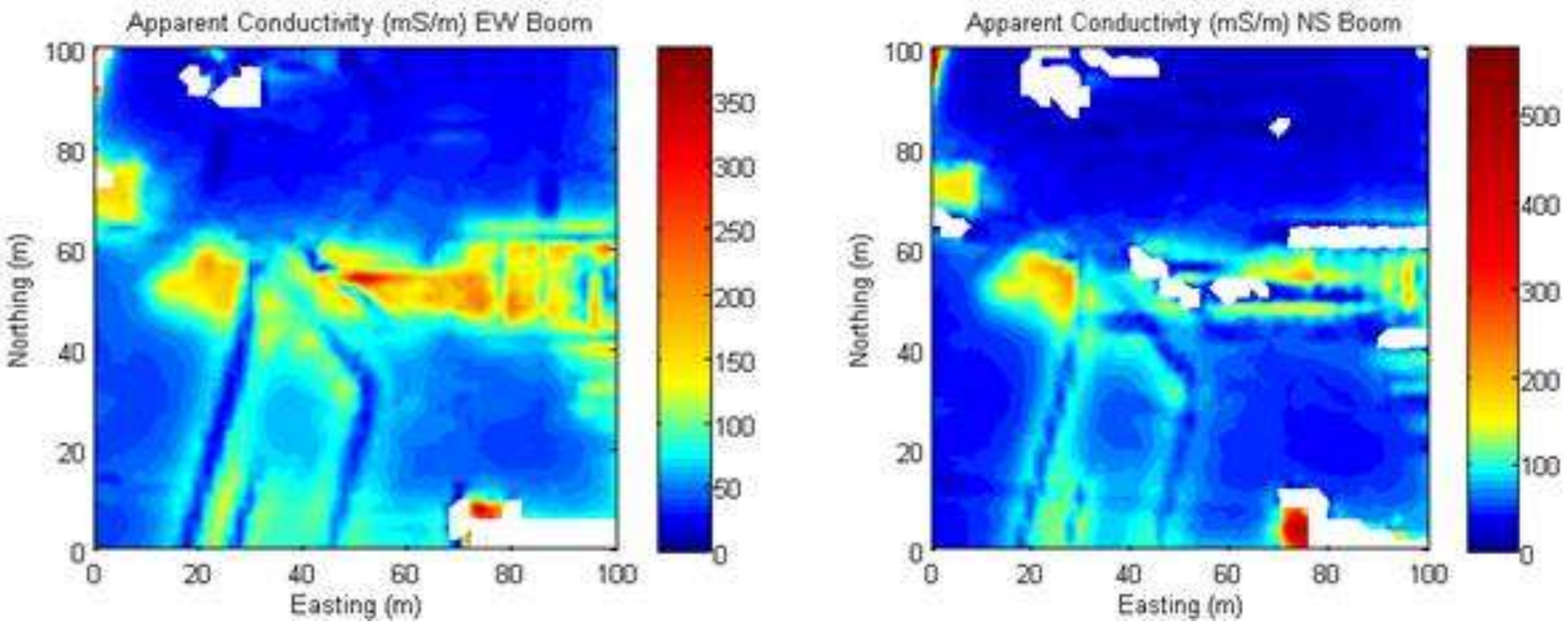

Small **Re** and small **Im** on the data maps, **α** big or small?

Low induction number:

- **$H^s$** data mostly in quadrature, **Im** > **Re** ≈ 0
- Very small induced current
- Subdivide the earth into many pieces; each piece interacts with Tx-Rx independently without interaction between any two pieces (**recall low induced magnetization in magnetics, easy calculation using superposition!**)

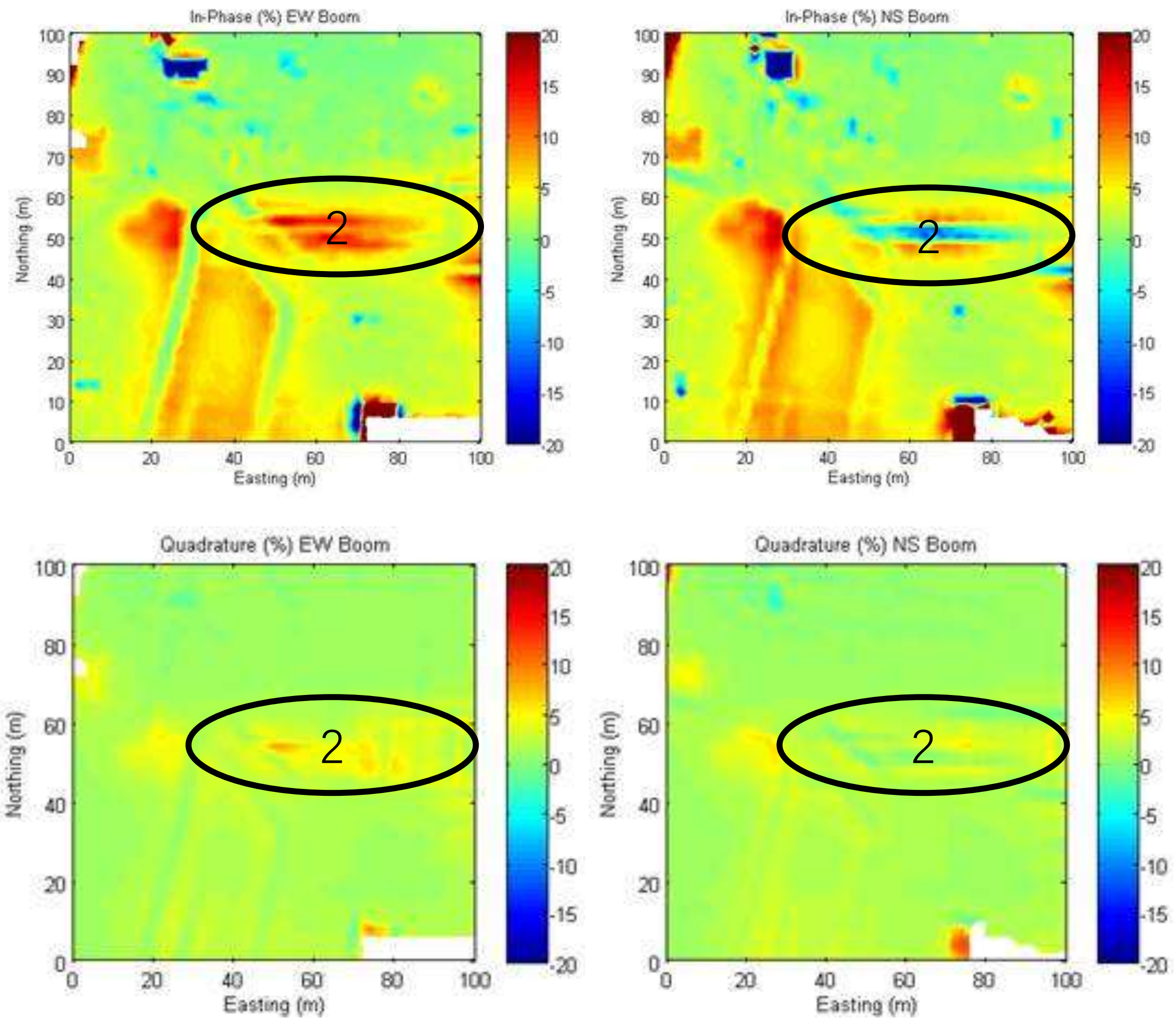
# Apparent Conductivity

$$\sigma_a = \frac{4}{\omega \mu_0 s^2} \mathbf{Im}$$




**Question**: Which area on the maps is the most likely to have a reliable estimate of the ground conductivity?

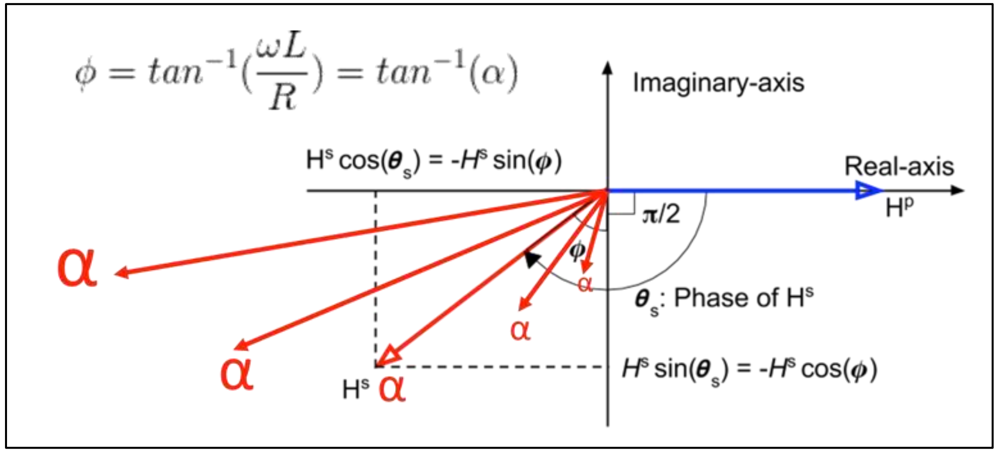
# EM-31 Data Interpretation

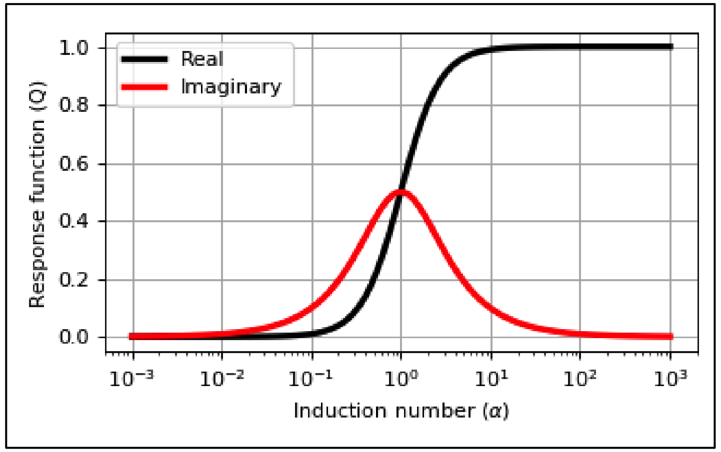



**Data Feature 1**:
Uniform, smooth and small

**Data Feature 2**:
Abrupt change
Positive and negative
Large **Re** and small **Im**

# EM-31 Data at High Induction

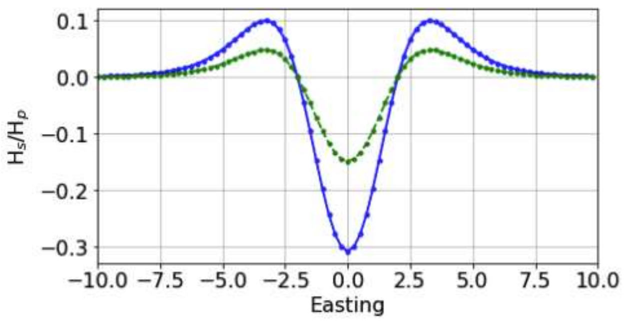


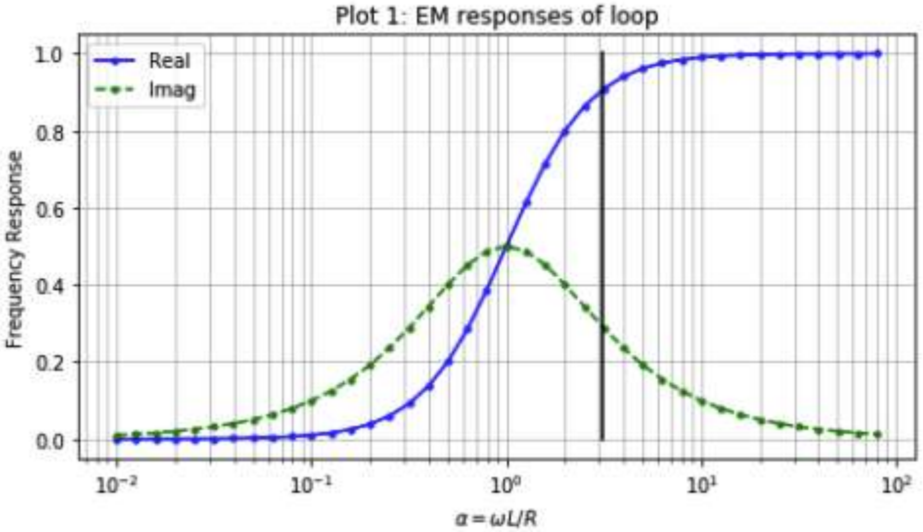

Large **Re** and small **Im** on the data maps, **α** big or small?

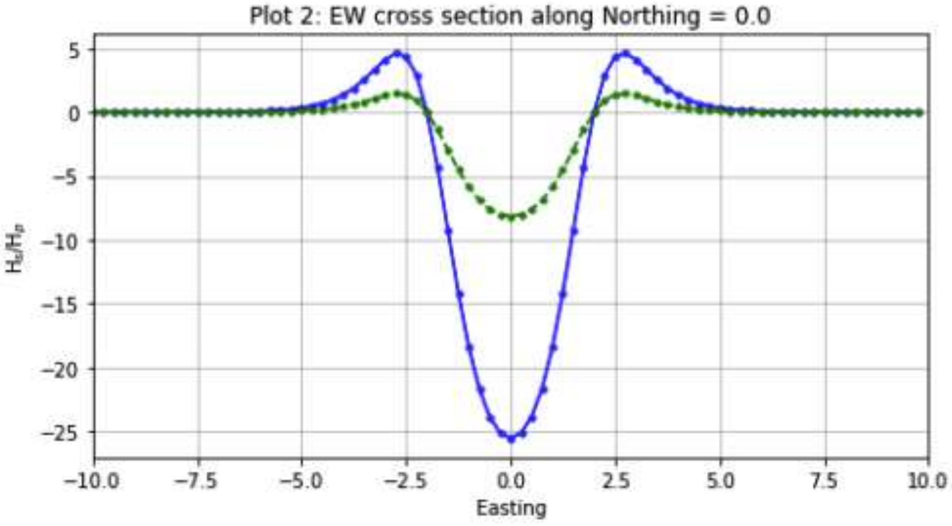
High induction number:

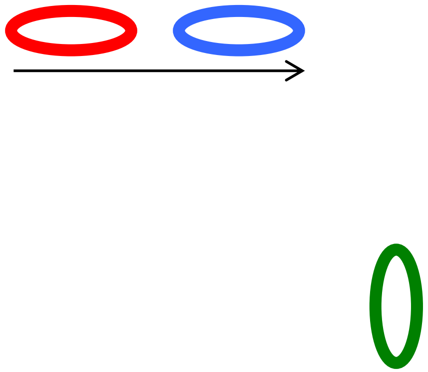
- **$H^s$** data mostly in in-phase, **Re** > **Im** ≈ 0
- Very strong induced current
- Cannot use apparent conductivity, but if the target is a good compact conductor, use the 3-loop model



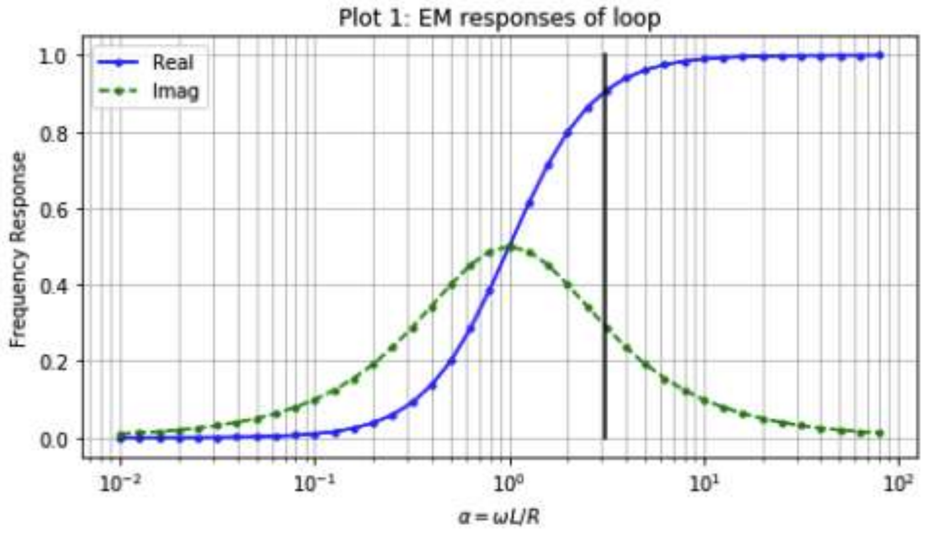
# Vertical Target Loop

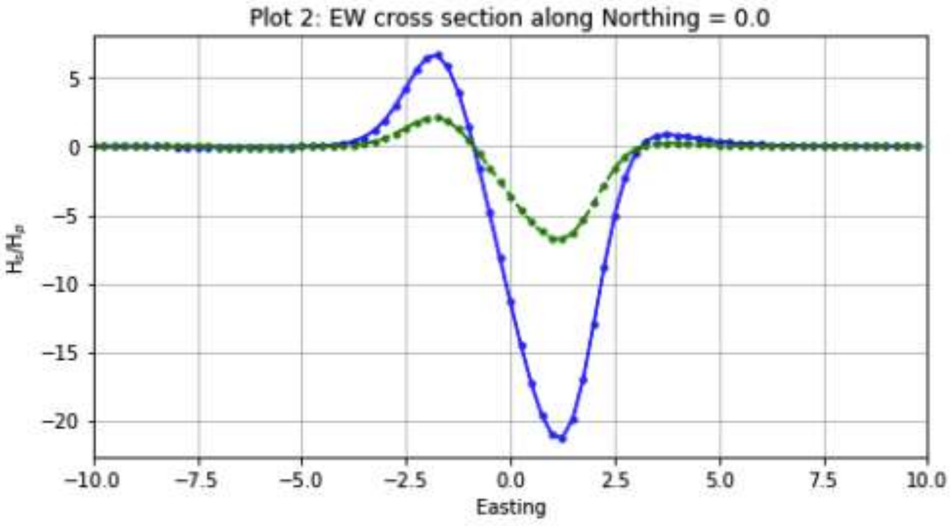


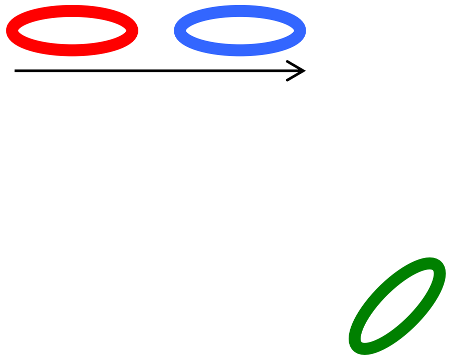



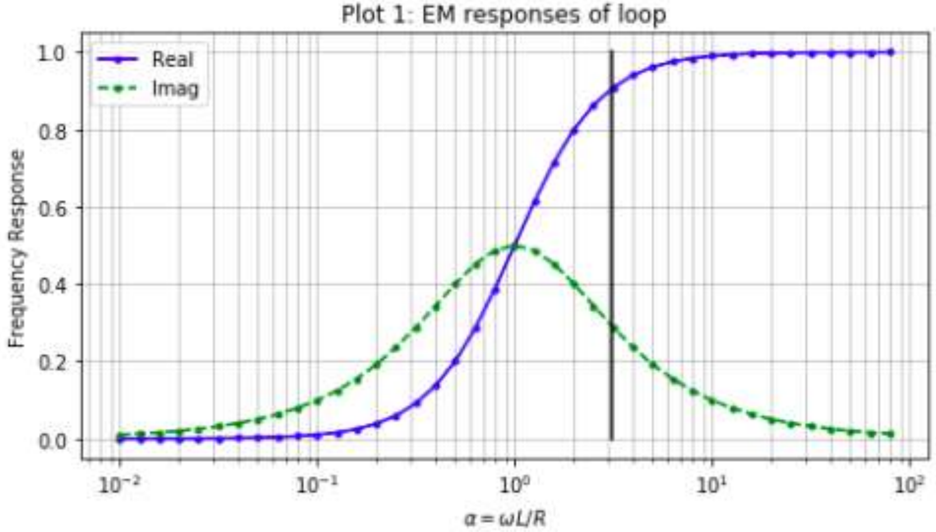
# 45 Degree Dipping Target Loop

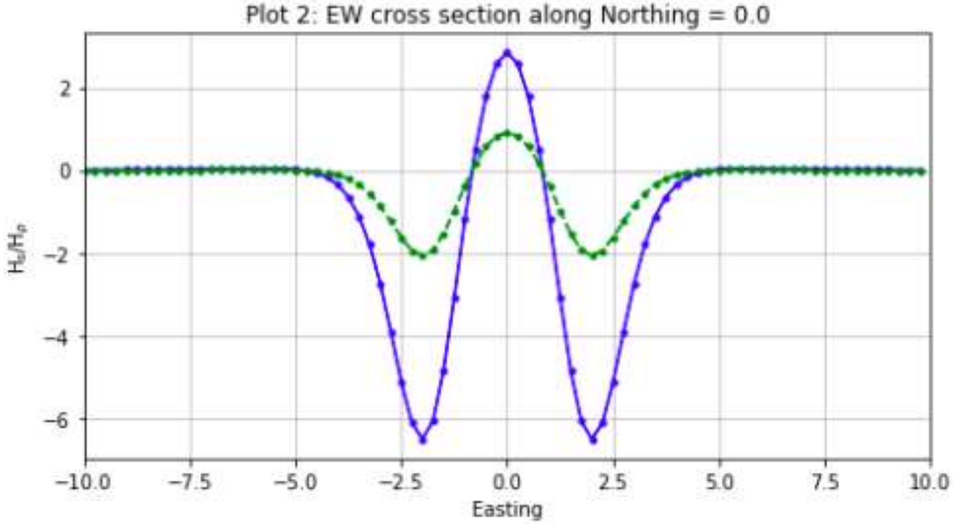


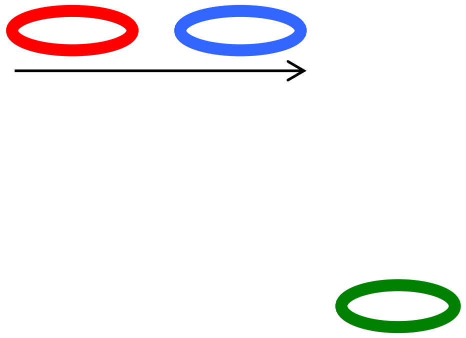



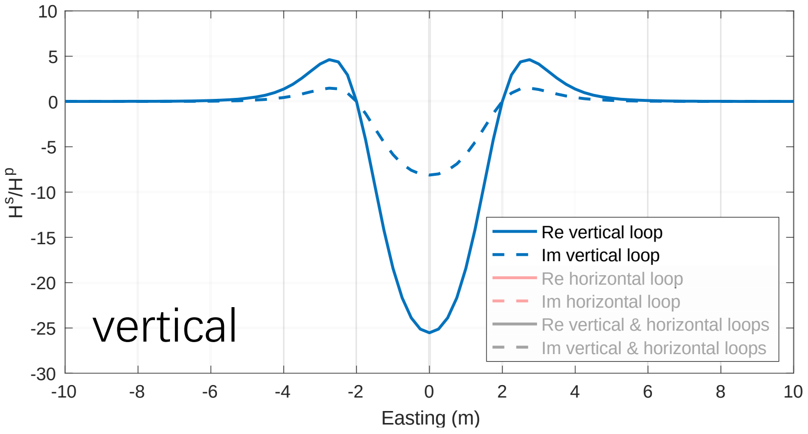
# Horizontal Target Loop

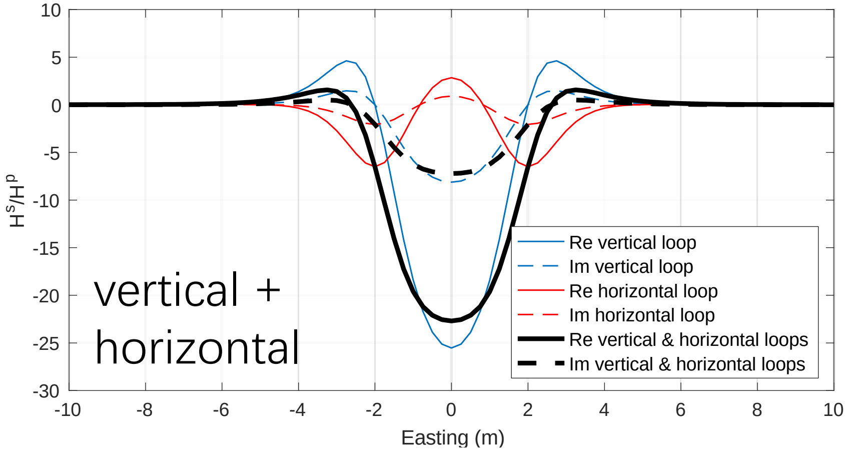


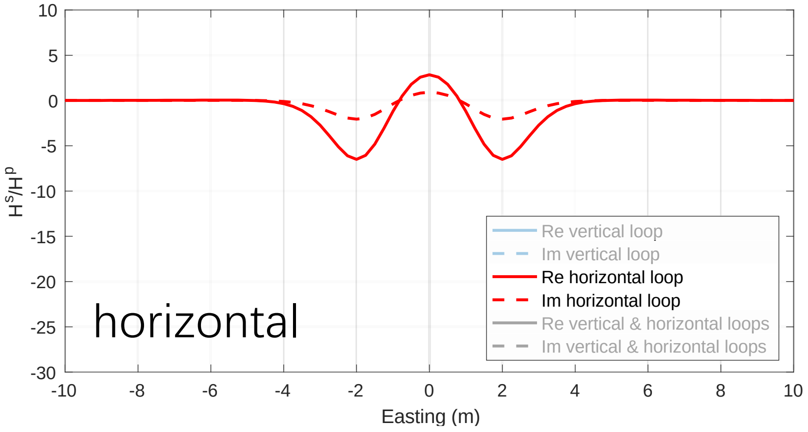



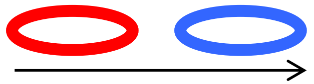



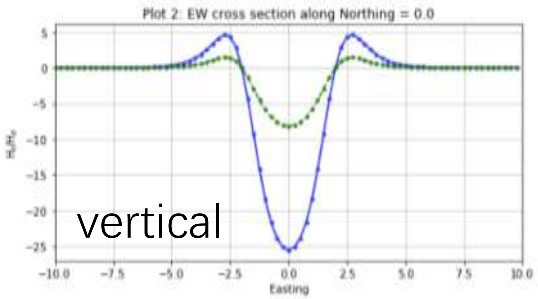
# Equiaxed Target

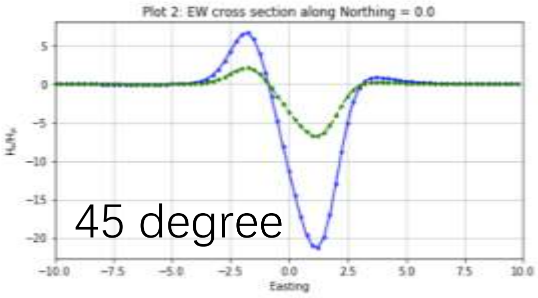


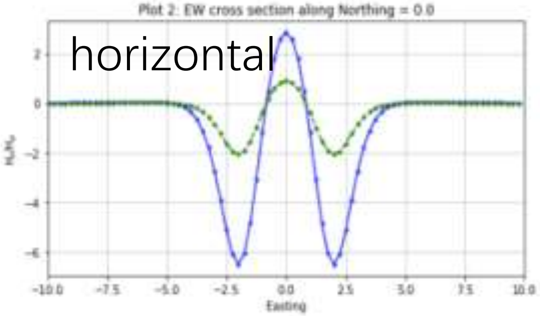



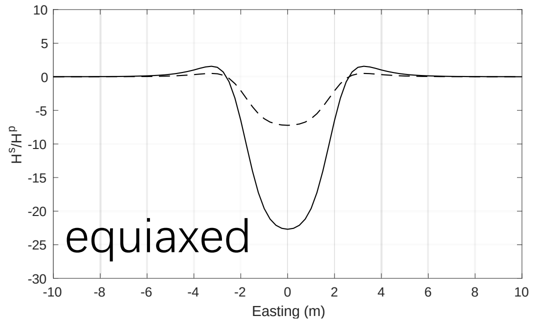



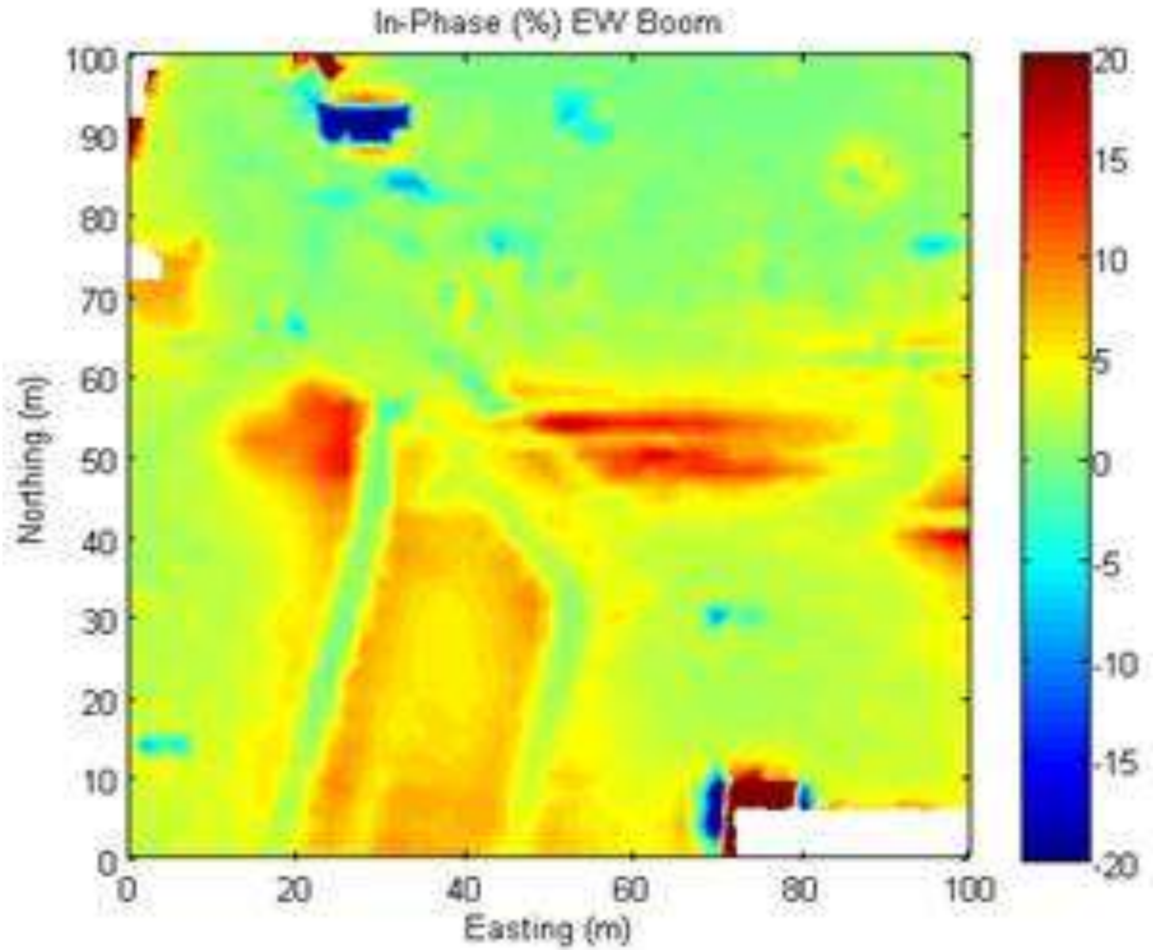





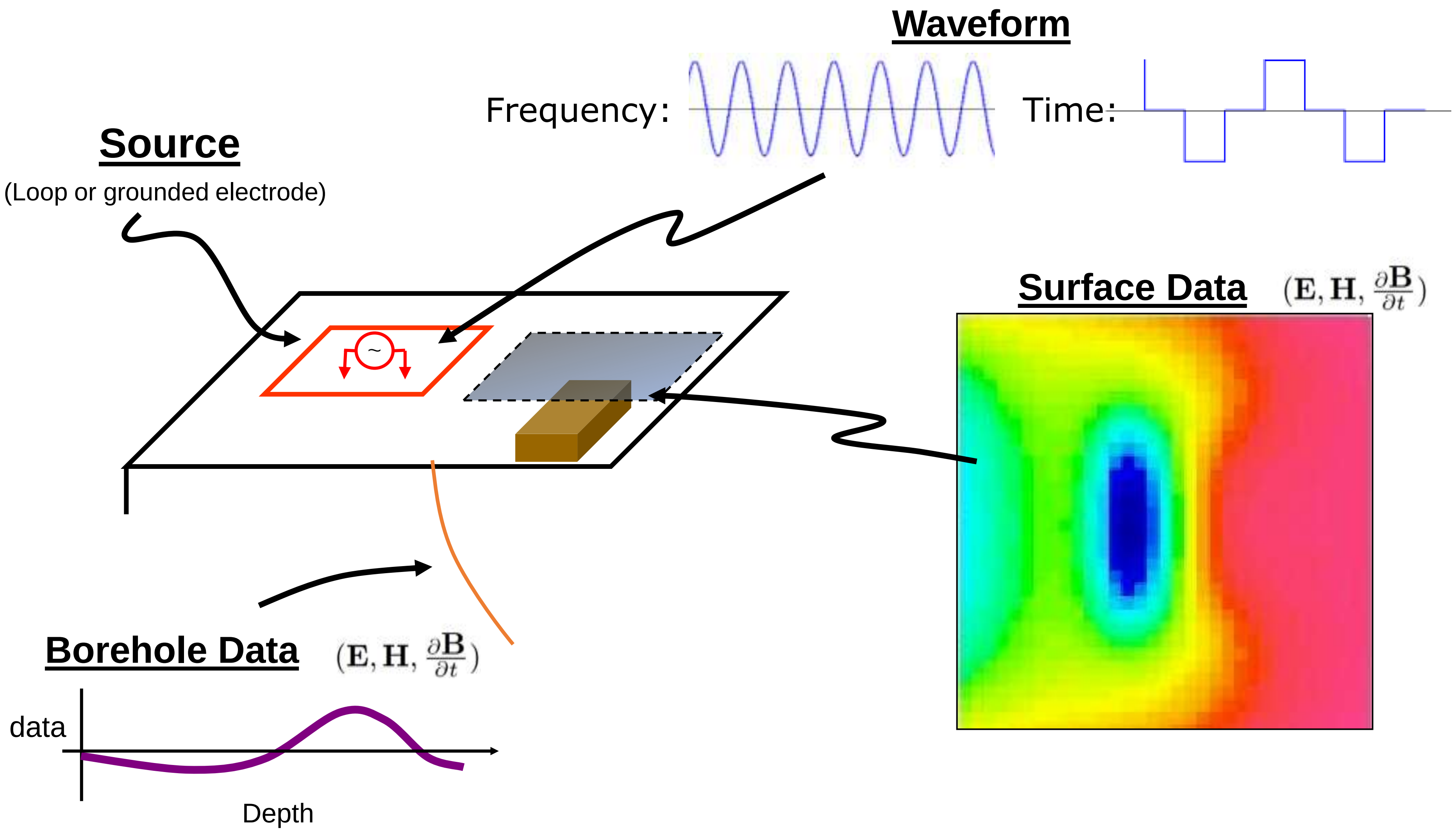




**Question**: Can you find those features on the data map and infer the geometry and orientations of the targets?

# Summary

- EM induction: Quasi-static
- Loop-loop system in FD: Three loop model
  - Ampere's Law and Faraday's Law
  - Coupling
  - Induction number and response function
- EM-31 as an example
  - Positive or negative?
  - Compare in-phase with quadrature

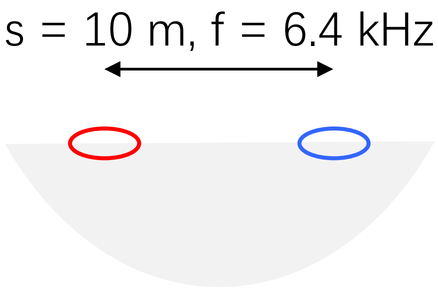
# EM Surveys


Waveform
Frequency:
Time:
Source
(Loop or grounded electrode)
Surface Data $(\mathbf{E}, \mathbf{H}, \frac{\partial \mathbf{B}}{\partial t})$
Borehole Data $(\mathbf{E}, \mathbf{H}, \frac{\partial \mathbf{B}}{\partial t})$
data
Depth

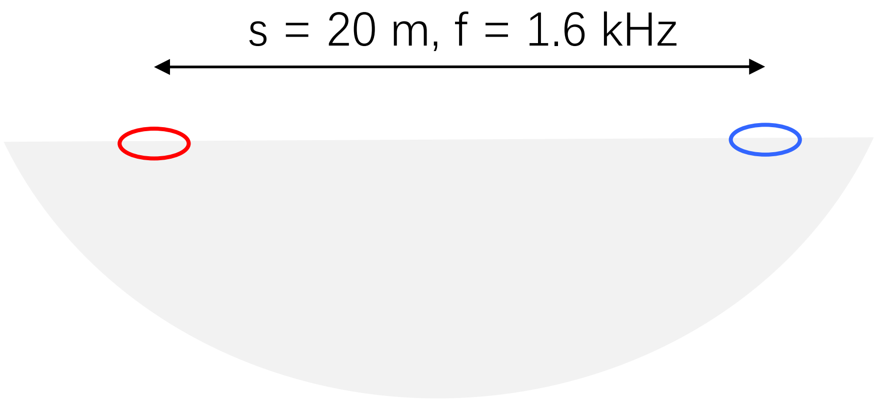
# EM Surveys

- Type of source: magnetic dipole, electric dipole, plane wave (natural source)
- Frequency or time domain
- Source waveform: harmonics,  square wave, pulse wave
- Operating frequencies or time channels
- Data: complex or real

# EM-41

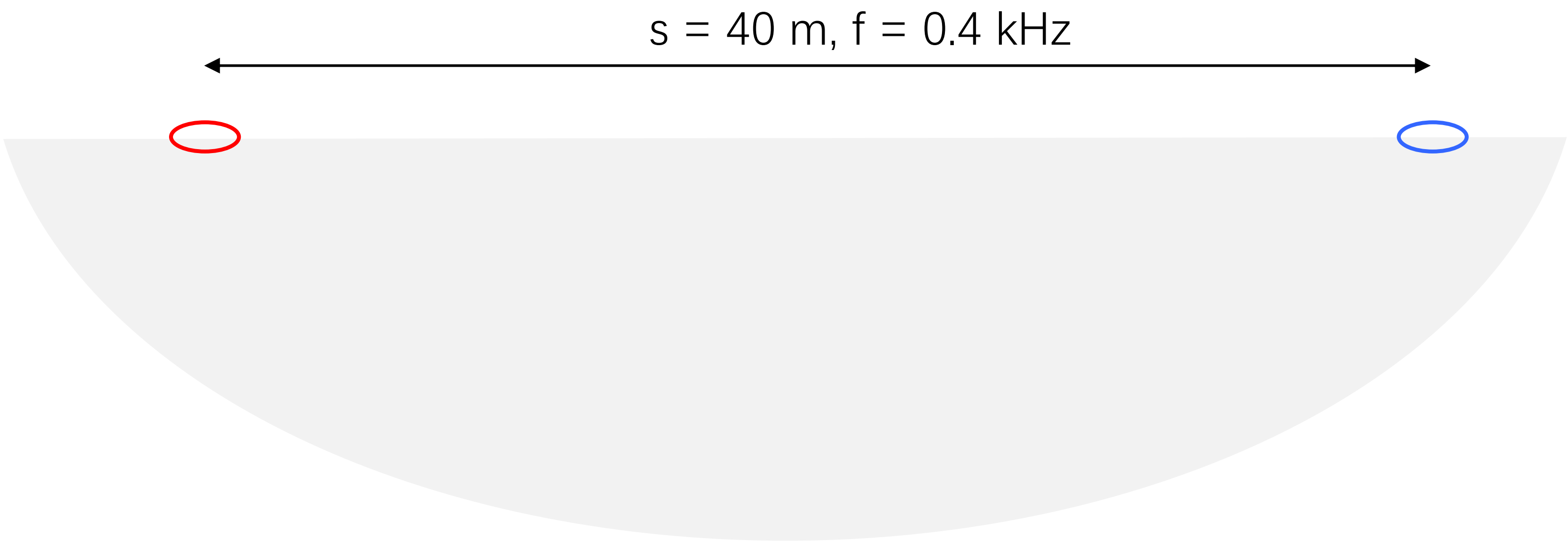


# EM-41



# EM-41

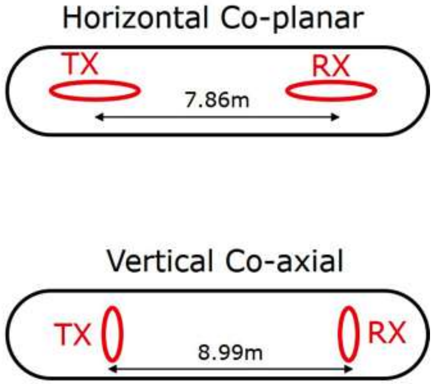
- Variable depth of exploration down to 60 m
- HCP or VCP coil configuration
- Groundwater exploration in fractured and faulted bedrock

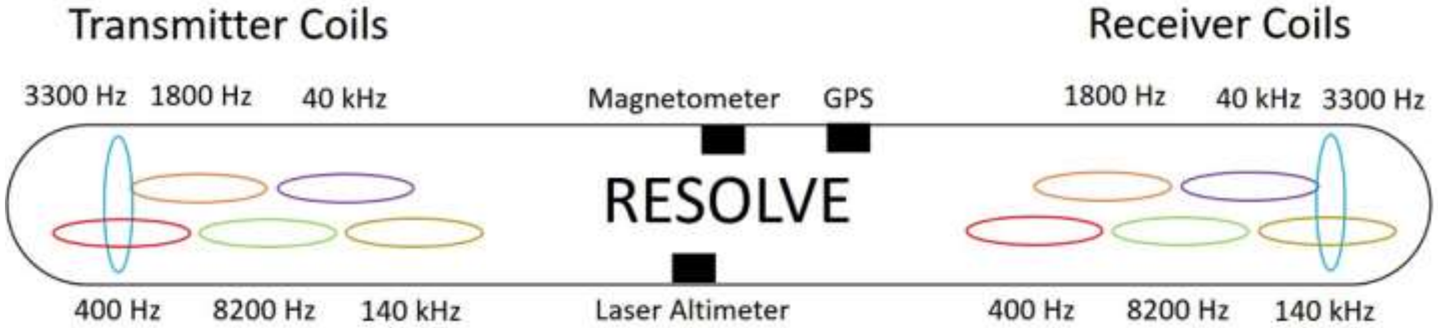


# GEM3


- Concentric Tx-Rx
- Frequency 60 Hz to 24 kHz
- Identify an object based on its spectral fingerprints

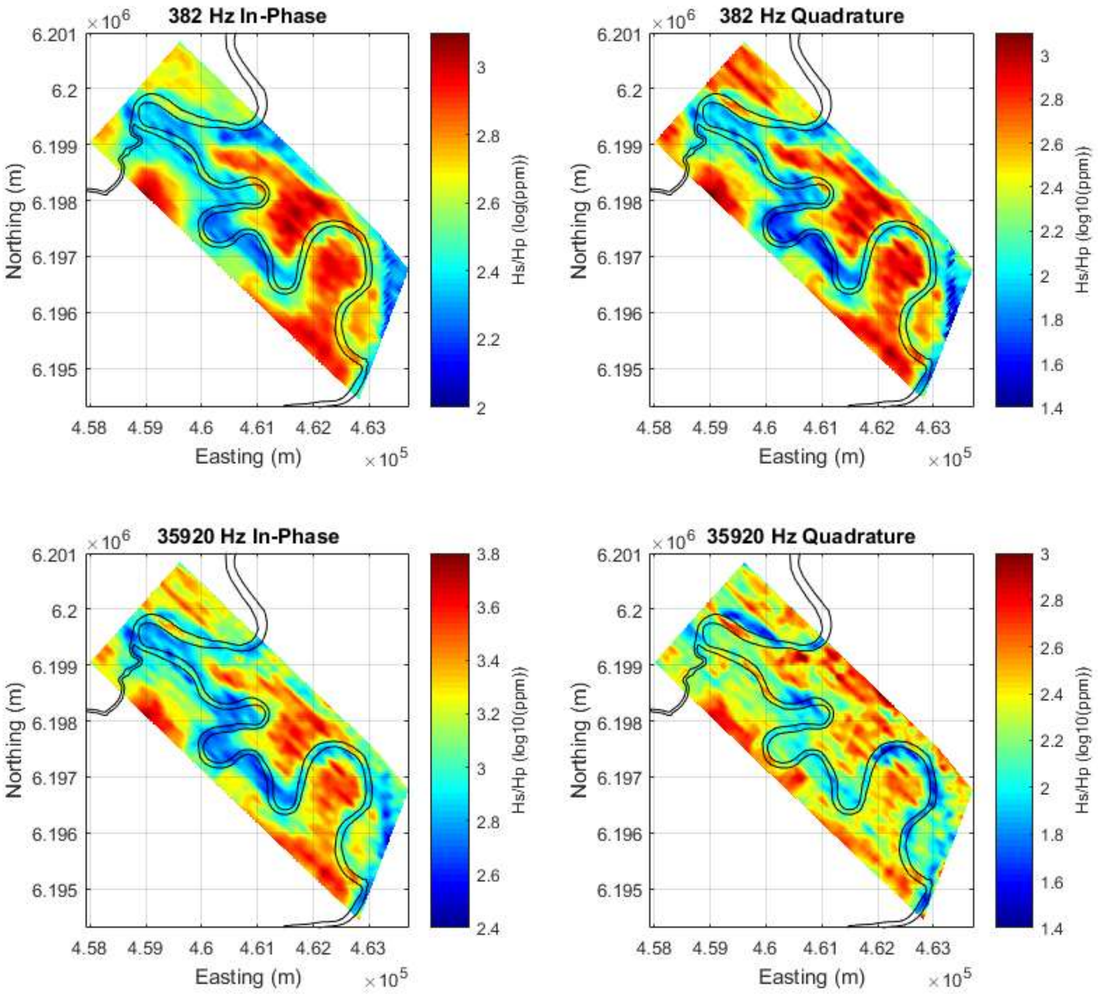
# Airborne EM

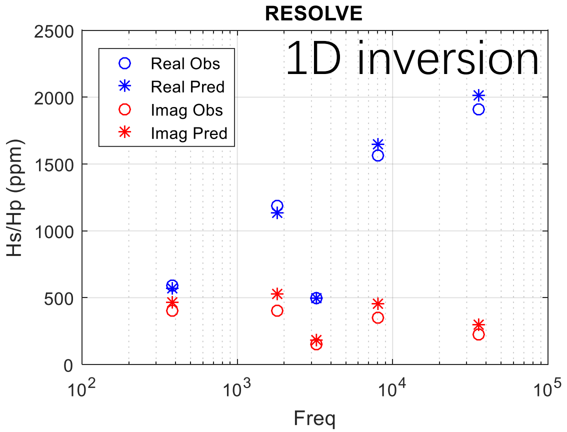



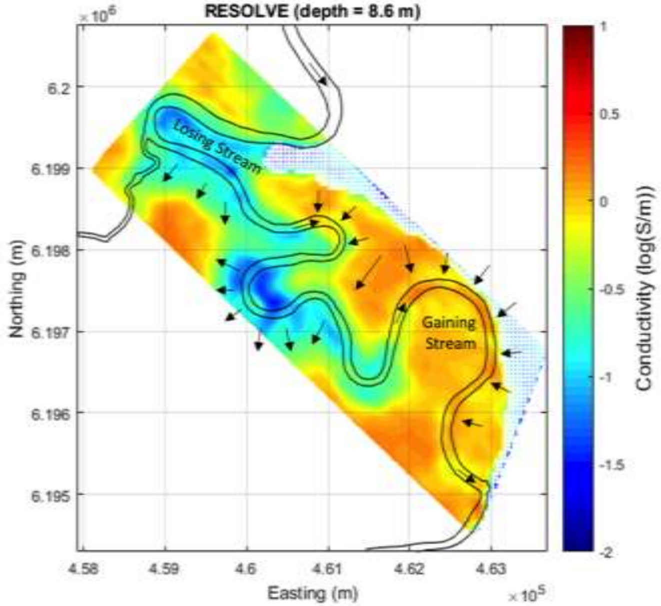




Skin depth: High frequency for shallow; low frequency for deep

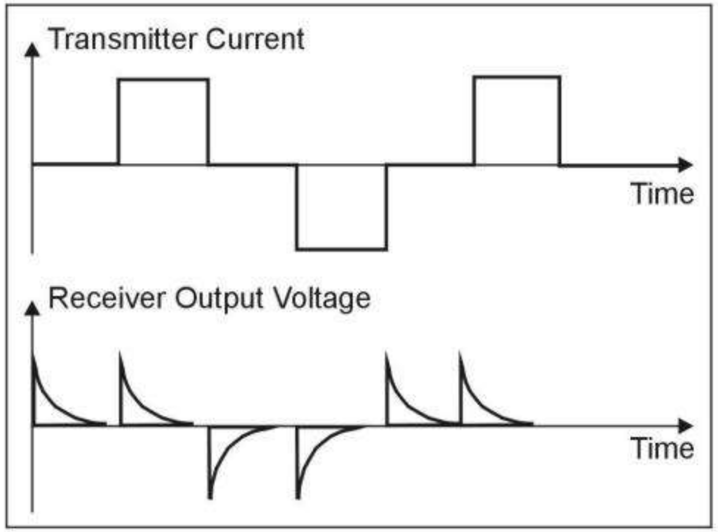
# Airborne EM – Groundwater Flow

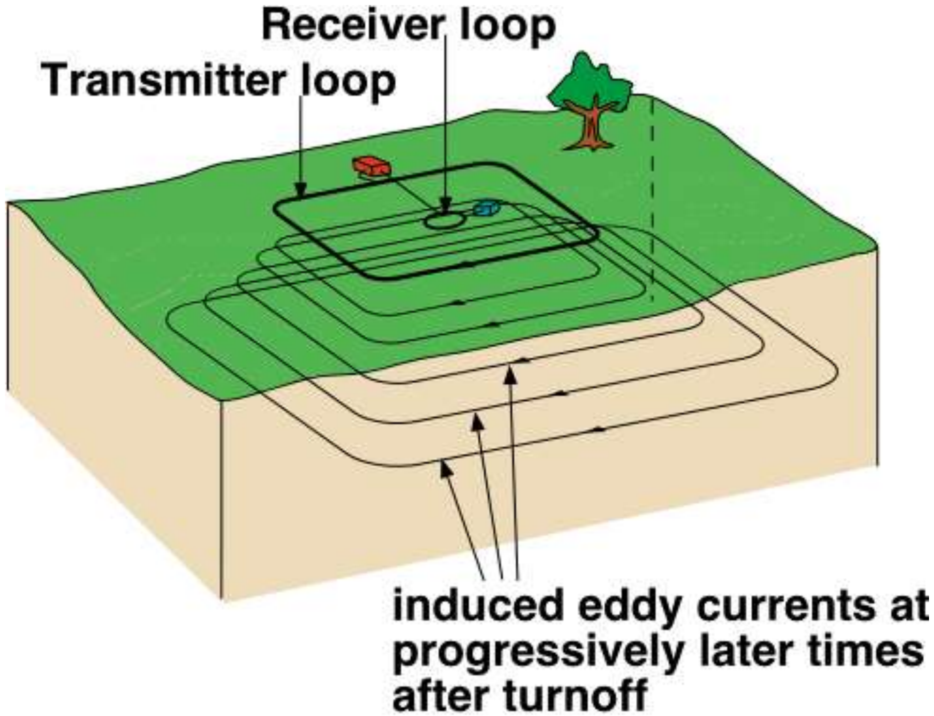


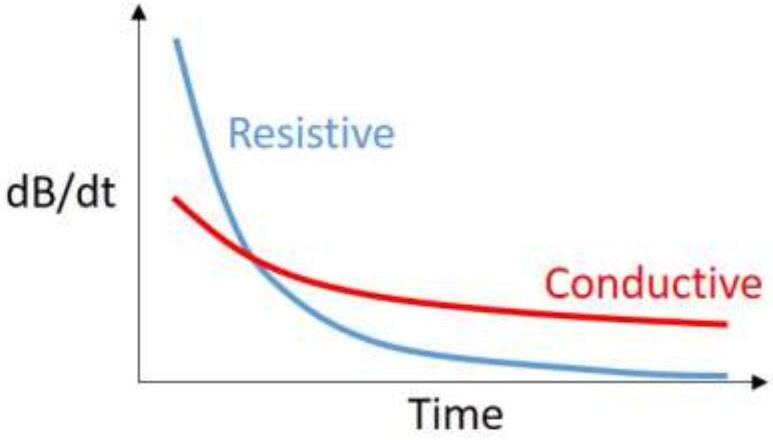



# Time-domain (Transient) EM

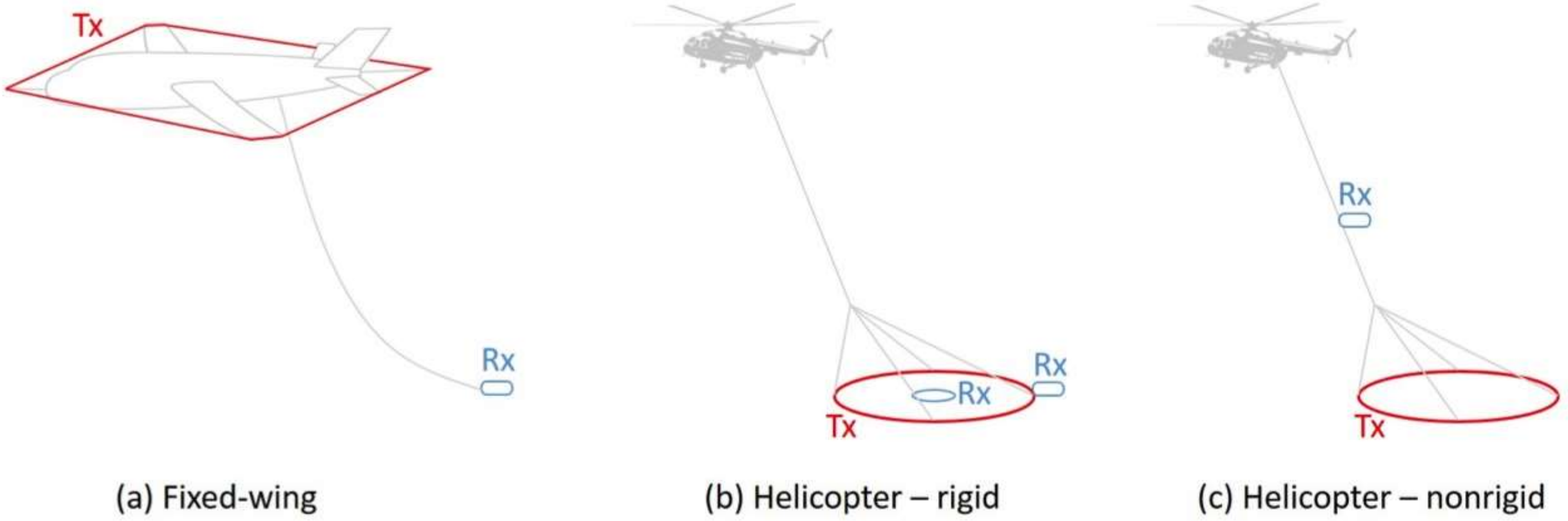


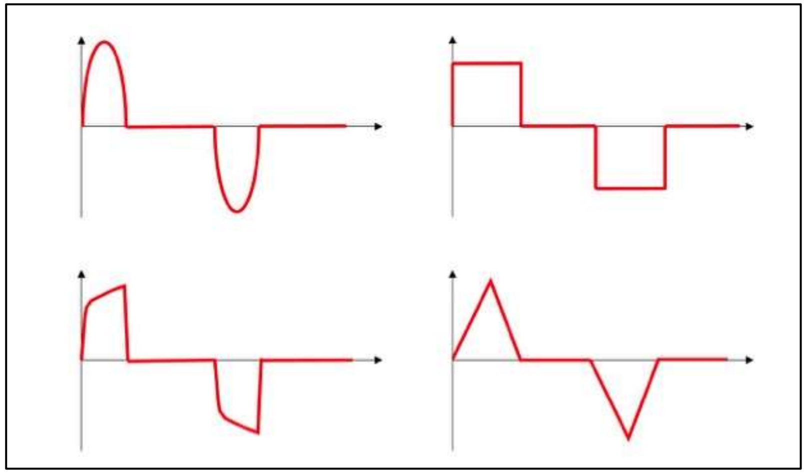




- Wider frequency bandwidth
- Deeper penetration
- Time channel: early for shallow, late for deep

# Airborne Time-domain EM (TEM)

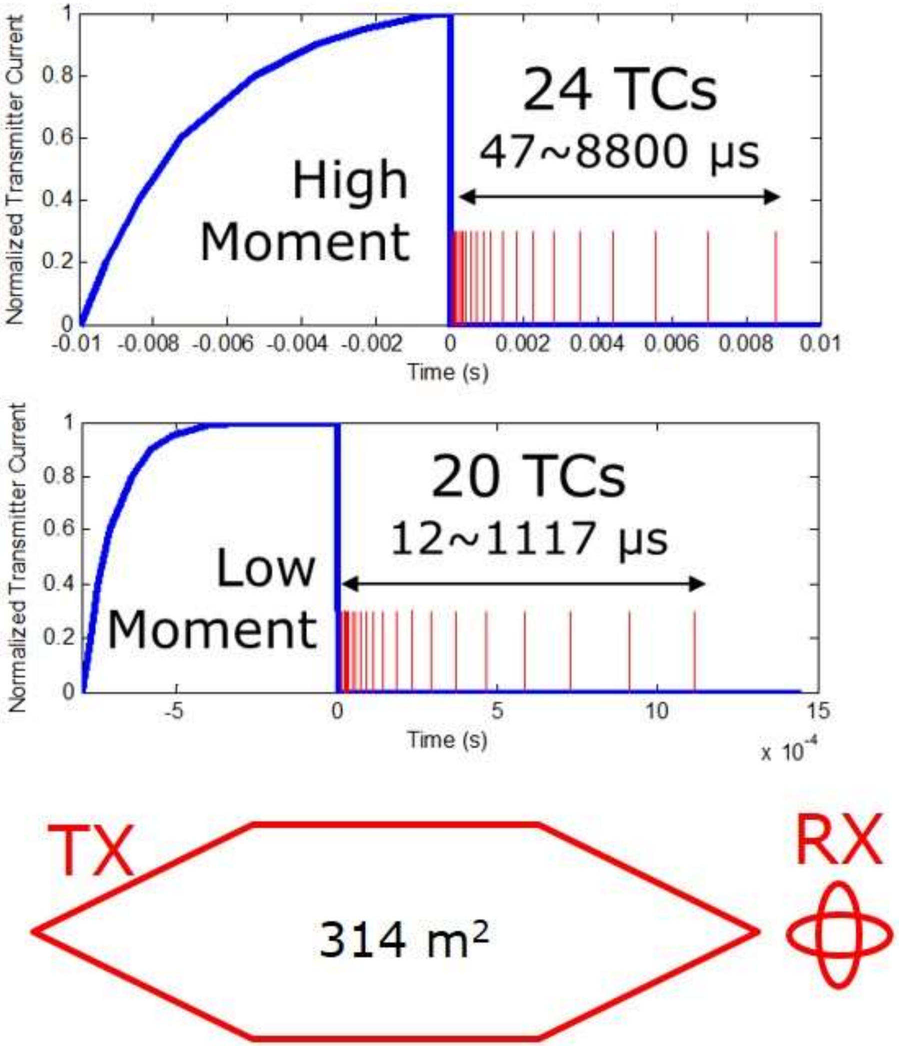



- Magnetic dipole Tx and Rx
- High efficiency
- Sensitive to conductors (water, minerals)
- Adjustable source moment
- Waveforms

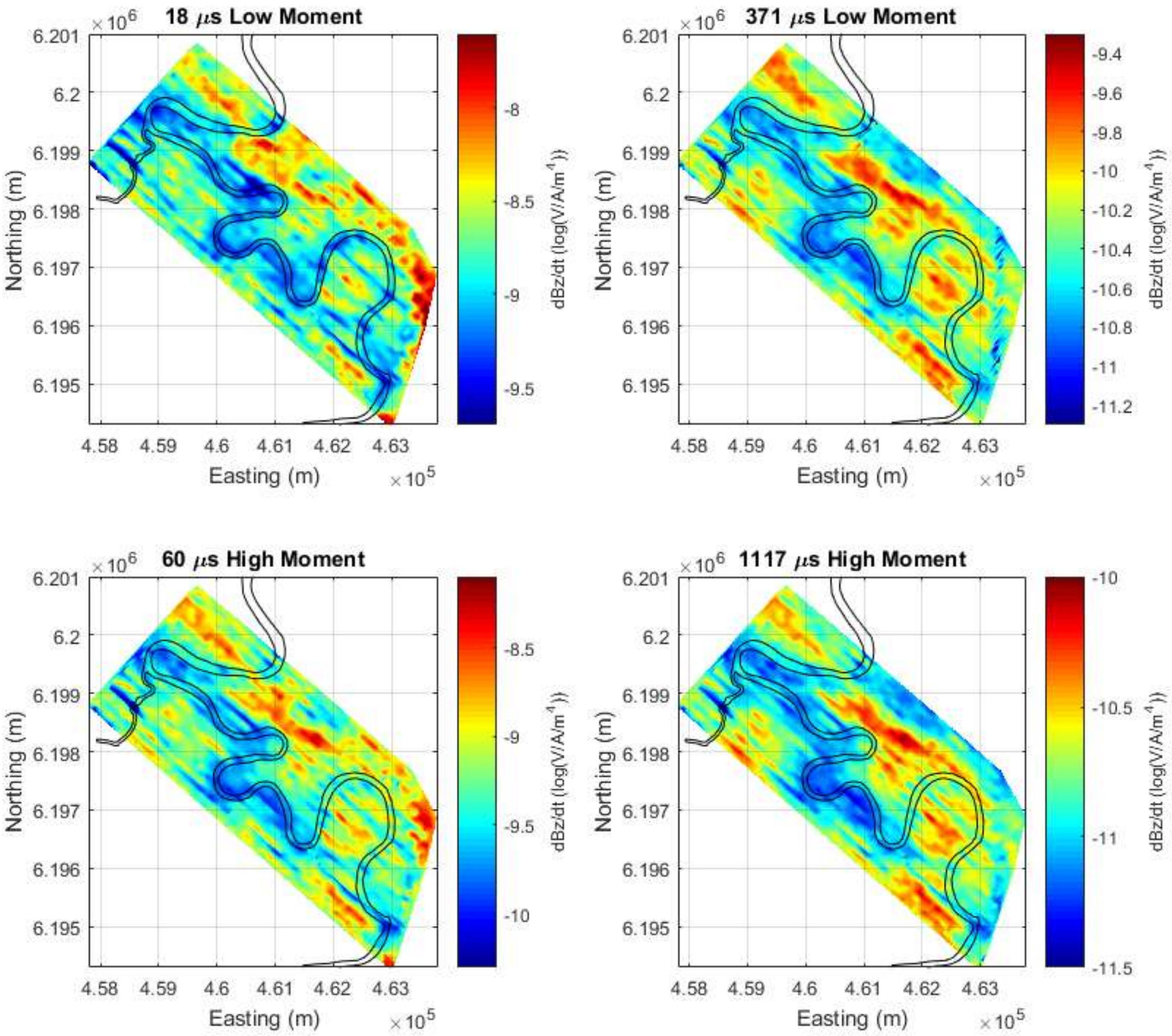


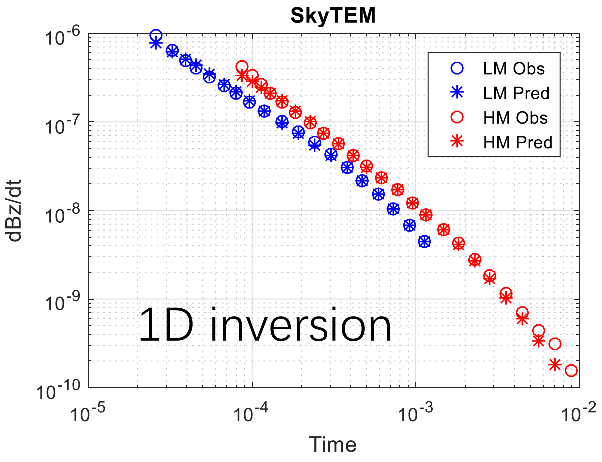
# ATEM - SkyTEM

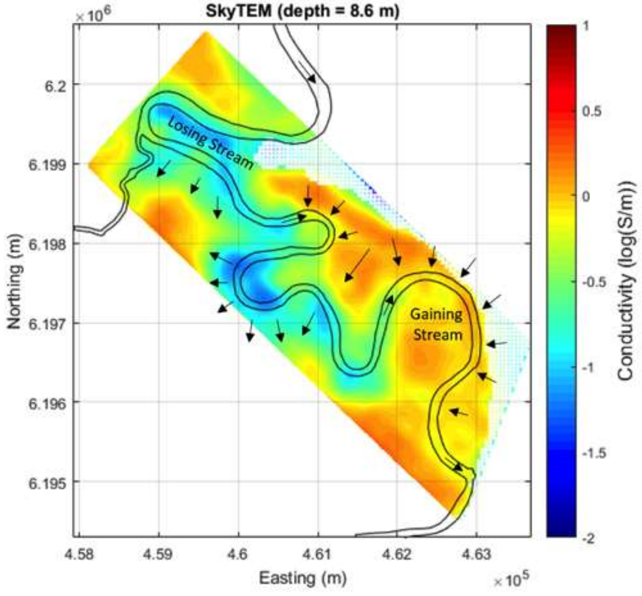

SkyTEM 2006

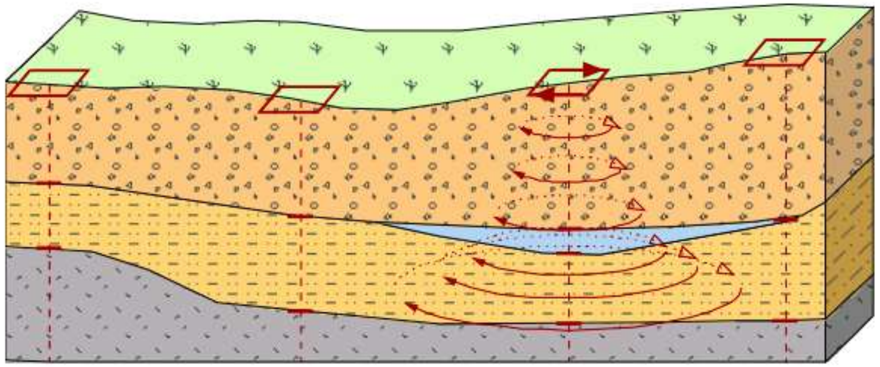

Normalized Transmitter Current
24 TCs
47~8800 μs
High
Moment
Time (s)
20 TCs
12~1117 μs
Low
Moment
Time (s)
x 10^-4
TX
RX
314 m²

# ATEM - Bookpurnong



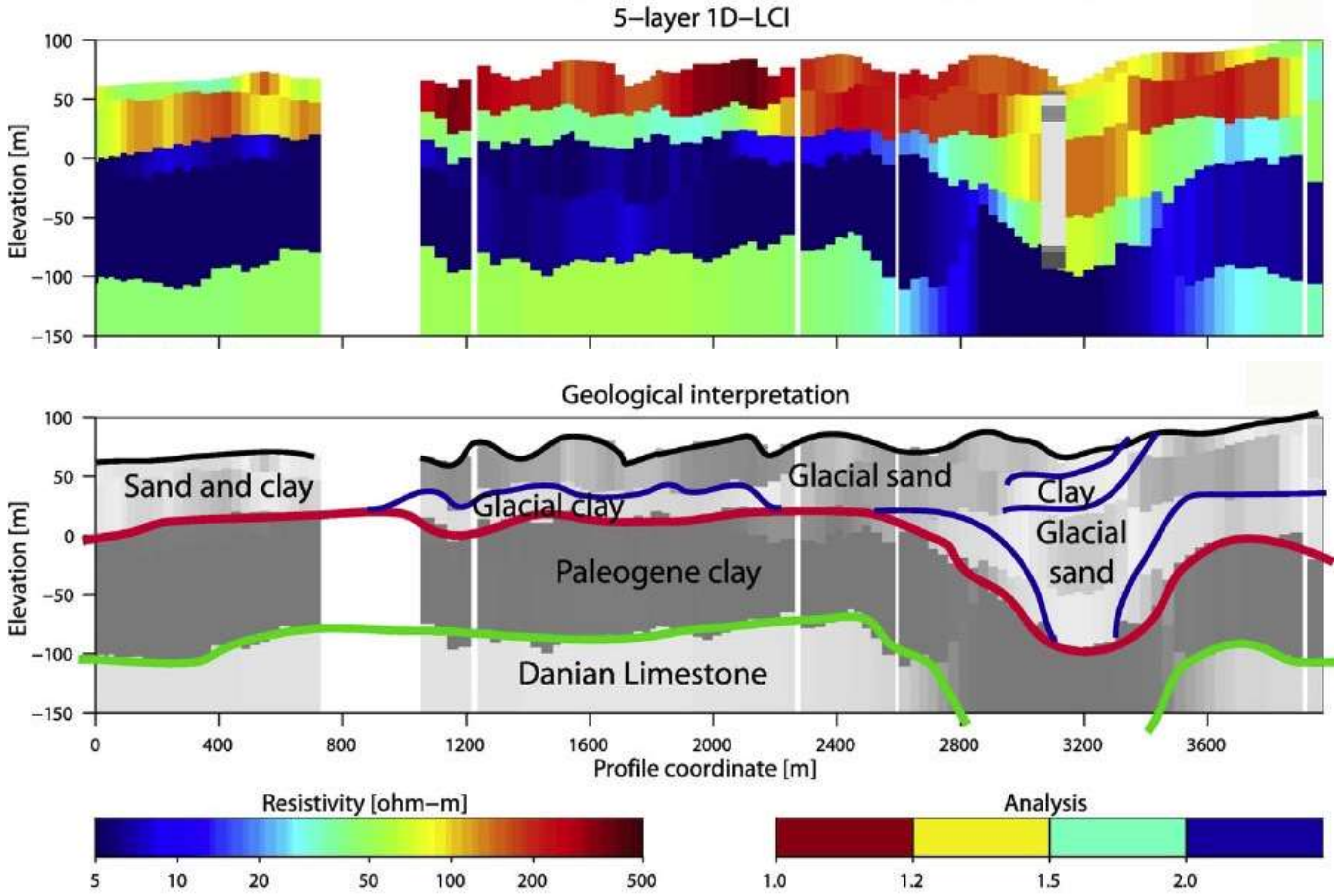





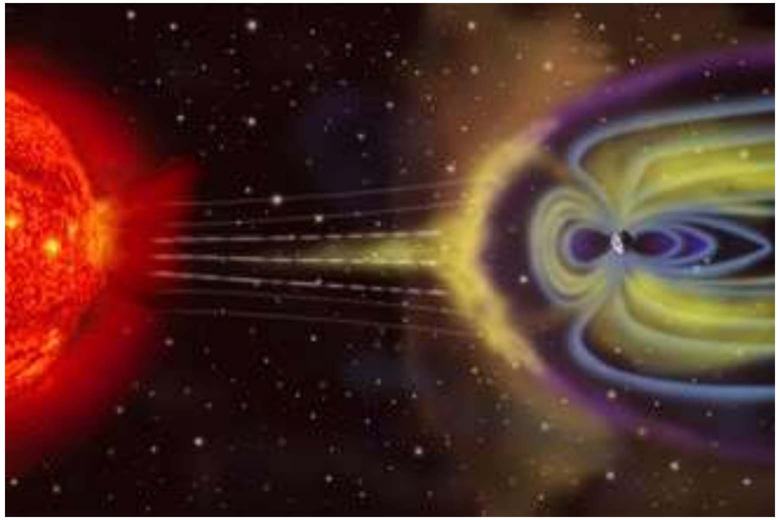
## Surface TEM

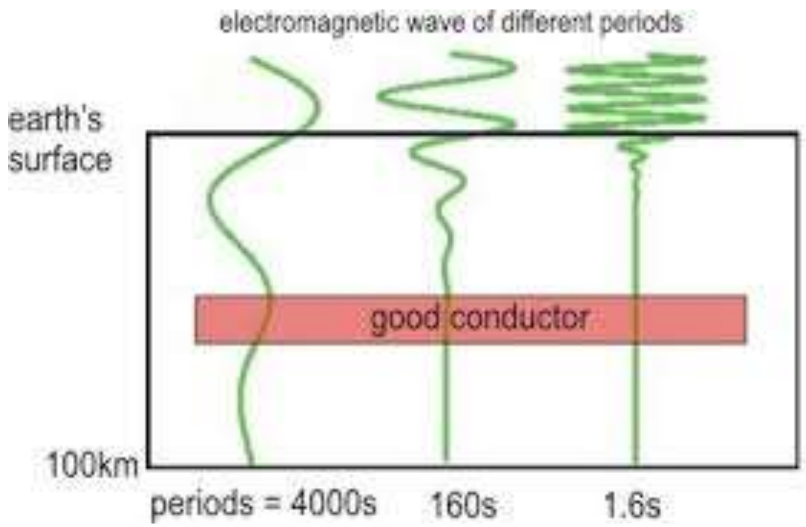
- Concentric Tx-Rx
- Time decay curve at each station
- 1D layered inversion at each station
- Stitch 1D models to form a 2D section




(NGA, EPA)

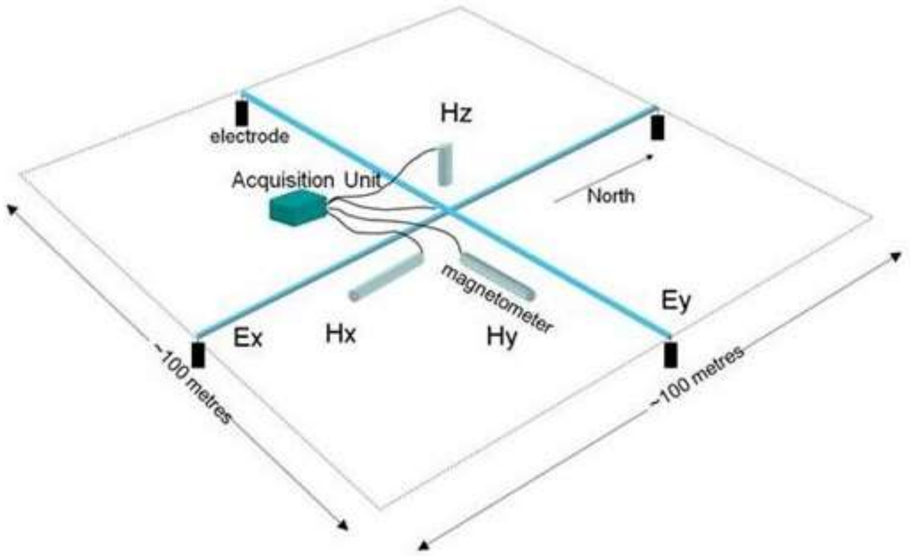
# Natural Source EM

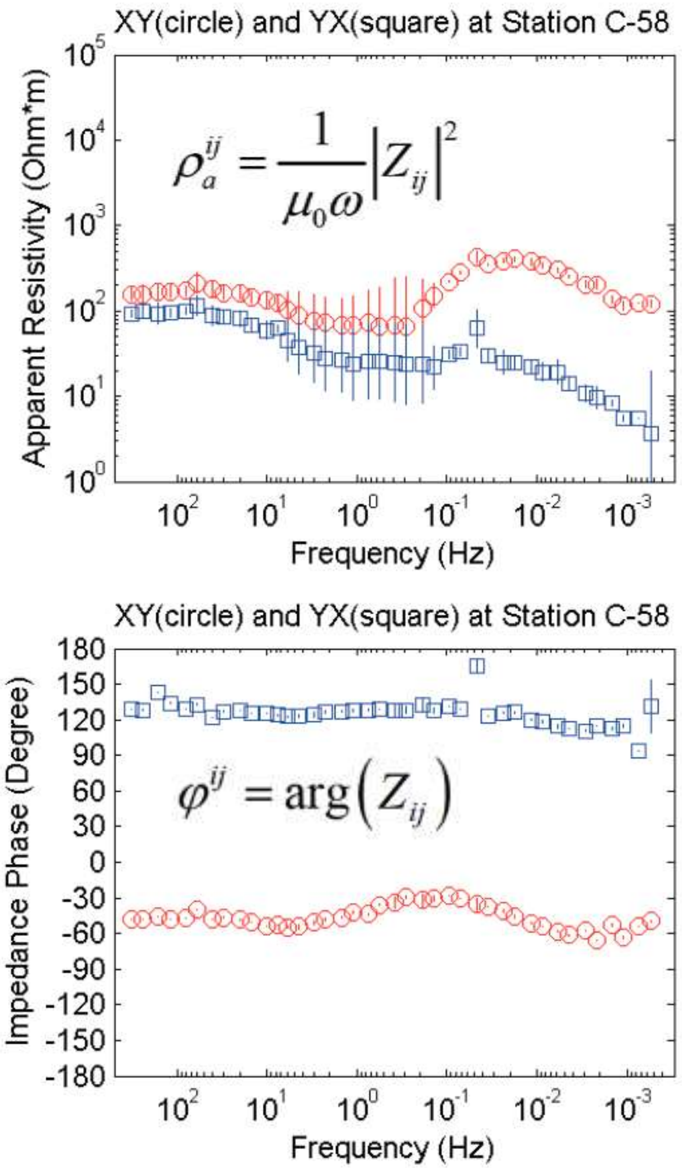





- Plane wave: horizontal E, H fields
- Frequency: 1 kHz – $10^{-4}$ Hz
- Depth of penetration: $10^{1}$ – $10^{5}$ m

# Magnetotellurics (MT)

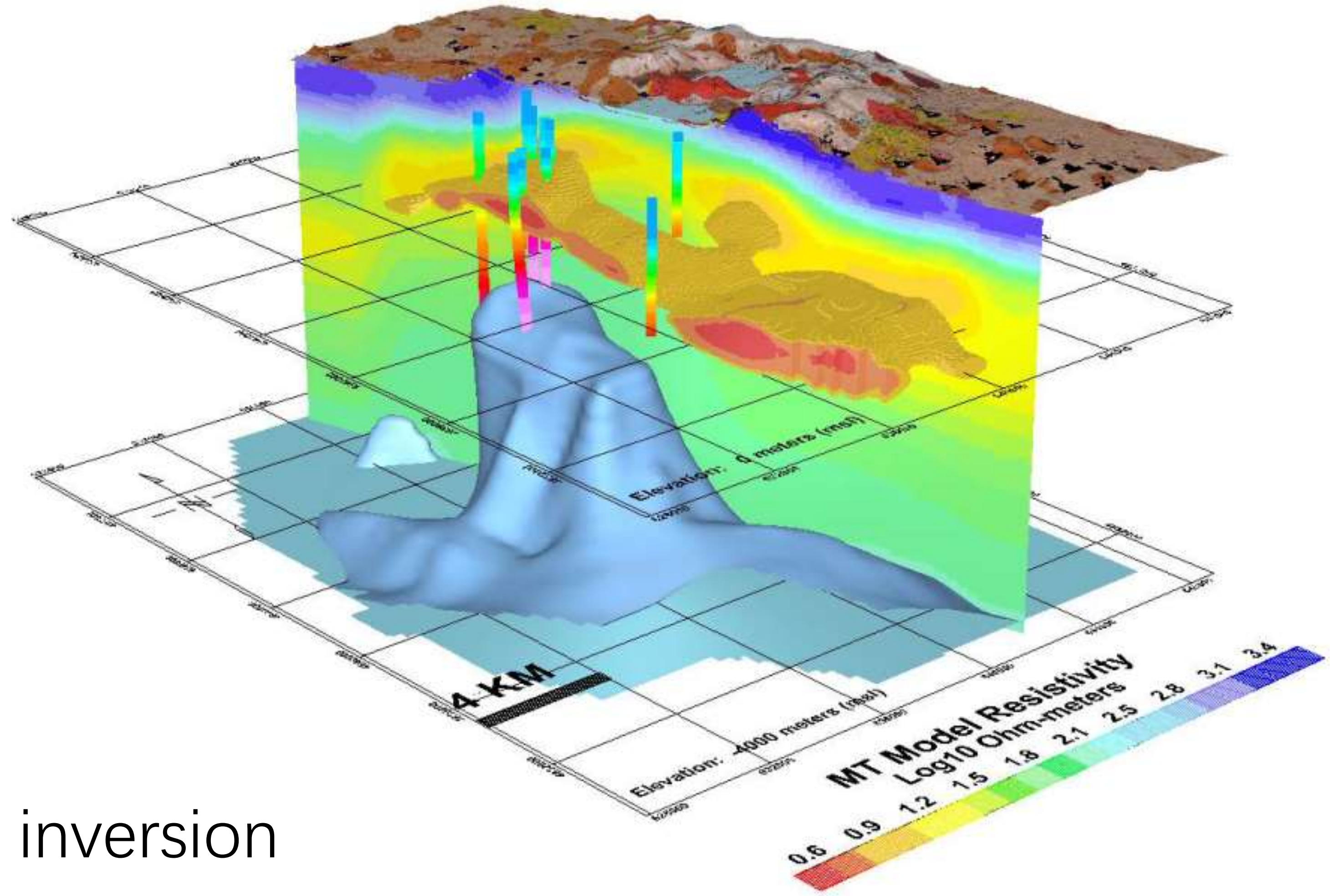



$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} \begin{bmatrix} H_x \\ H_y \end{bmatrix}$$

Impedance tensor element $Z_{ij}$ is complex and a function of sounding frequency and the earth's conductivity at different depths.

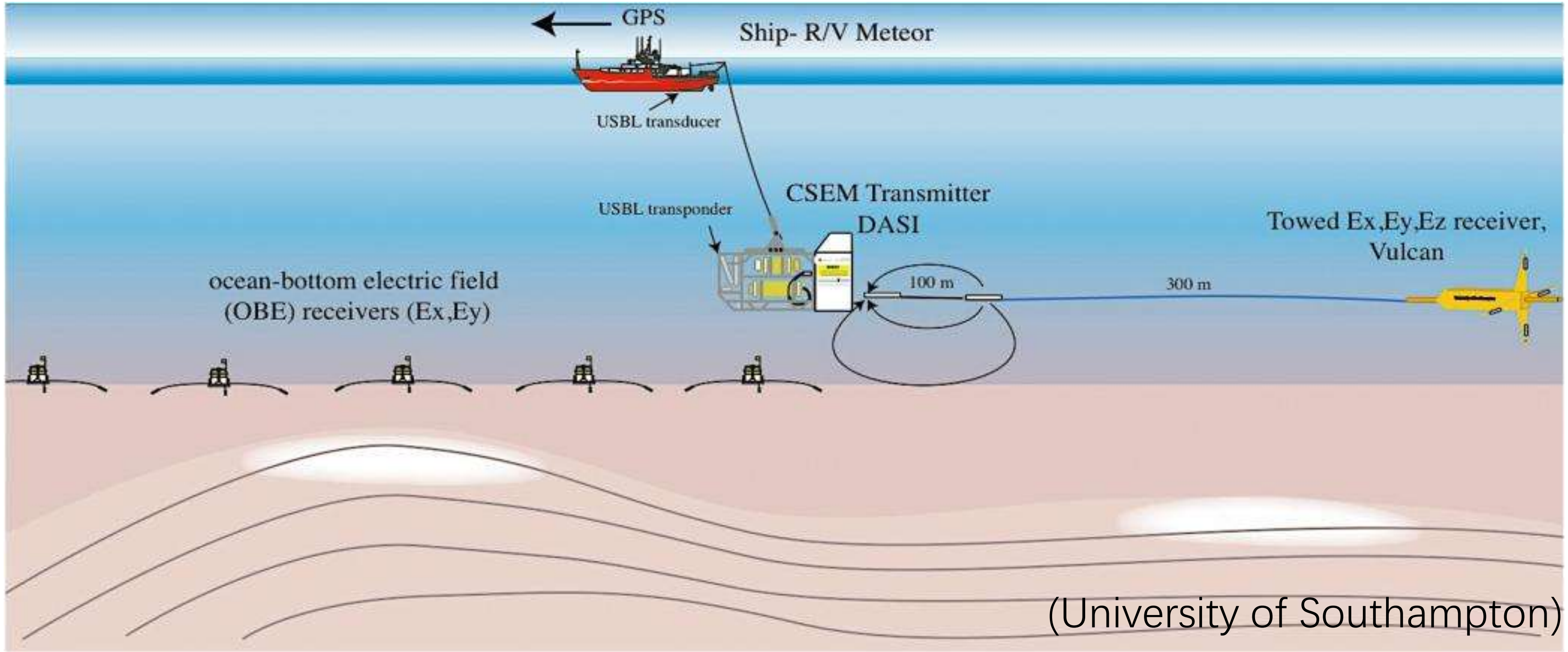
# MT - Geothermal




3D inversion

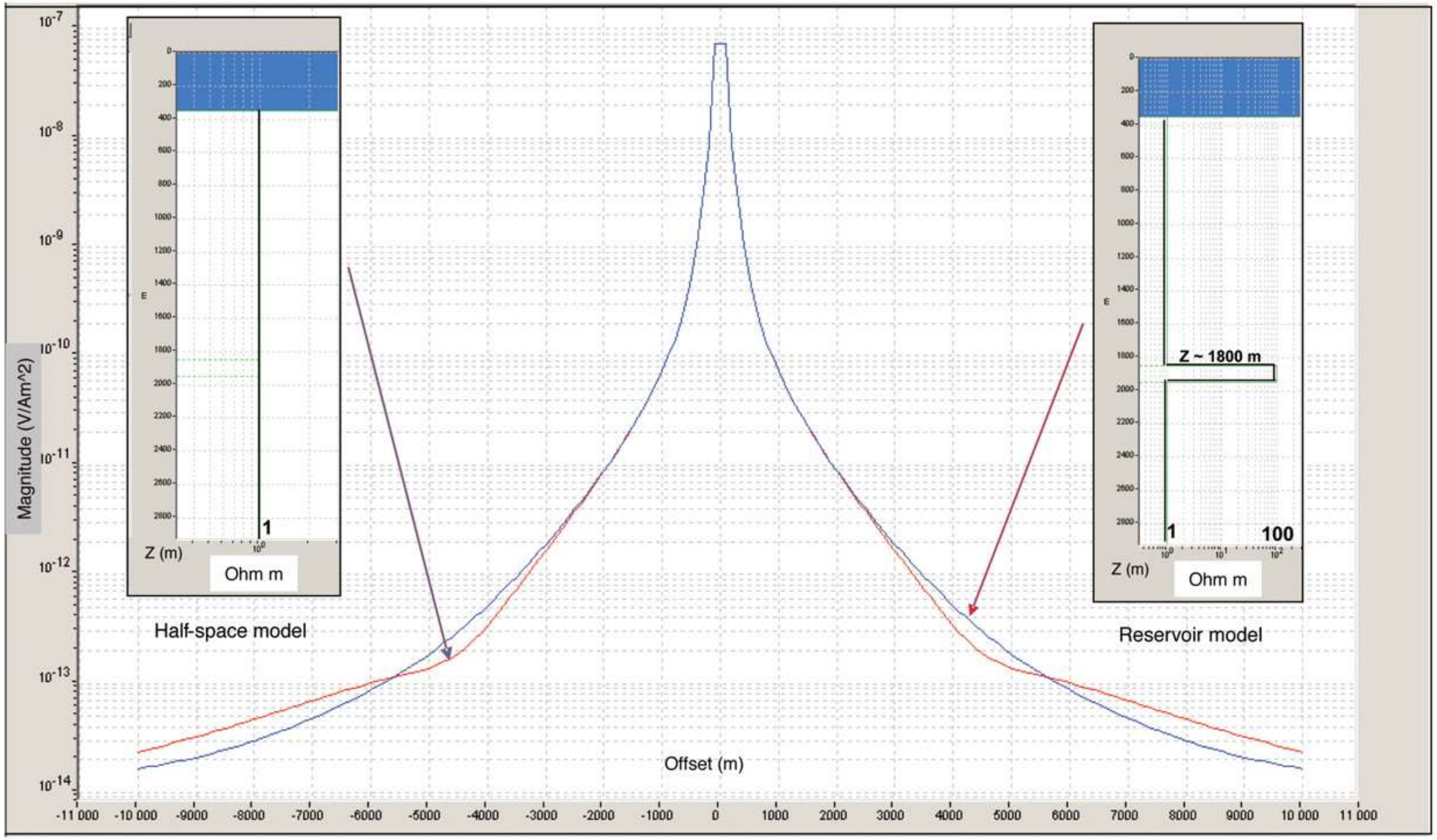
(Zonge)

# Marine CSEM




- Electric dipole source
- Towed or ocean-bottom E-field receivers (electric dipoles too)
- Widely used in hydrocarbon exploration (resistors in a conductive background)

# Marine CSEM




(Dell'Aversana)

# Summary

- More EM surveys
  - Multi-frequency systems: EM-34, GEM3
  - Airborne EM: RESOLVE
  - Time domain EM: SkyTEM, concentric Tx-Rx
  - Natural source EM (MT)
  - Marine CSEM
- Applications
  - Groundwater/geothermal
  - Geologic mapping
  - Geotechnical, UXO
  - Petroleum