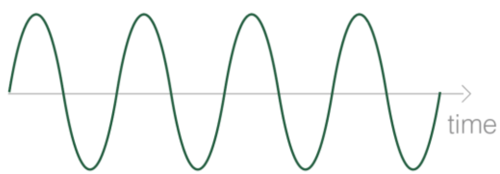
From last time

Sources

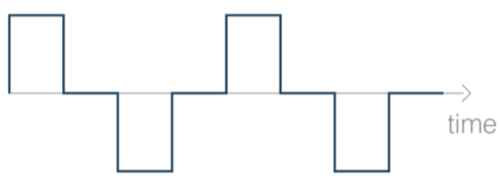
- Type
  - Inductive
  - Grounded

- Waveform

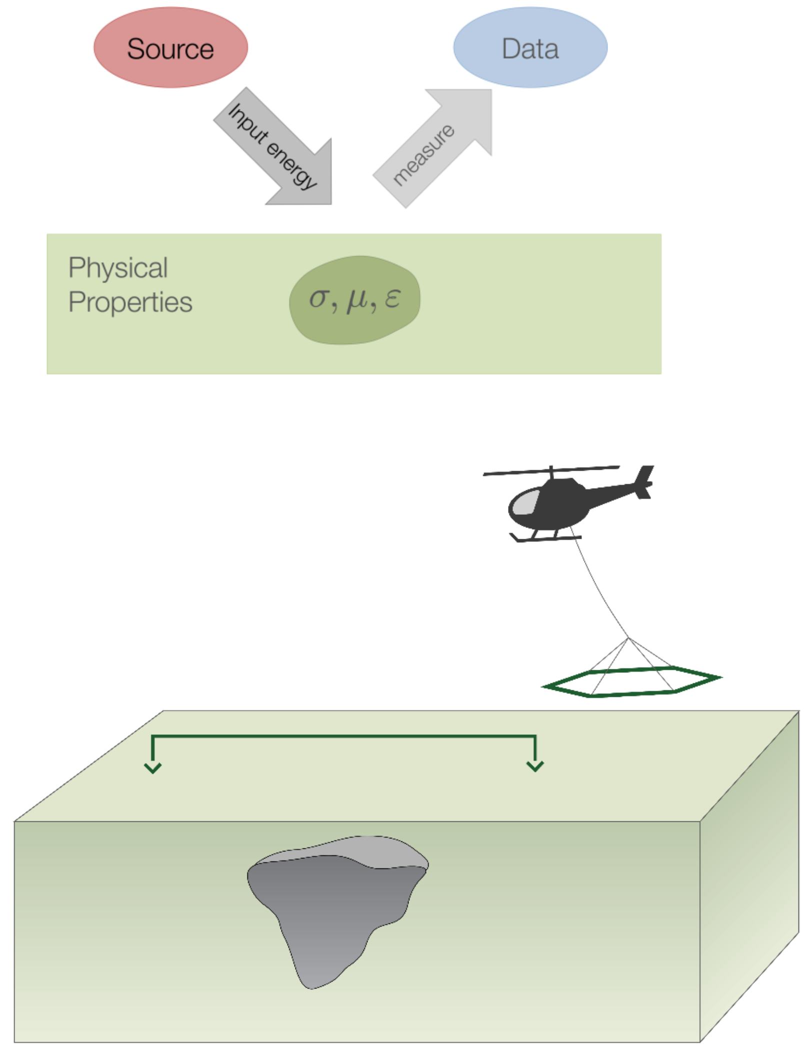
Harmonic (FDEM)



Transient (TDEM)

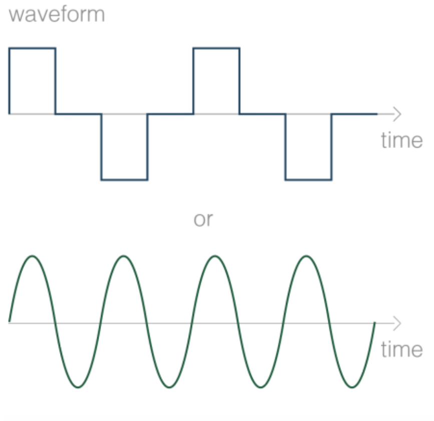


- Location
  - Airborne
  - Ground
  - Borehole



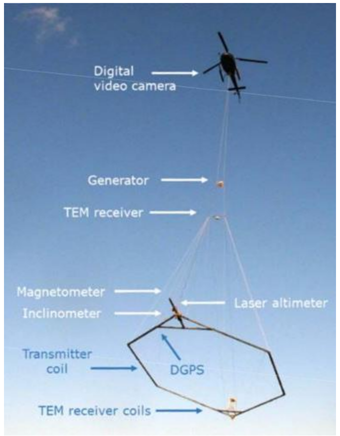
Transmitter considerations

- Time or frequency?



Airborne Survey

Resolve

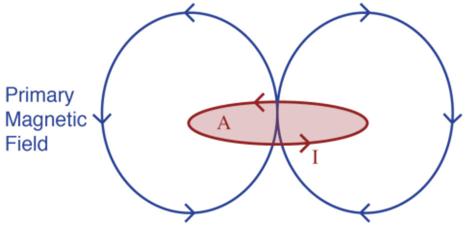


SkyTEM

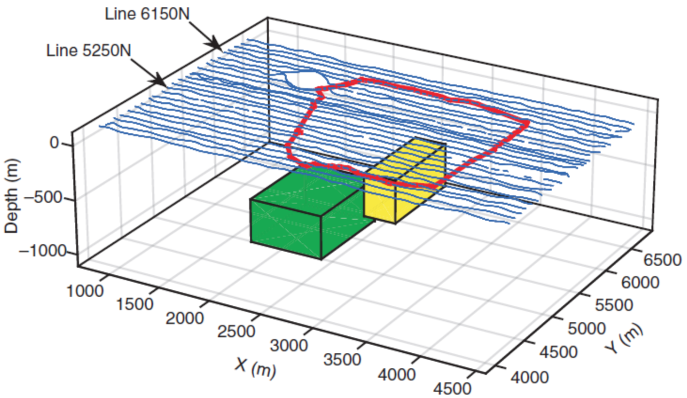
- Key factor is moment

$$m = I \text{ (current) } A \text{ (area) } N \text{ (\# of turns)}$$

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi}\left(\frac{3\mathbf{r}(\mathbf{m}\cdot\mathbf{r})}{|\mathbf{r}|^5} - \frac{\mathbf{m}}{|\mathbf{r}|^3}\right)$$

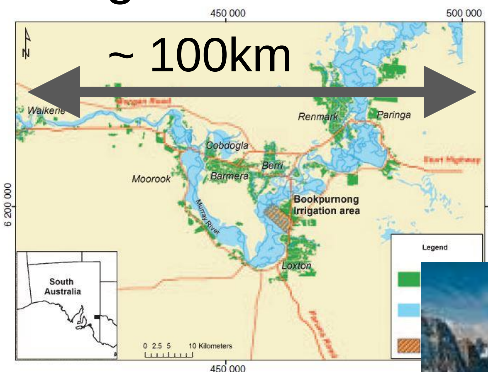


Large Loop



Applications for different systems

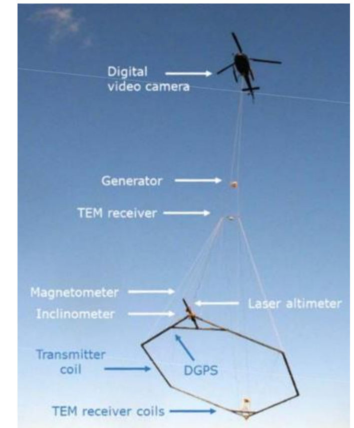
Large areas



Rugged terrain

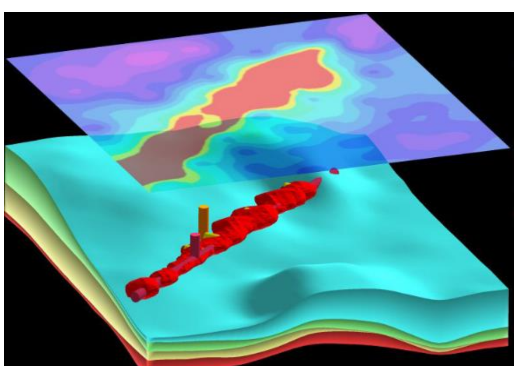
Airborne Survey

Resolve

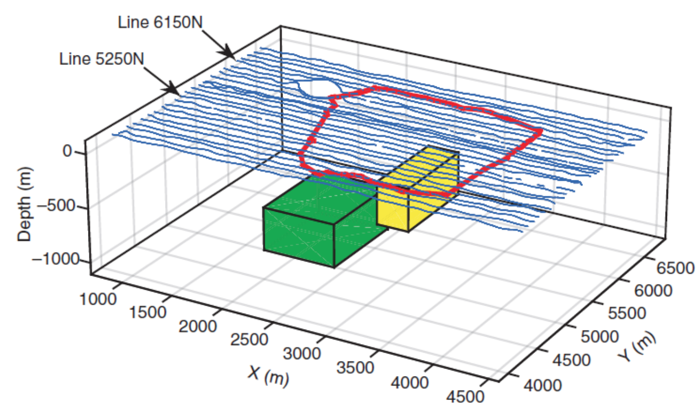


SkyTEM

Deep Targets



Large Loop

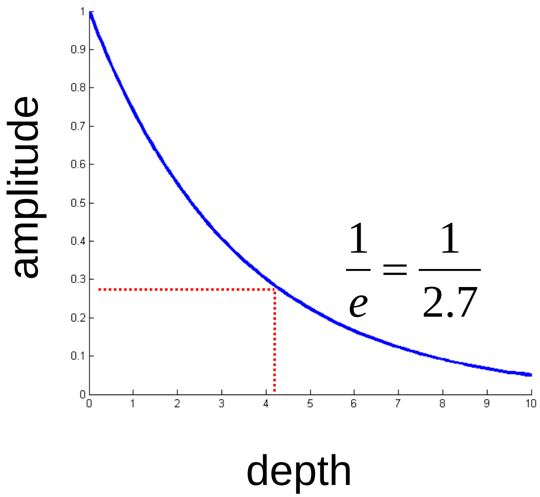


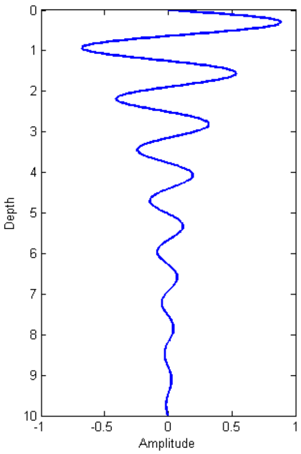
Skin Depth

- EM waves decay when propagating in a conducting earth

- Skin depth

$$\delta \approx 500\sqrt{\frac{\rho}{f}} \quad \text{meter}$$





where ρ is resistivity in Ωm
and *f* is frequency in Hz

Today's Topics

- Data and Processing
  - Sounding curves
  - Apparent conductivity/resistivity
  - In-phase and quadrature maps
  - 1D Inversion

- Examples
  - Sand and gravel quarries
  - Bookpurnong

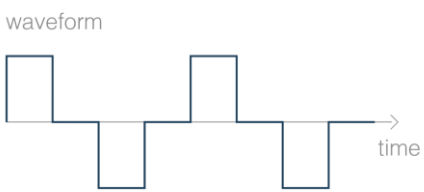
- Recap of EM Methods

Data and Processing

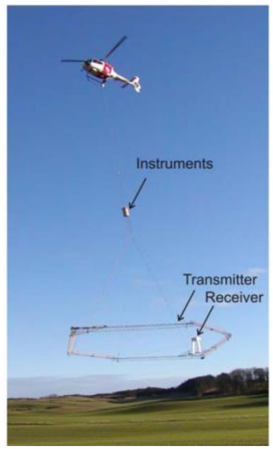
Data: Sounding Curve

Data obtained at a single location

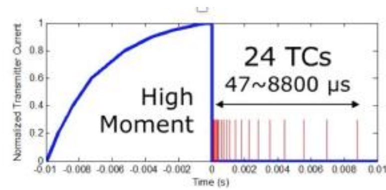
- Time



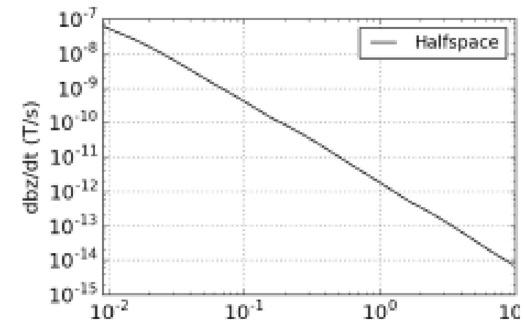
SkyTEM



Sampling times



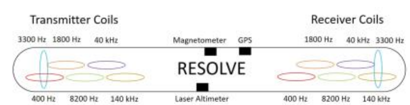
Sounding curve



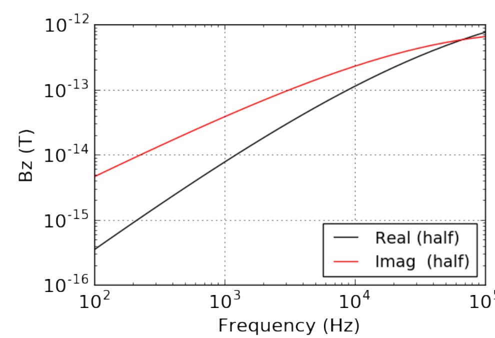
- Frequency

Resolve

Sampling frequencies

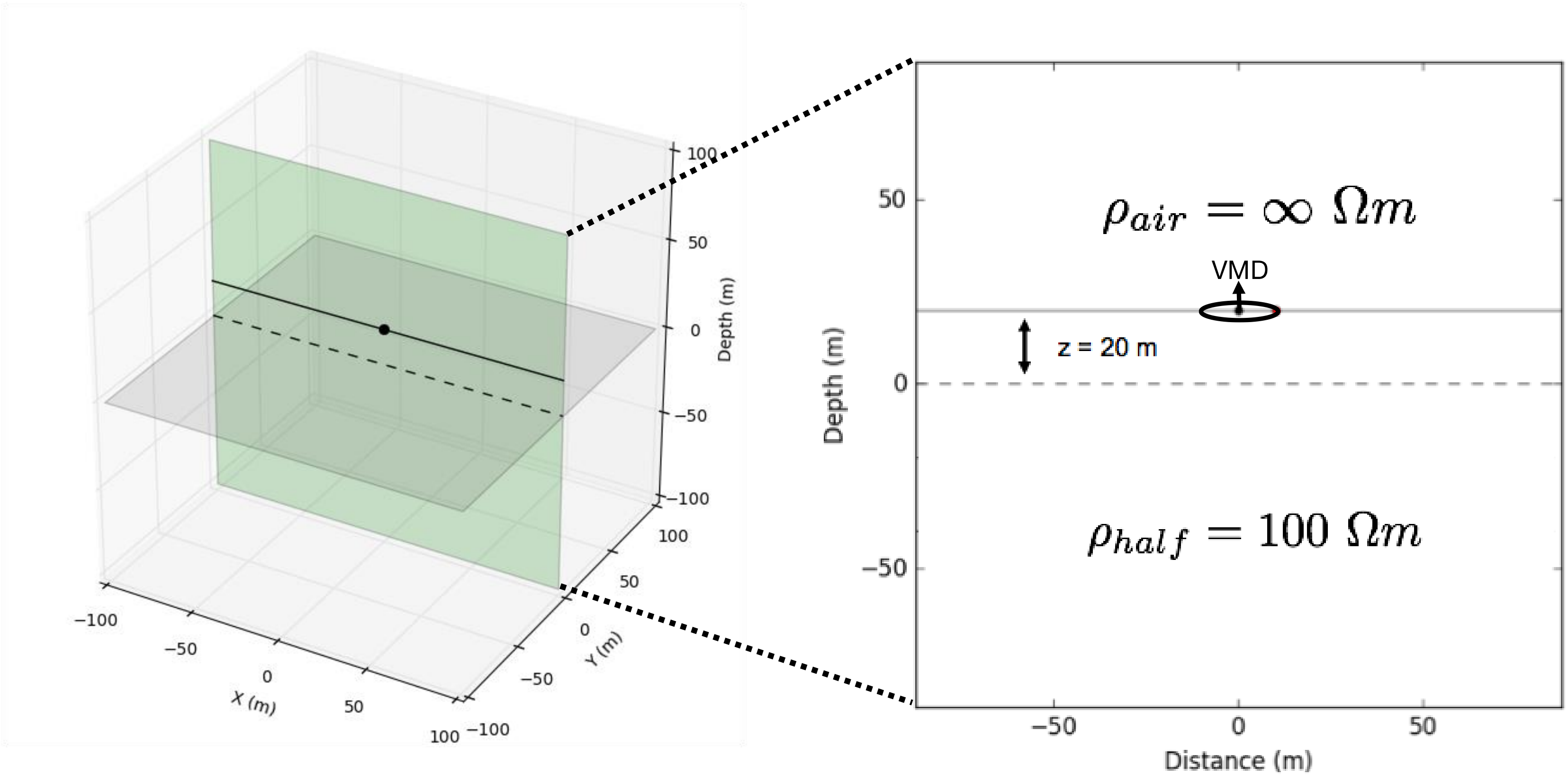


Sounding curve

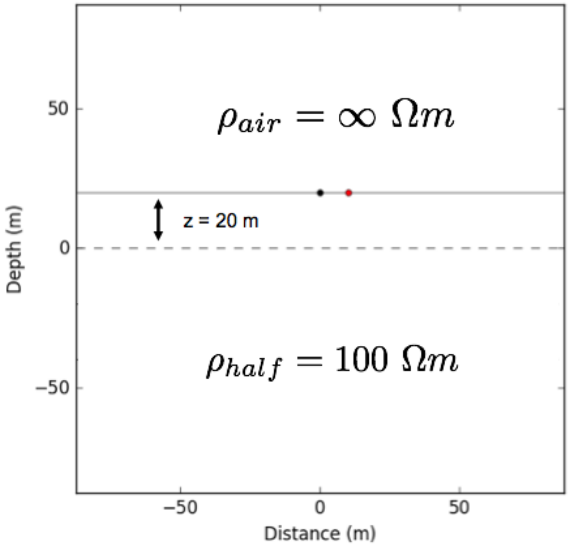


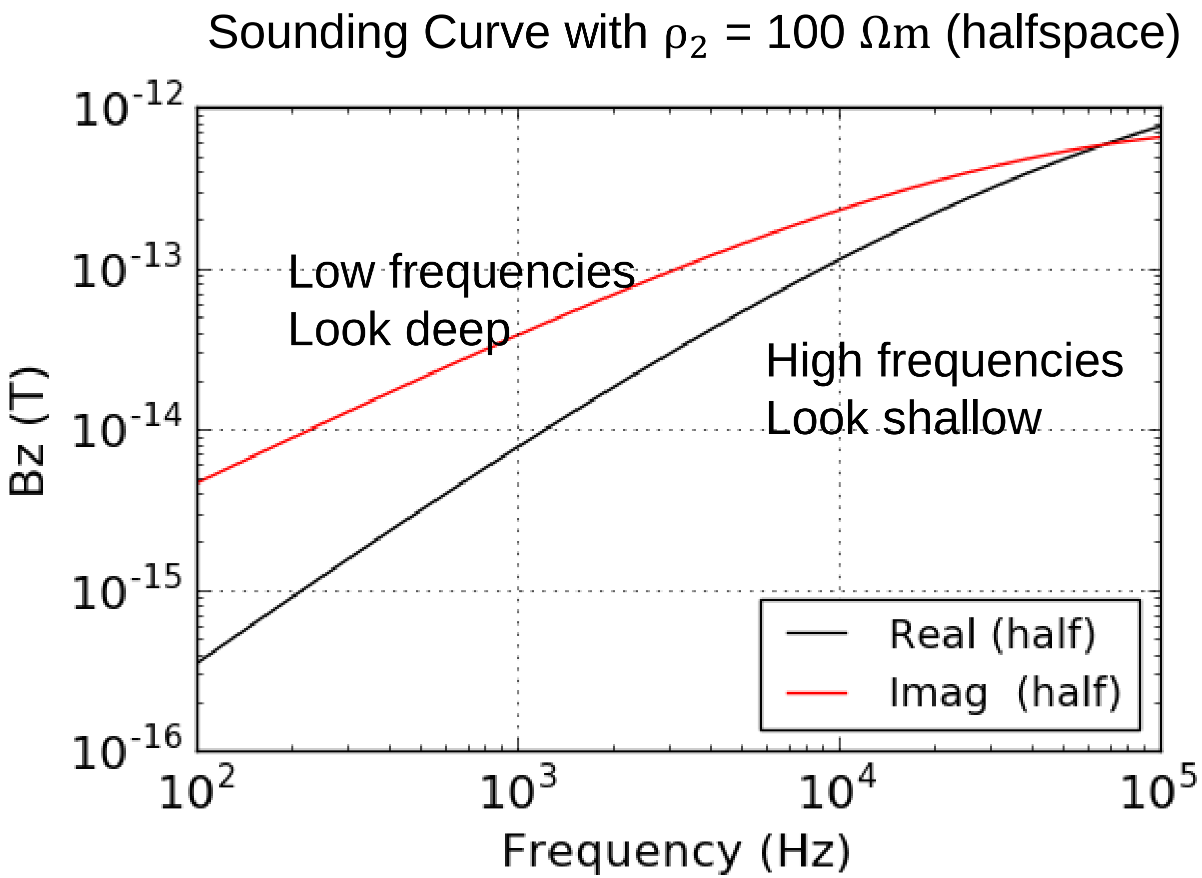
FEM sounding curve example

- Coincident loop system
- VMD source and receiver measuring Bz(f)



FEM sounding curve example

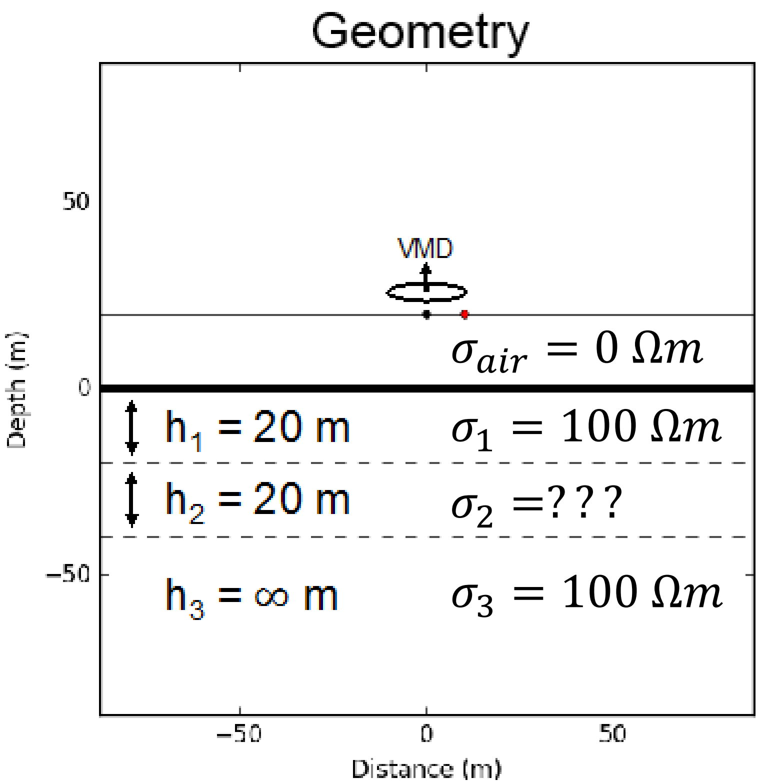




Information about conductivity is captured by the sounding curve

FEM sounding curve example

- 3 layers + air,
- ρ_2 varies



- Four different cases:
  - Halfspace

    $\rho_2 = 100\ \Omega\mathrm{m}$
  - Resistive

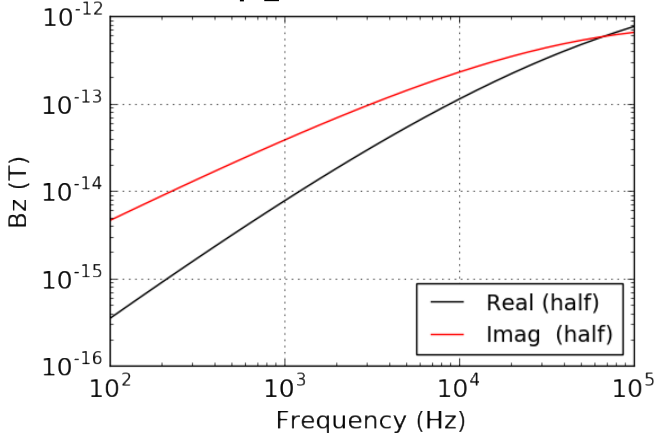
    $\rho_2 = 1000\ \Omega\mathrm{m}$
  - Conductive

    $\rho_2 = 10\ \Omega\mathrm{m}$
  - Very conductive

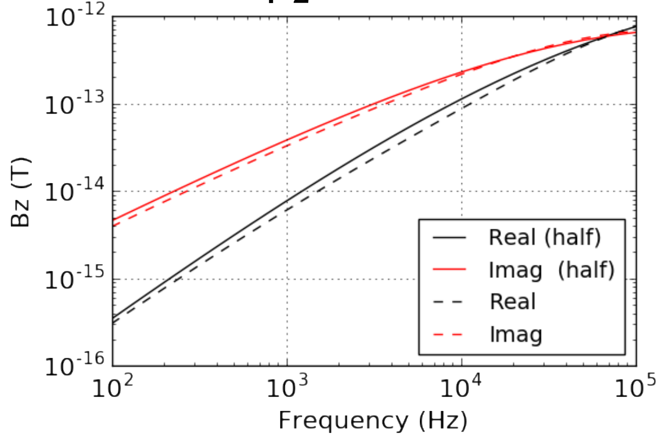
    $\rho_2 = 1\ \Omega\mathrm{m}$
- Fields
  - J_y imag
  - Secondary **B** imag

Curves for different layer conductivities

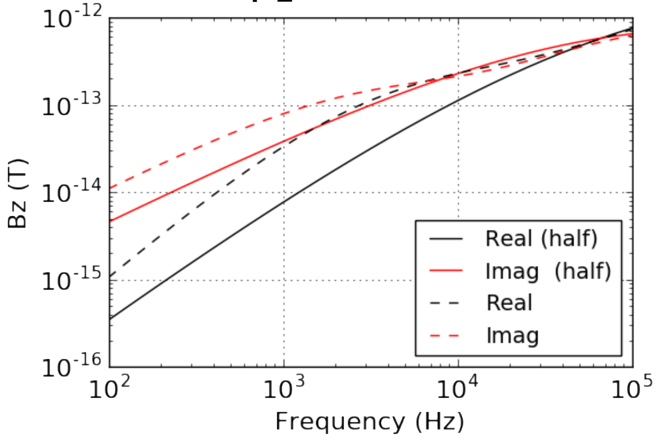
$\rho_2 = 100\ \Omega\text{m}$



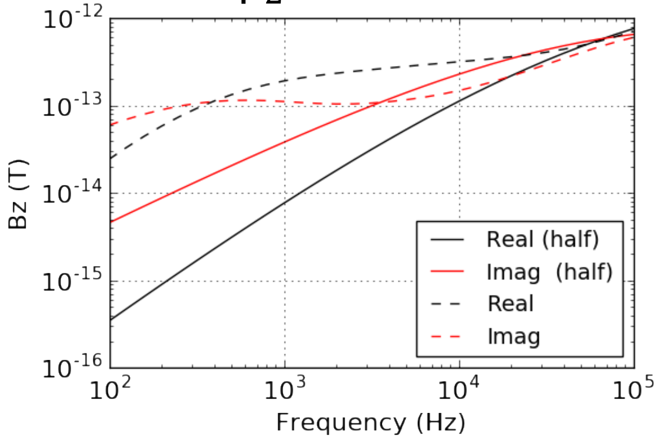
$\rho_2 = 1000\ \Omega\text{m}$



$\rho_2 = 10\ \Omega\text{m}$

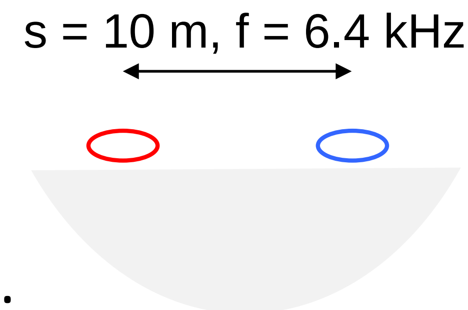


$\rho_2 = 1\ \Omega\text{m}$



Data: Apparent Conductivity

- For horizontal coplanar FEM systems



$$\delta \approx 500\sqrt{\frac{\rho}{f}}$$

- If $s \ll \delta$ and $Re[Hs] \sim 0$ then for a half-space:

$$\frac{H_s}{H_p} \simeq i\frac{\omega\mu_0\sigma s^2}{4}$$

- **Apparent conductivity:**

$$\sigma_a = \frac{4}{\omega\mu_0 s^2}\mathrm{Im}\left\{\frac{H_s}{H_p}\right\}$$

- Could compute apparent resistivity
- Could turn sounding curve into apparent resistivity curve for background response

Processing: Apparent Conductivity Map

- Lateral variability in near surface conductivity from EM 31
- Taken for two different transmitter-receiver orientations

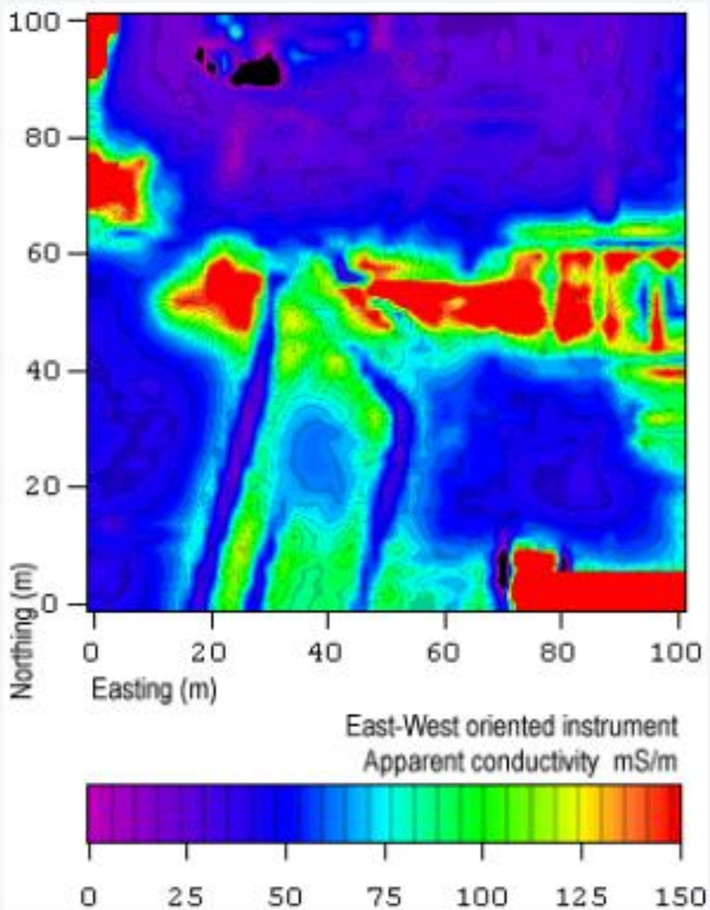


Fig. 154 : σ_{app} map from the EW orientation

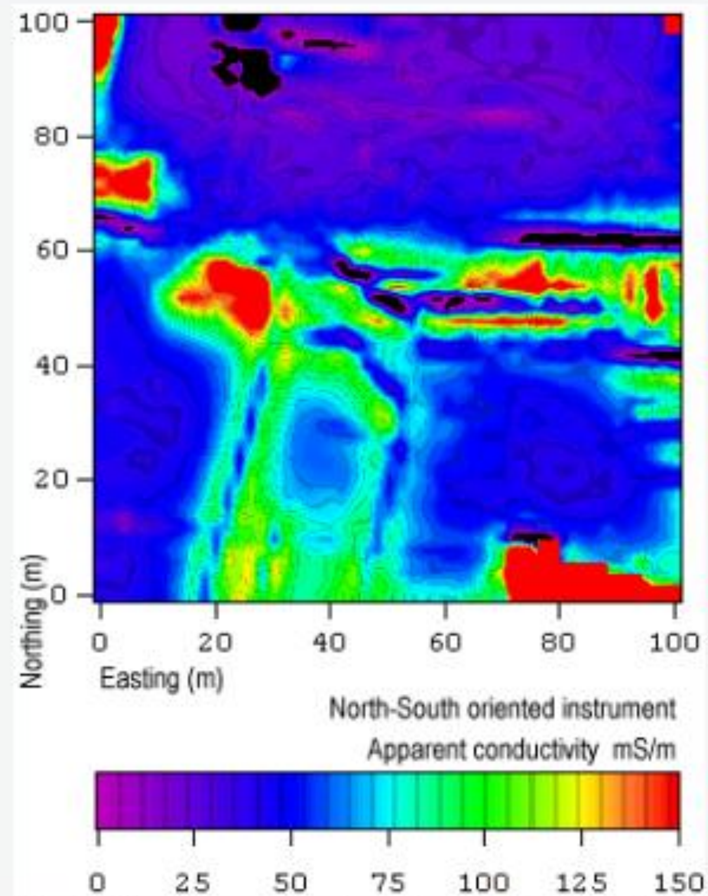
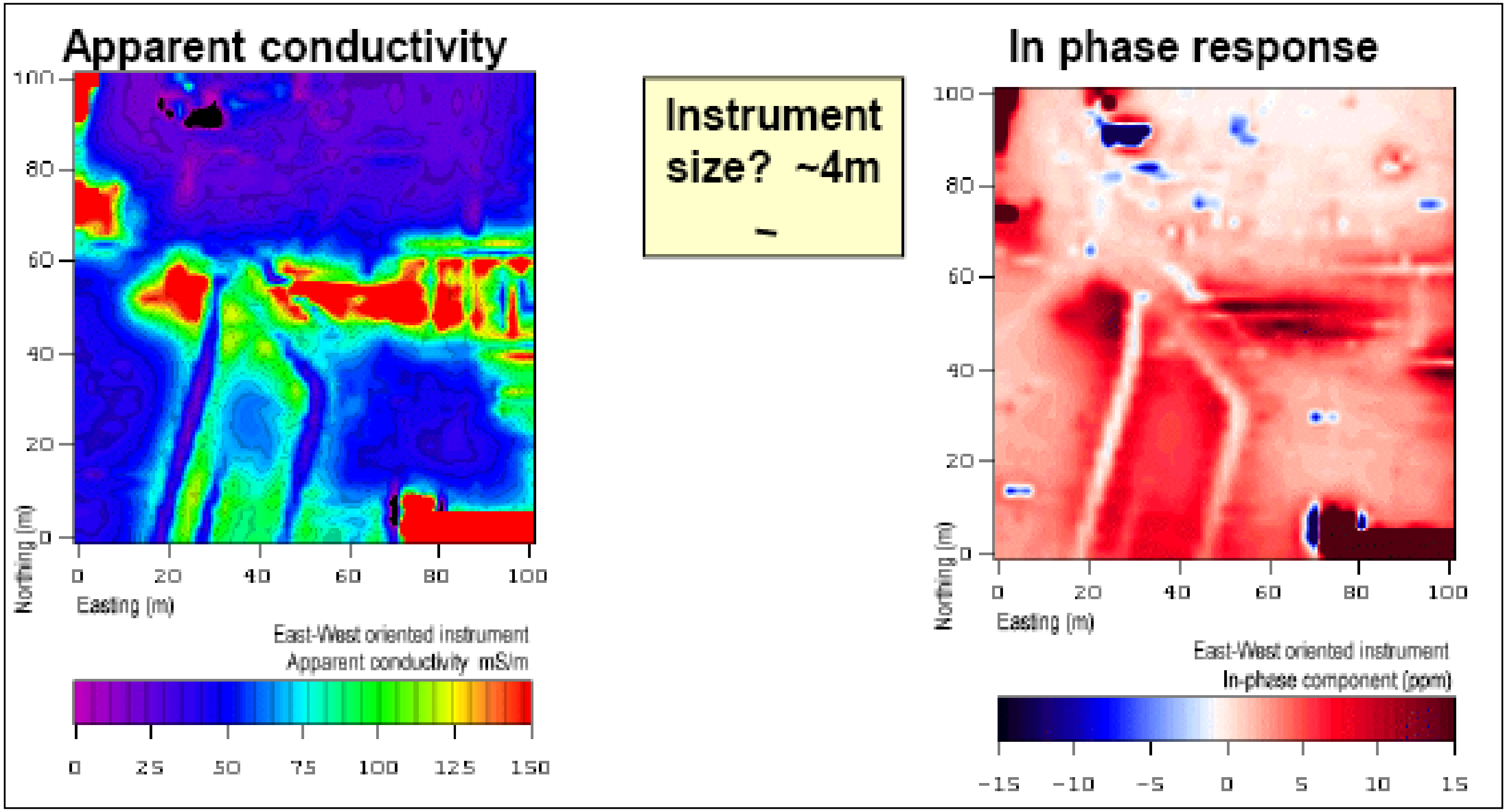


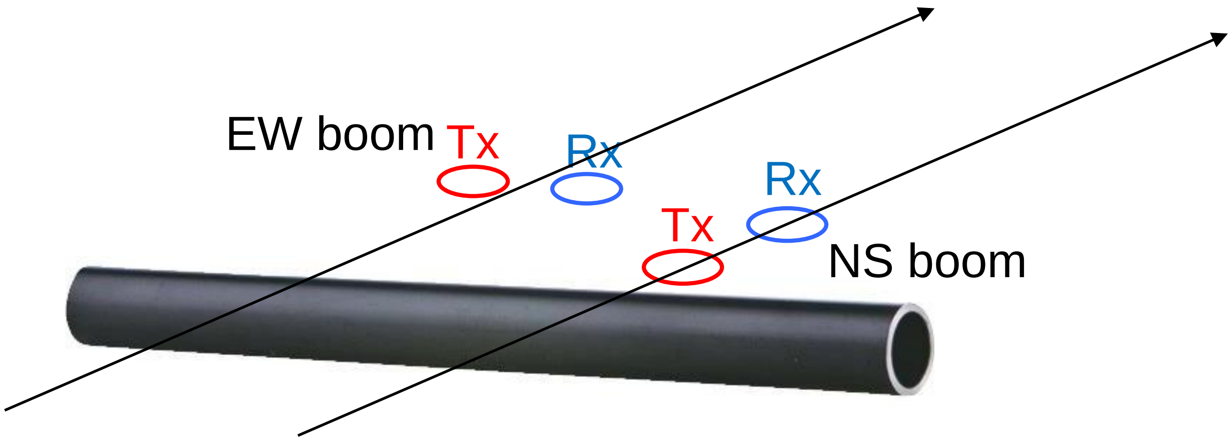
Fig. 155 : σ_{app} map from the NS orientation

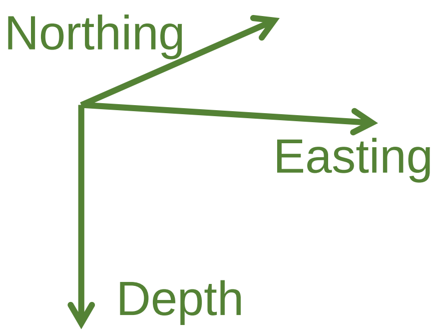
Processing: Apparent Conductivity and In-Phase Data

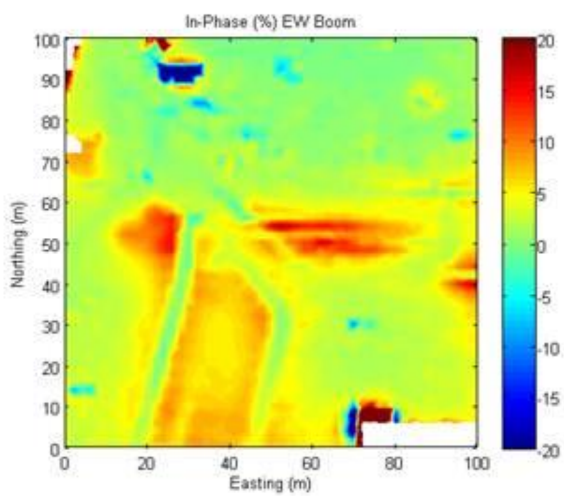


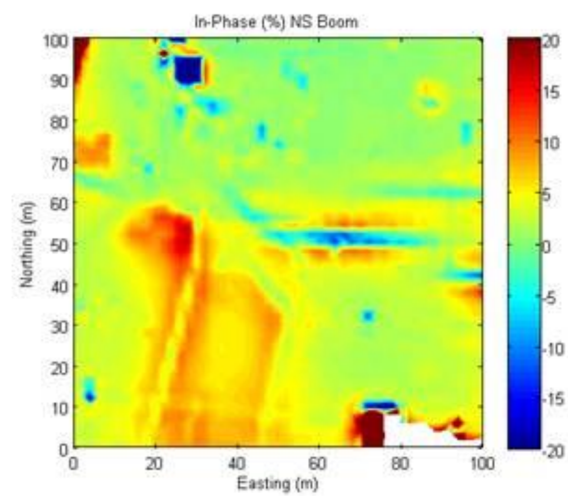
- **Apparent conductivity (mS/m):** lateral changes in conductivity
- **In-phase (ppm):** Large value highlights buried conductors

EM-31 and Pipe







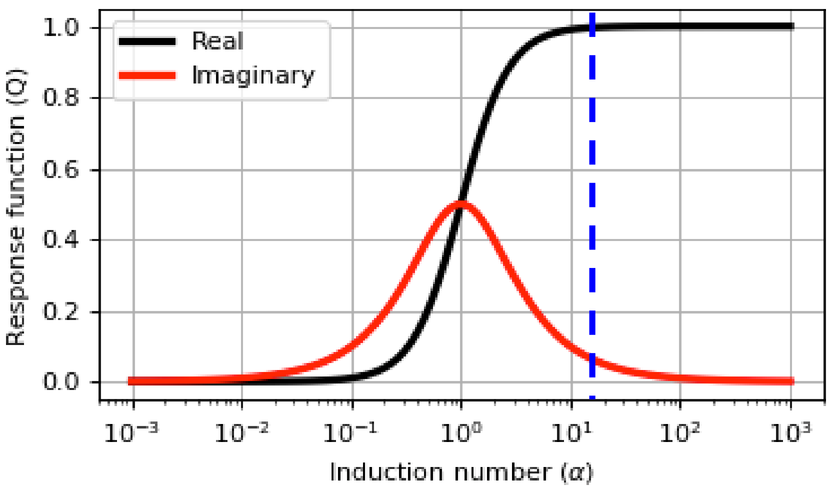


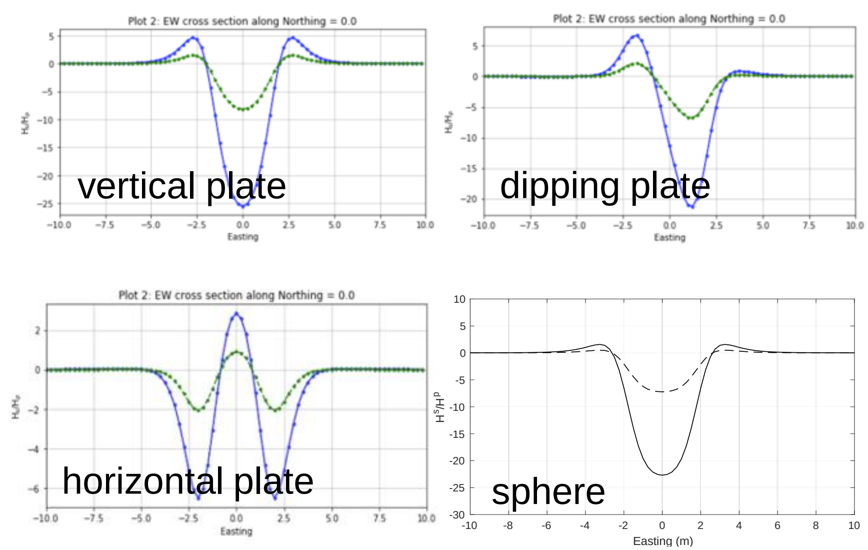
EM-31 and Conductors

Finding good conductors

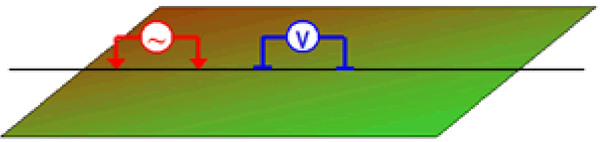
Finding metallic objects

High induction number over a conductor



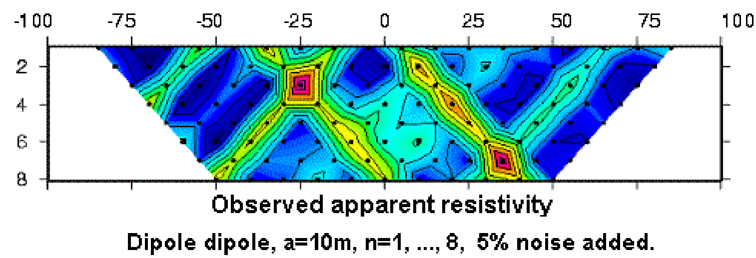


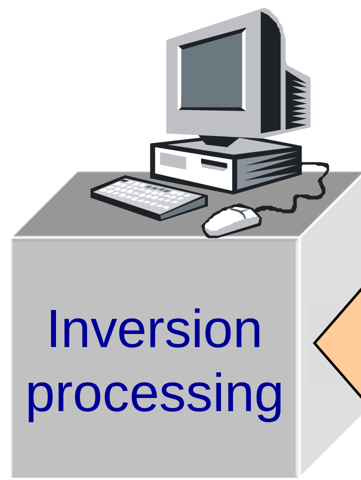
Inversion

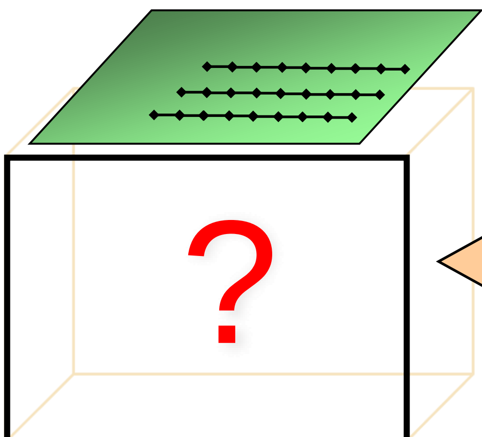


Data

Measurements over the Earth are data.





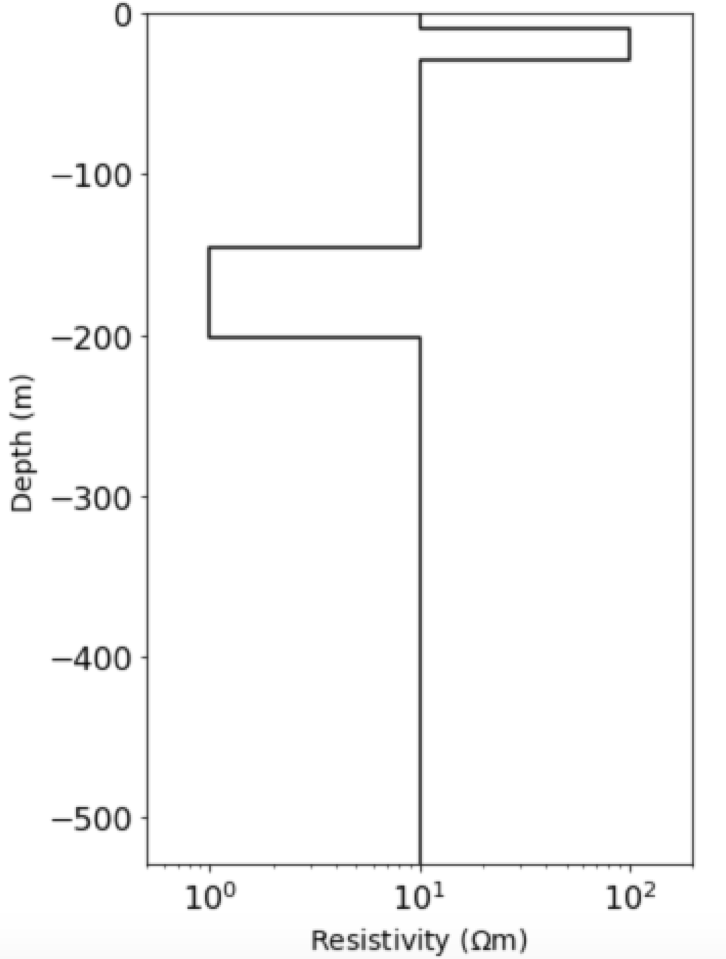


Model

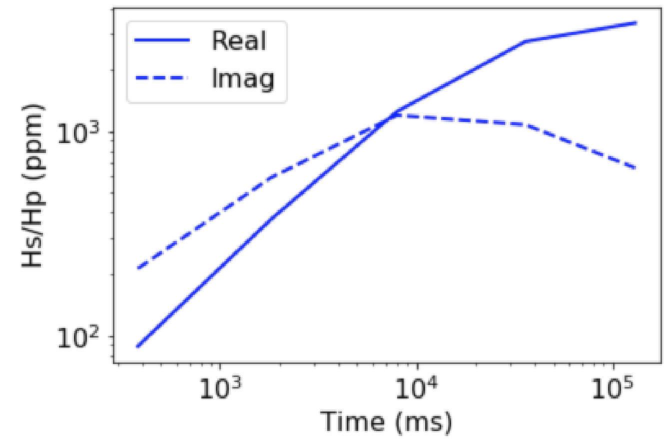
Inversion estimates Earth models based upon data and prior knowledge.

1D Inversion example

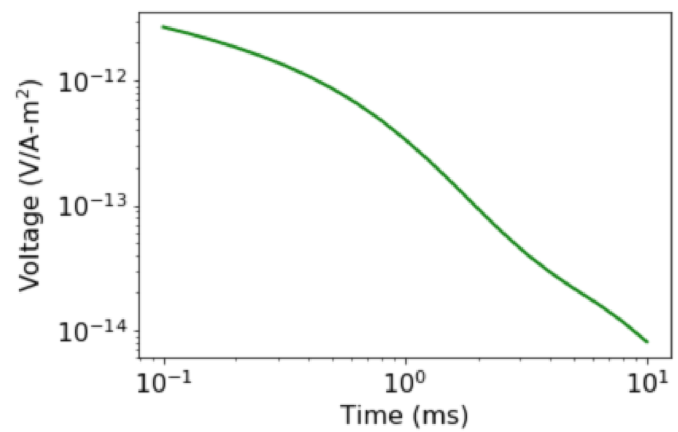
Earth resistivity



Frequency sounding

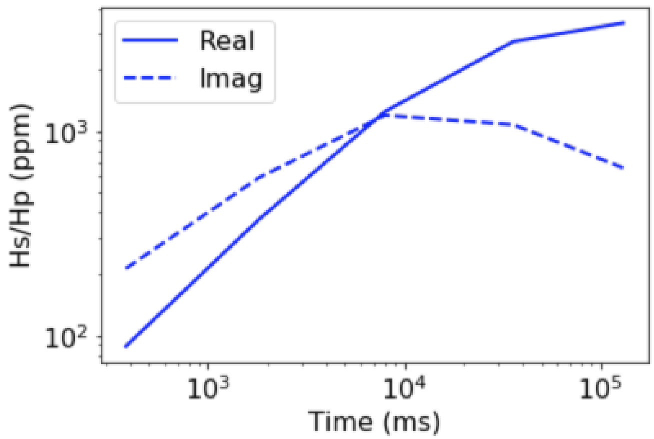


Time sounding

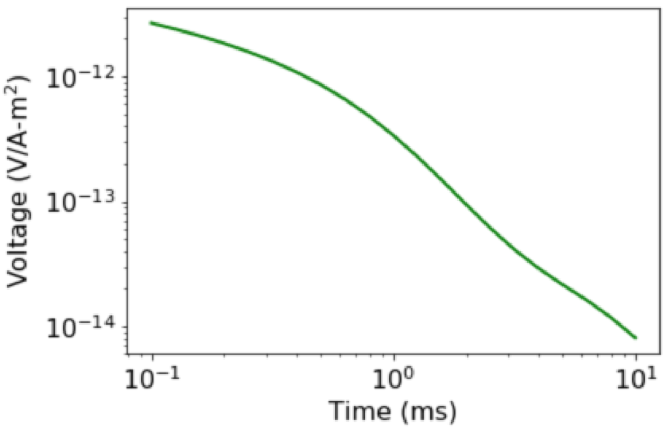


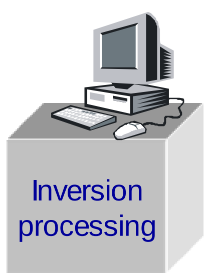
1D Inversion example

Frequency sounding

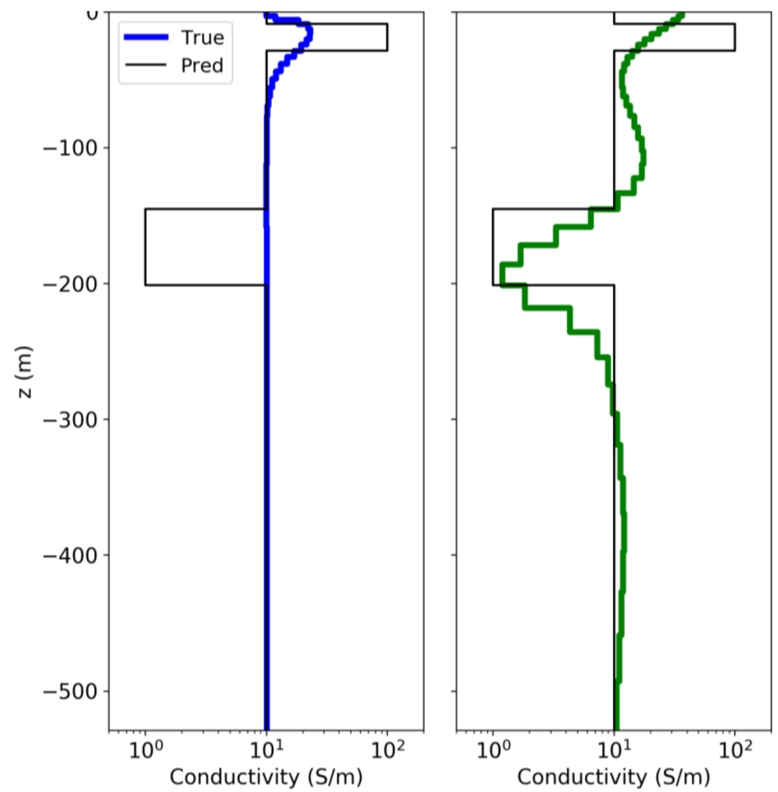


Time sounding





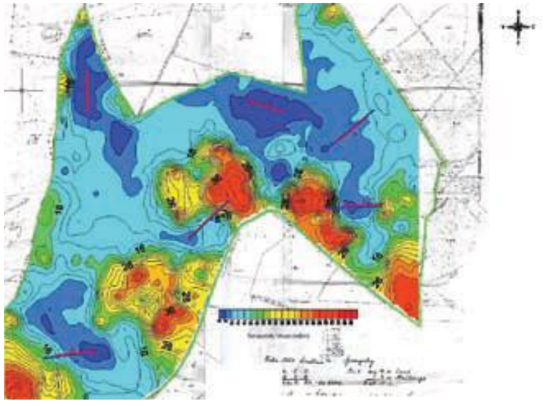
Estimated earth resistivity



Example: Sand and Gravel Quarries

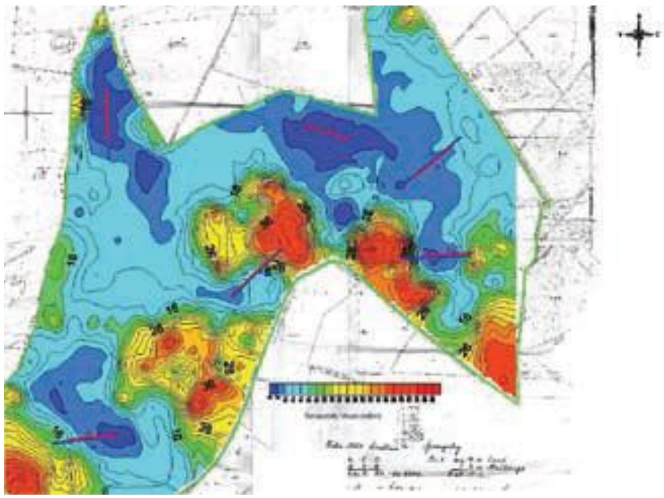
Sand and Gravel Quarries

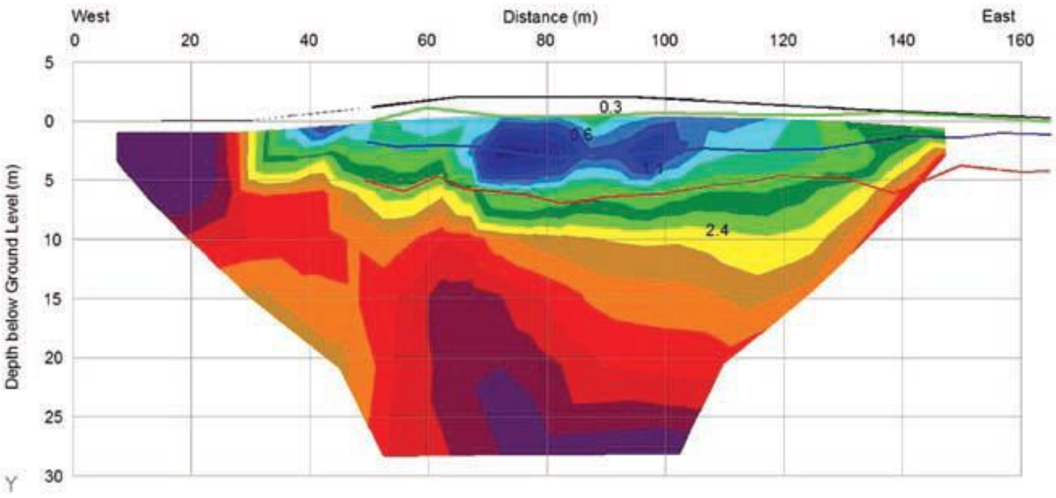
- **Setup:** Find sand and gravel quarries. Area has granitic mountains, rolling hills and lakes. Glacial deposits are responsible for potential sand and gravel resources. Some of the area is bog and agricultural land. (Picture)
- **Properties**: Bog material is wet and conductive. Gravel deposits are resistive (low conductivity). Gravels are unconsolidated and have a low seismic velocity.
- **Survey**: Preliminary EM survey (EM31) Logistically easy and gives an estimate of ground conductivity in the top few meters. Good reconnaissance tool. More detailed follow-up using DC resistivity to get 2D conductivity structure and seismic to find the base of the gravel.
- **Data:** EM31data. Also DC and seismic are acquired along selected line profiles.



Sand and Gravel Quarries

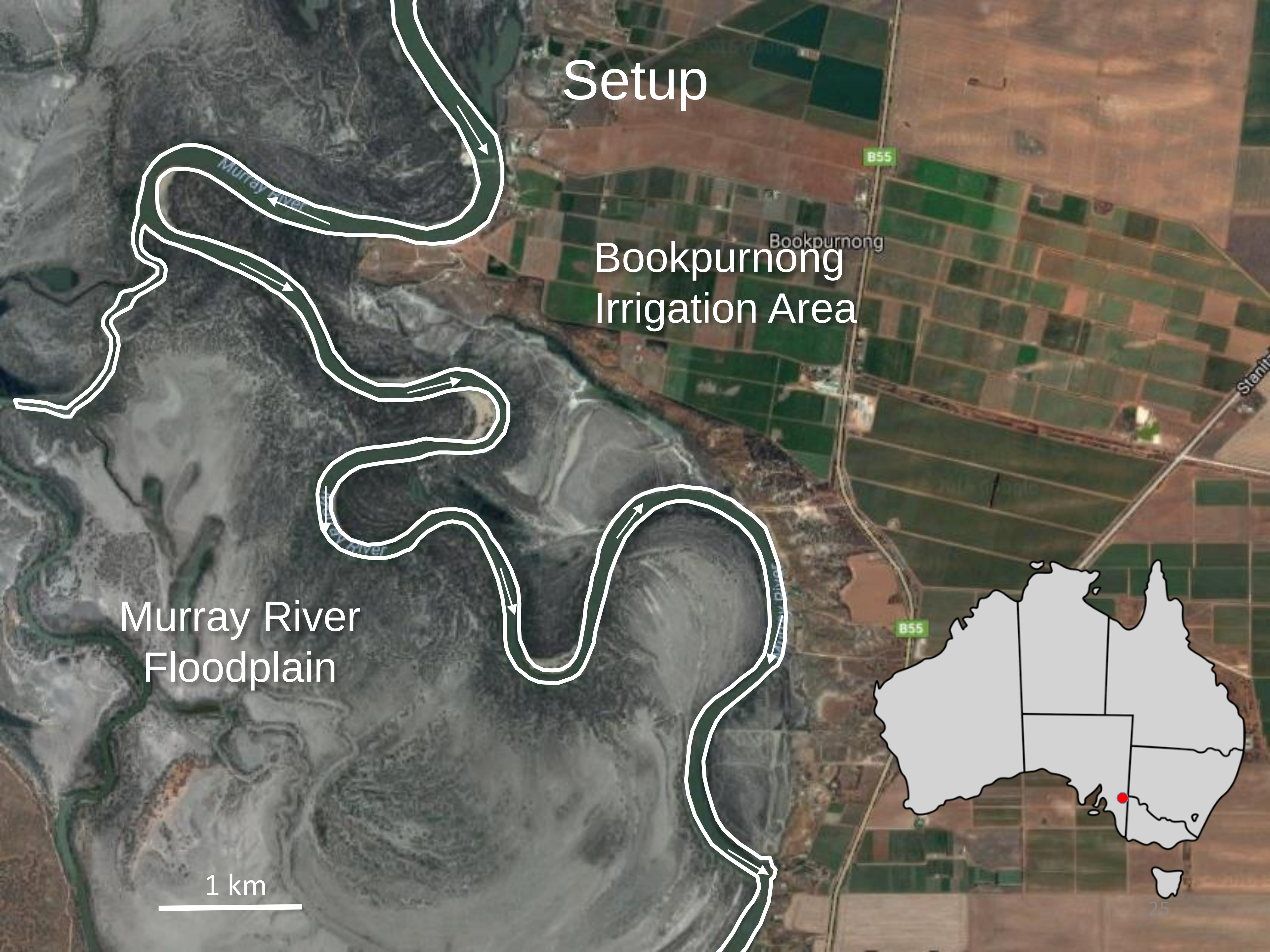
- **Processing:** EM31 data is converted to ground conductivity. (Picture). DC resistivity data is inverted to get a 2D cross section. Seismic data are inverted to provide location of refracting interfaces.
- **Interpretation:** Areas of low conductivity are identified from the EM survey. The inversion of DC and seismic data outline a gravel lens along one of the transects. Gravel lens is 5-8 meters in thickness and 40-50 meters in length.
- **Synthesis**: Seems successful. Have found gravel lenses and results have helped assess the potential tonnage across the site.



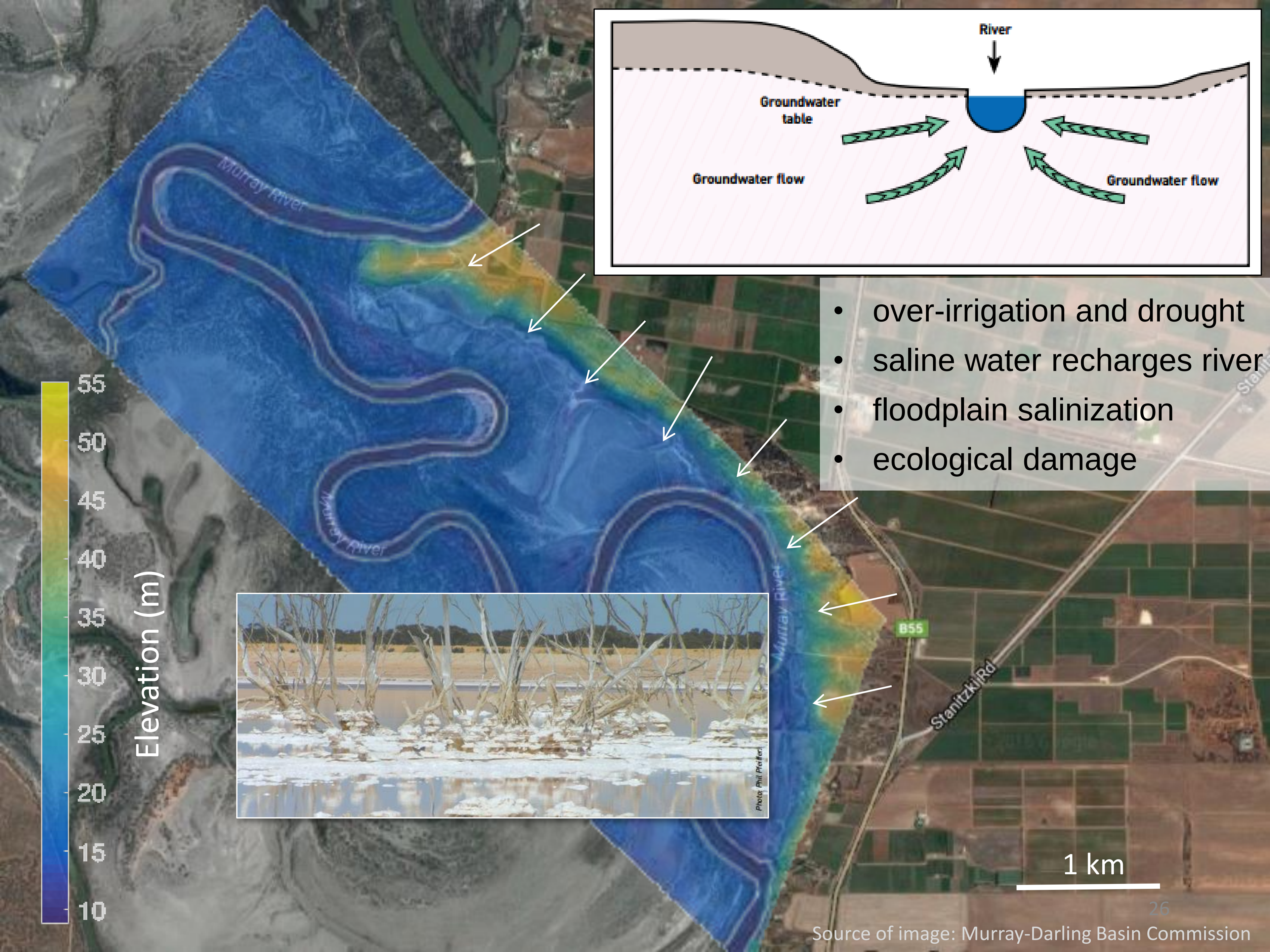


Example: Bookpurnong

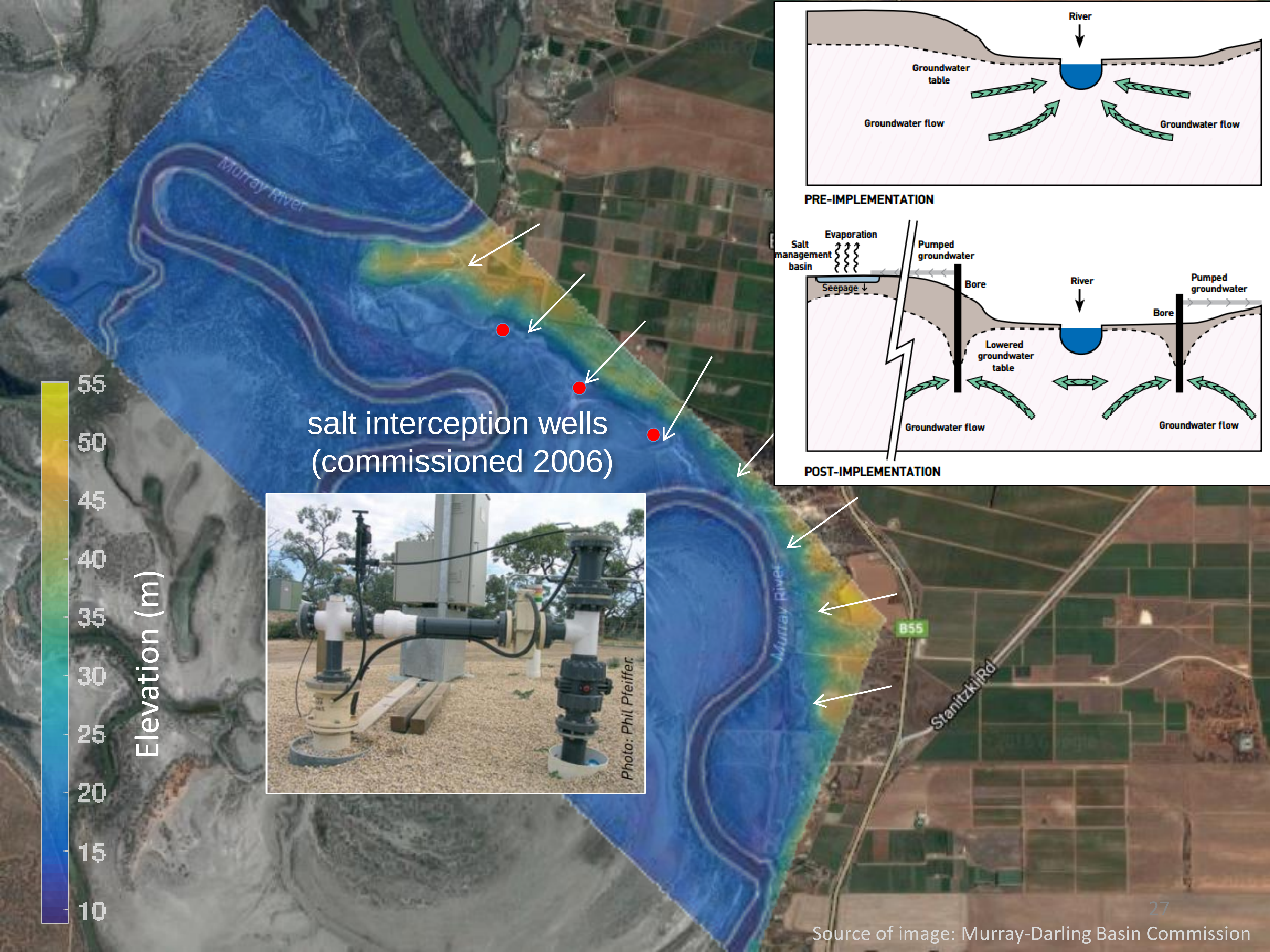
Viezzoli et al., 2009


Setup
Bookpurnong Irrigation Area
Murray River Floodplain
Murray River
Bookpurnong
B55
B55
1 km

- over-irrigation and drought
- saline water recharges river
- floodplain salinization
- ecological damage

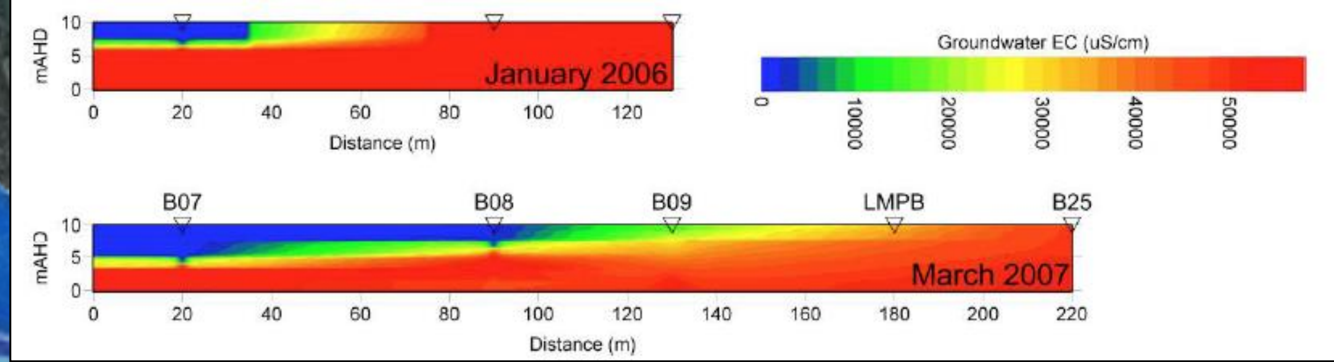


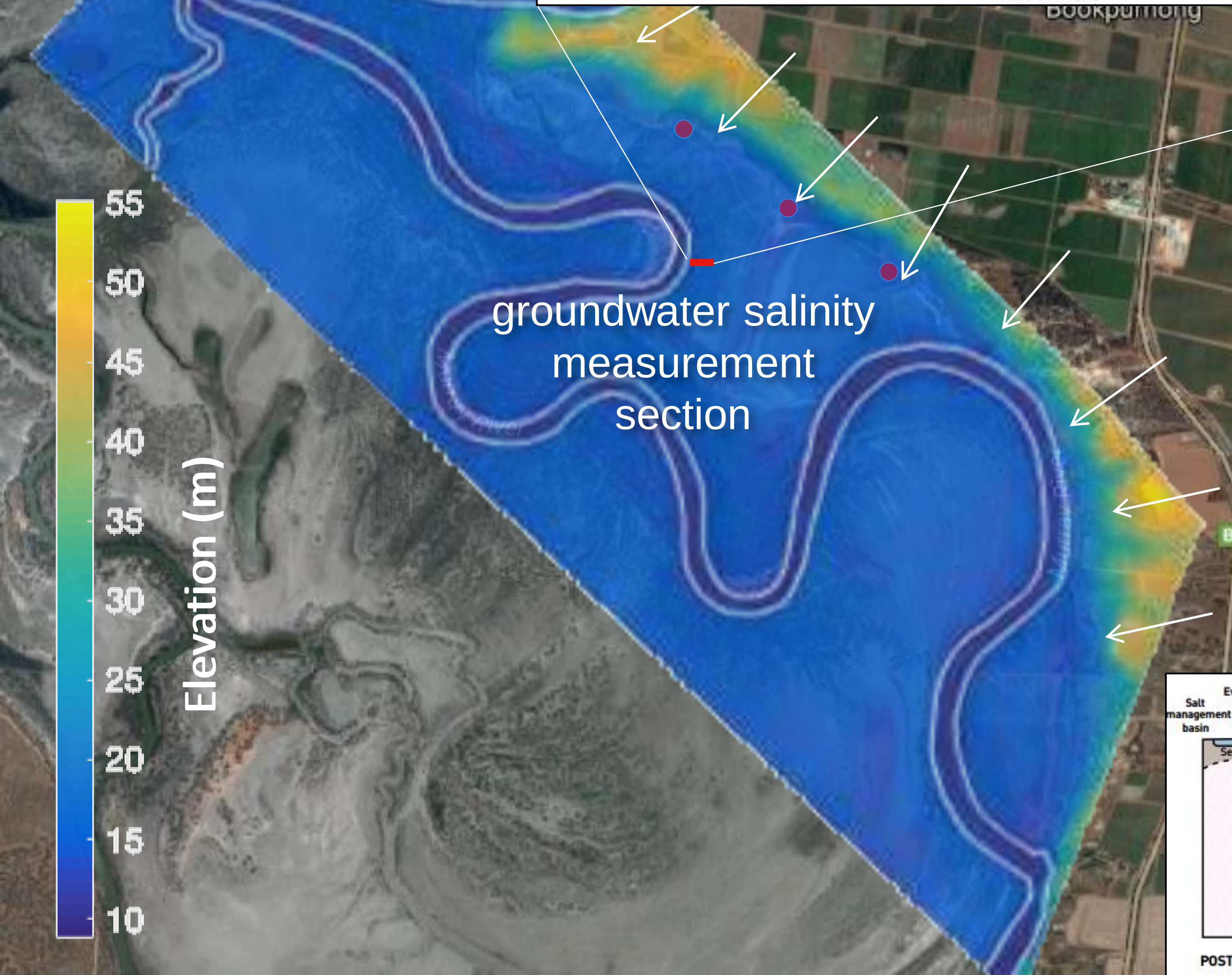
Source of image: Murray-Darling Basin Commission



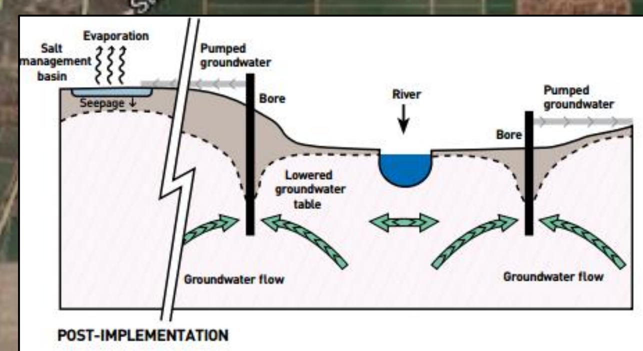
salt interception wells
(commissioned 2006)

Source of image: Murray-Darling Basin Commission



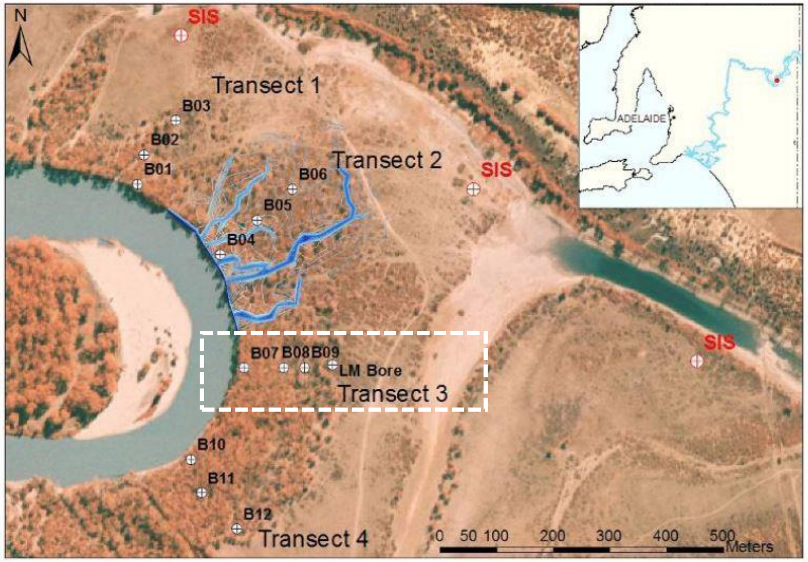


- pumping freshened shallow water near the river
- impractical to drill and sample the entire floodplain
- use airborne EM to quickly survey large areas



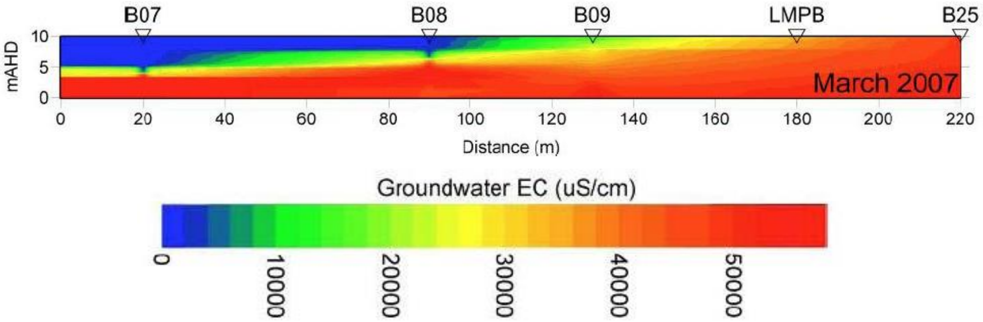
Properties

Location map for salinity measurements



Unit	Conductivity
Saline water	High, 3 - 5 S/m
Fresh water	Low, 0.01 S/m

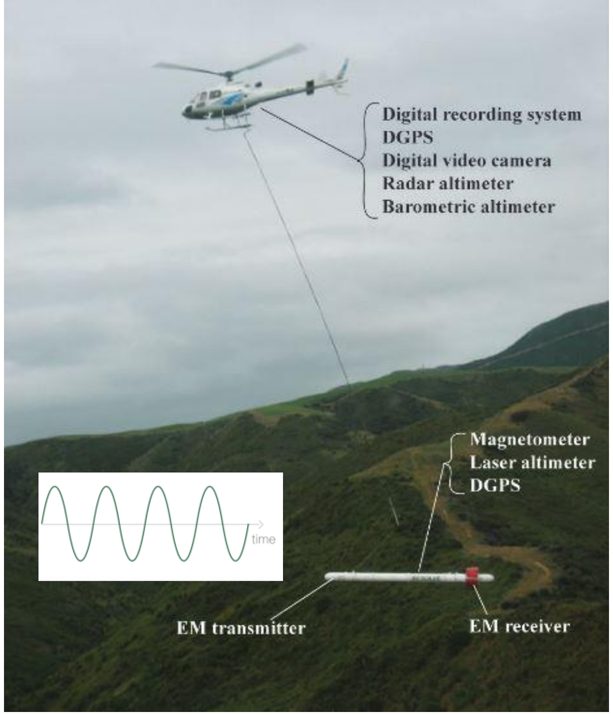
Conductivity from salinity measurements



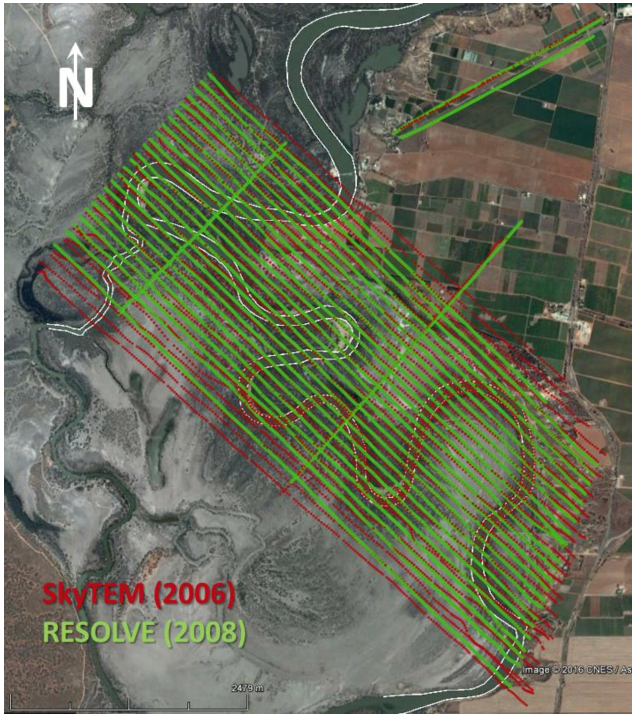
Holland et. al., 2008.

Survey

Resolve system (2008)



Flight lines

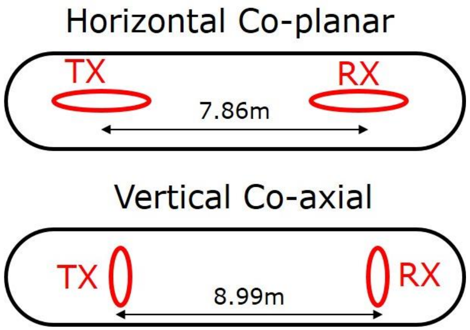


Horizontal Co-planar (HCP) frequencies:

- 382, 1822, 7970, 35920 and 130100 Hz

Vertical Co-axial (VCA) frequencies:

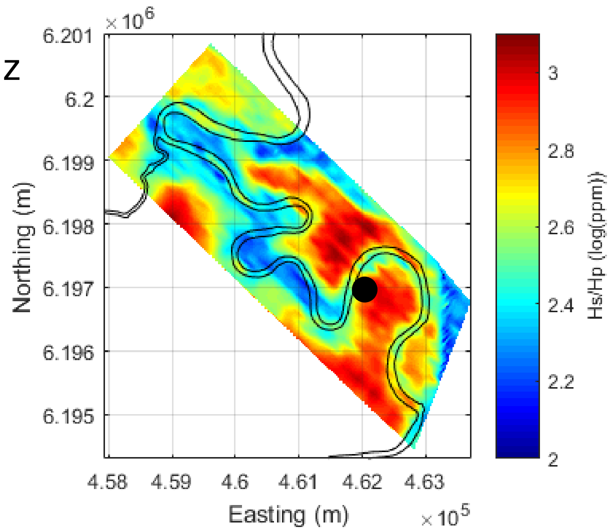
- 3258 Hz

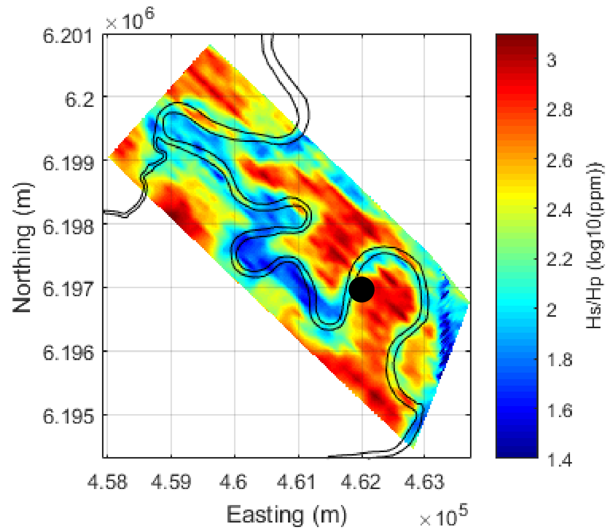


Horizontal Co-planar (HCP) data

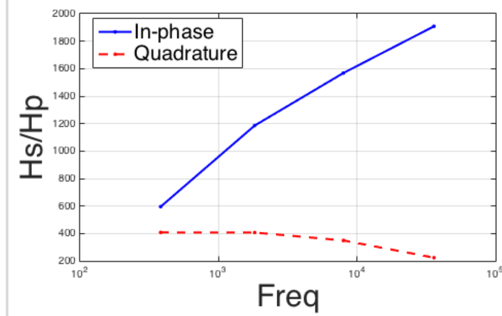
In-Phase (Real) | Quadrature (Imaginary)

382 Hz

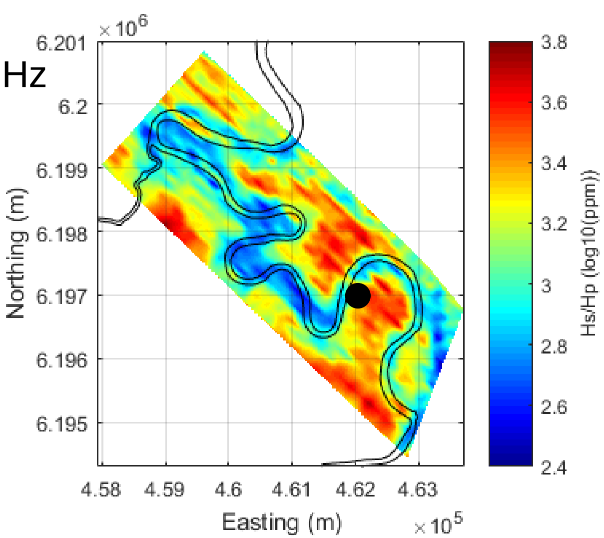


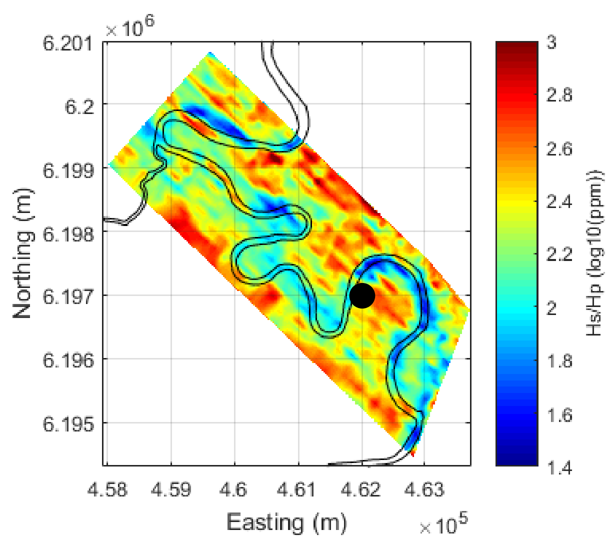


Sounding curve

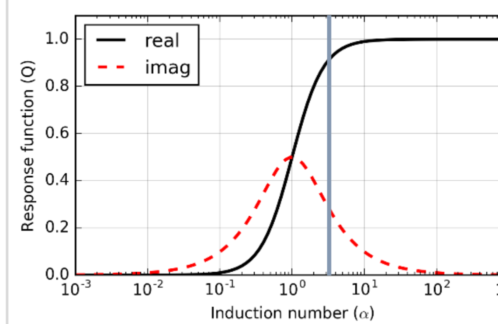


35920 Hz



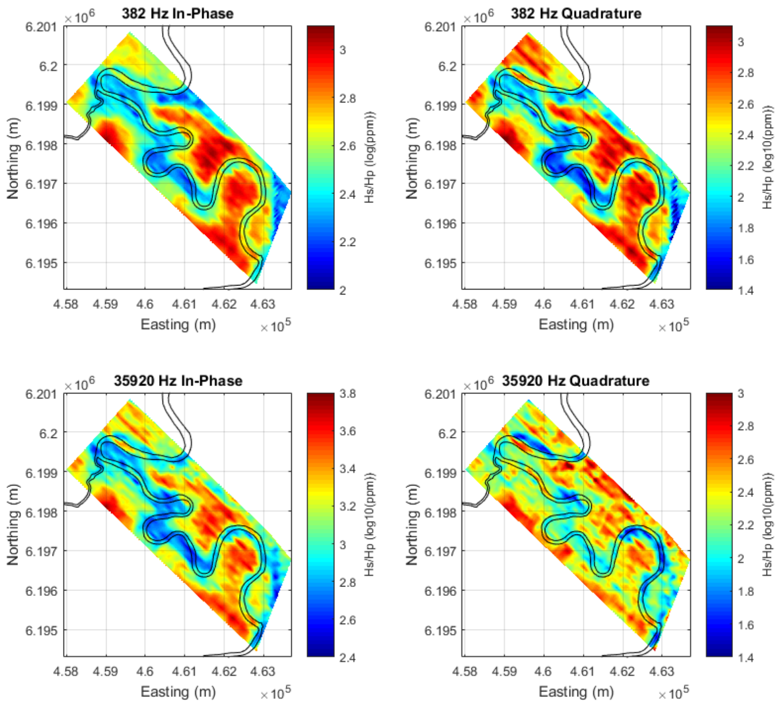


Response curve

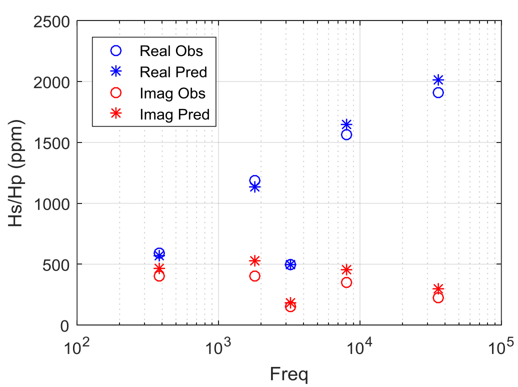


Processing: 1D inversion

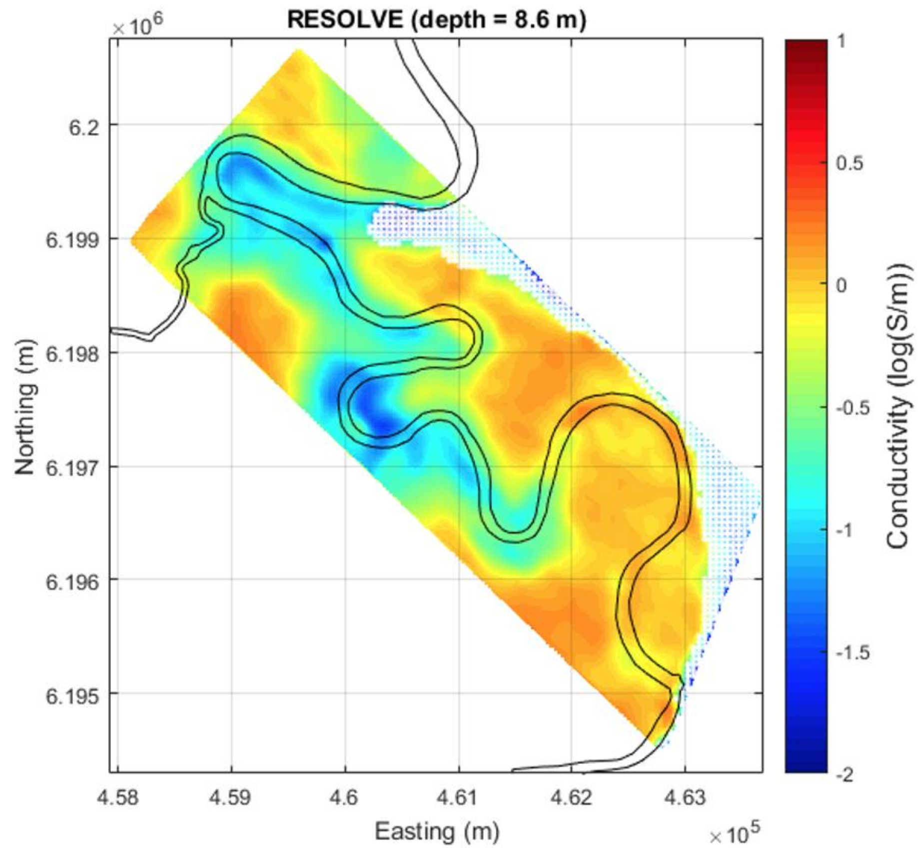
Data



Data fit

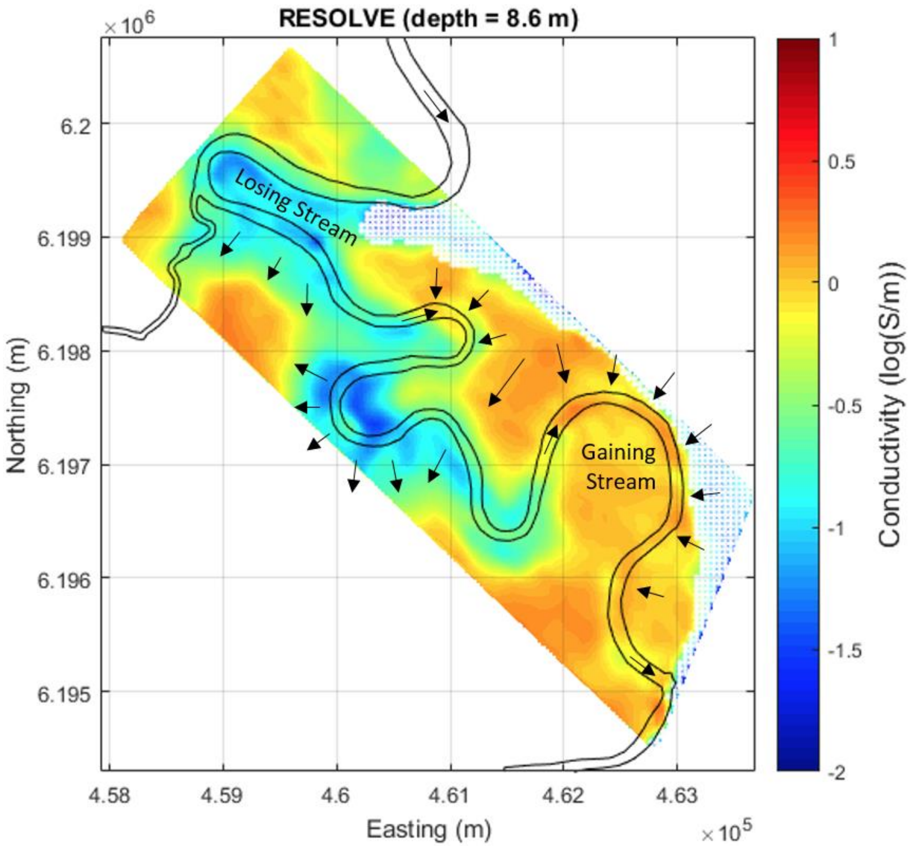


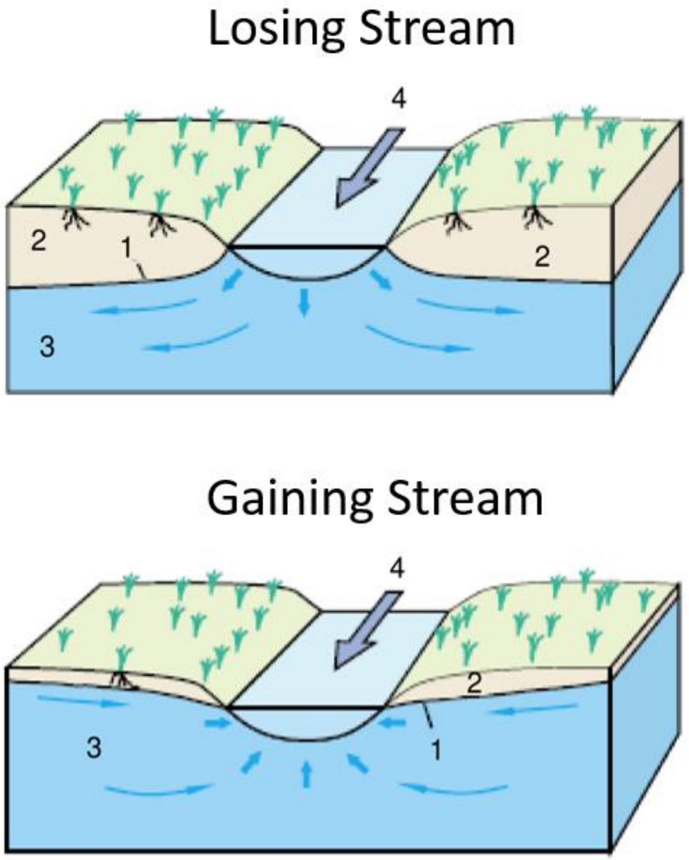
Conductivity model (stitched)



Interpretation

Conductivity model (stitched)



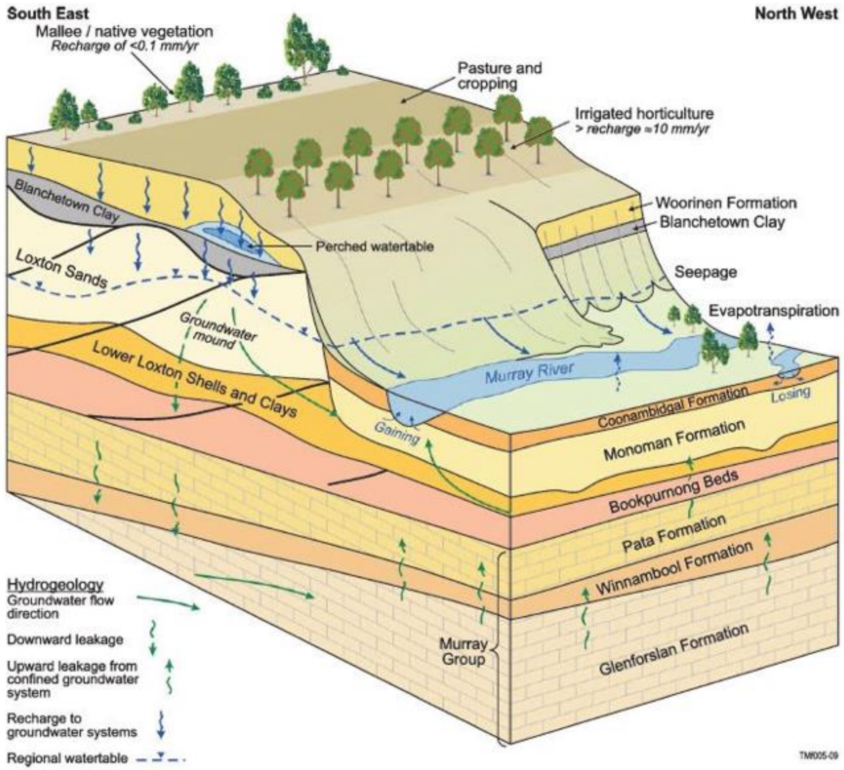


1 – Water table 2 – Unsaturated zone

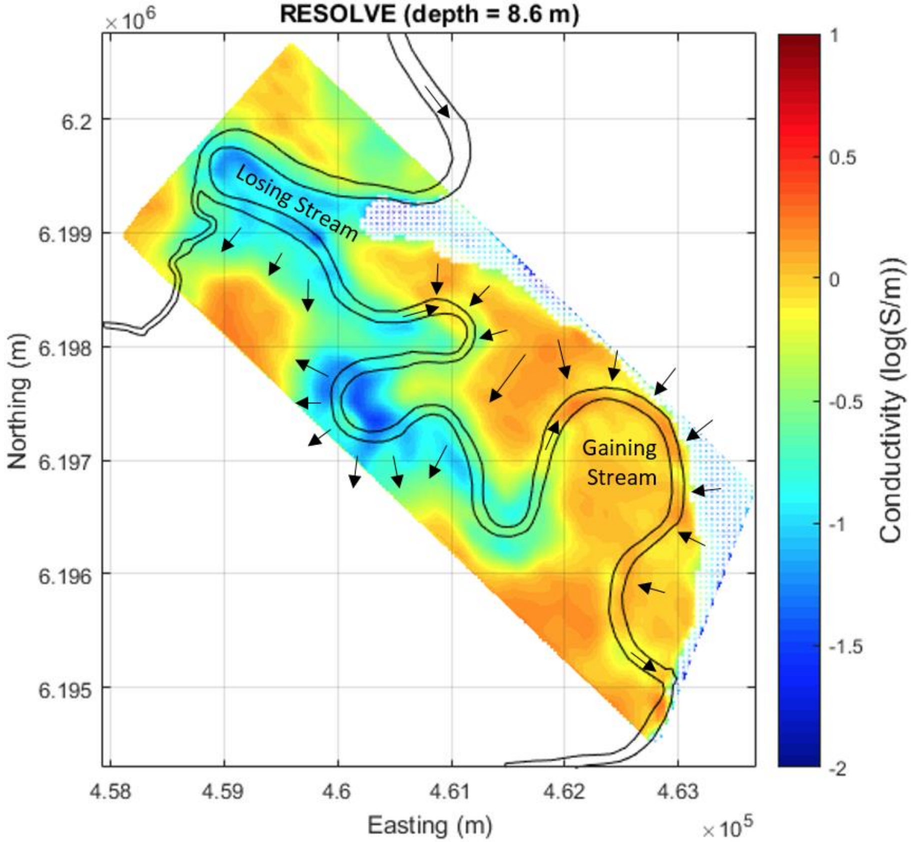
3 – Saturated zone 4 – Flow direction

Synthesis

Hydrological model

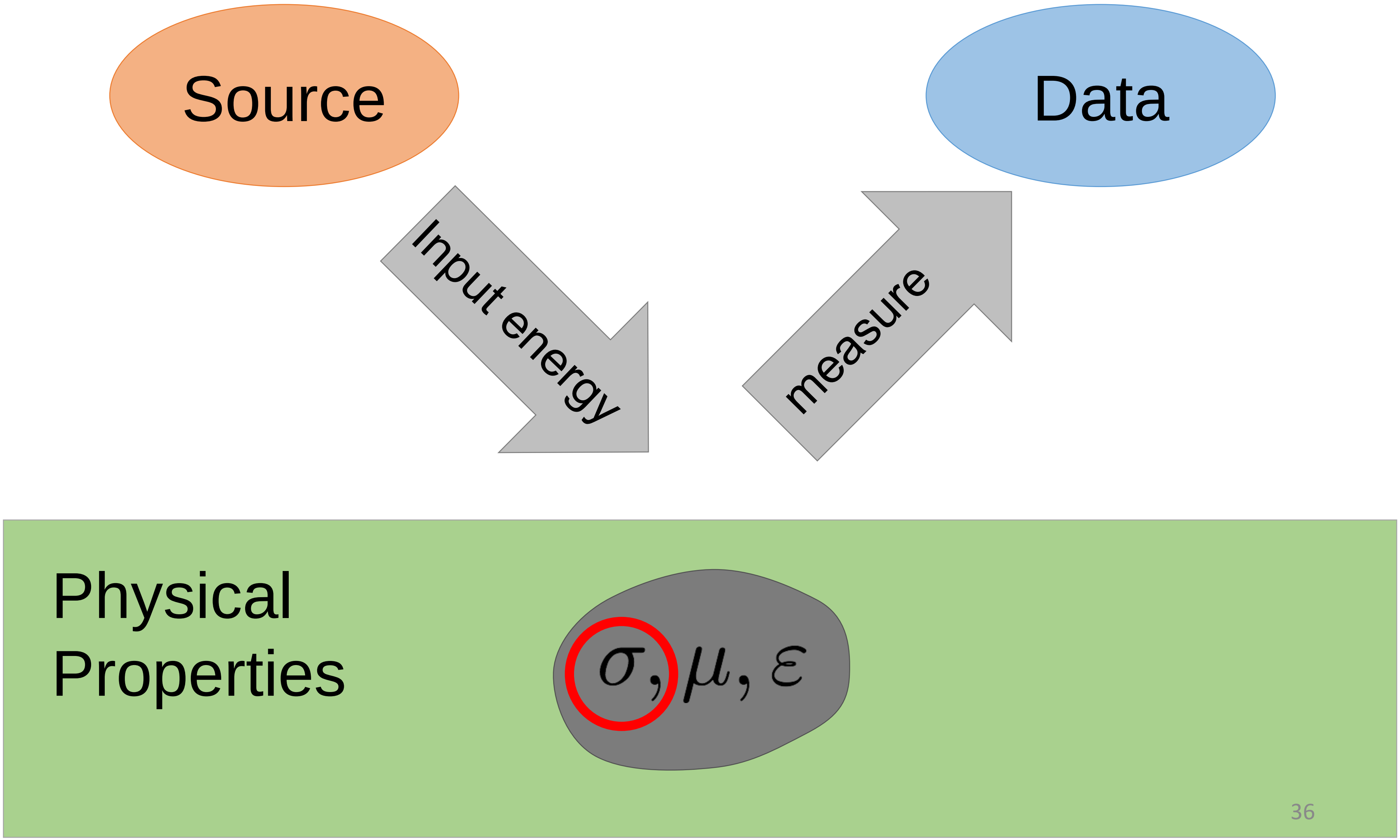


Conductivity model (stitched)



EM Recap

EM Survey & Physical Properties



Basic Experiment

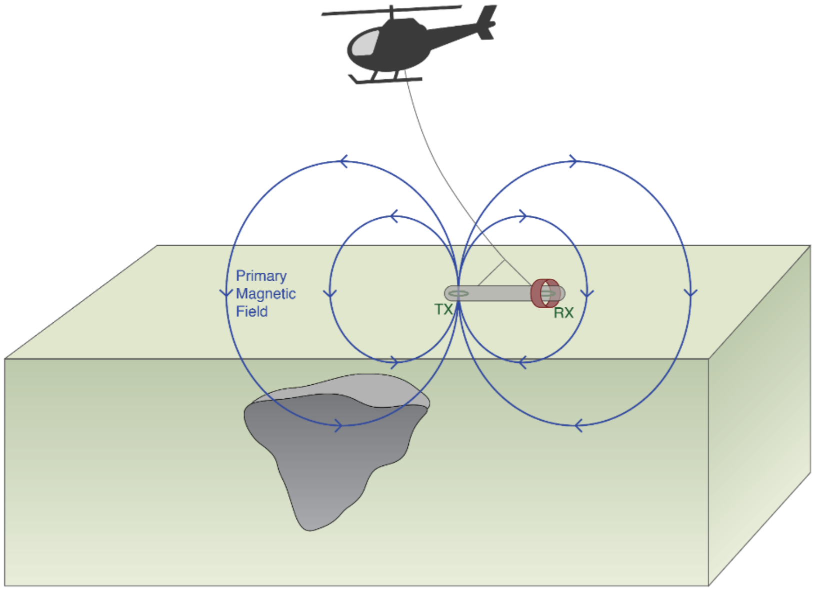
- **Source (Tx):**
  Current loop makes primary magnetic field

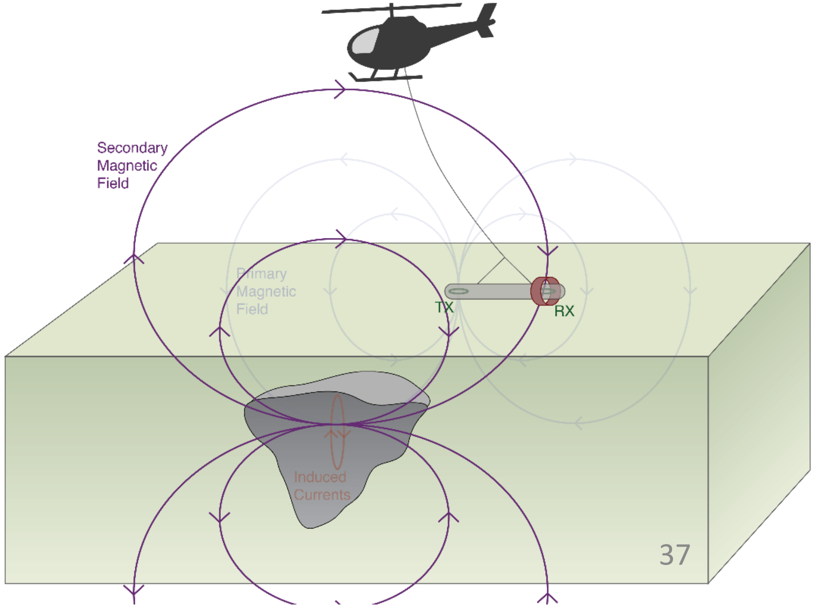
- **Induction:**
  Time-varying magnetic fields induce electric fields everywhere

  → Large induced currents in conductors

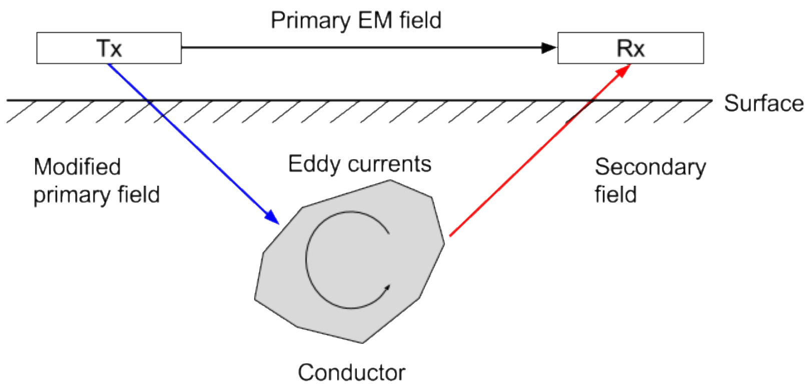
- **Secondary Fields:**
  Induced currents in conductors produce secondary magnetic fields

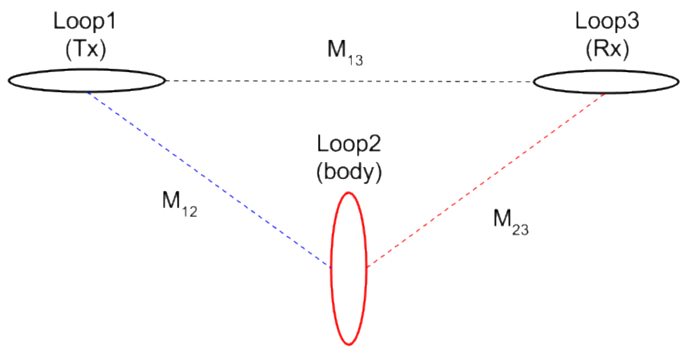
- **Receiver (Rx):**
  Measures magnetic fields





EM Response from Targets



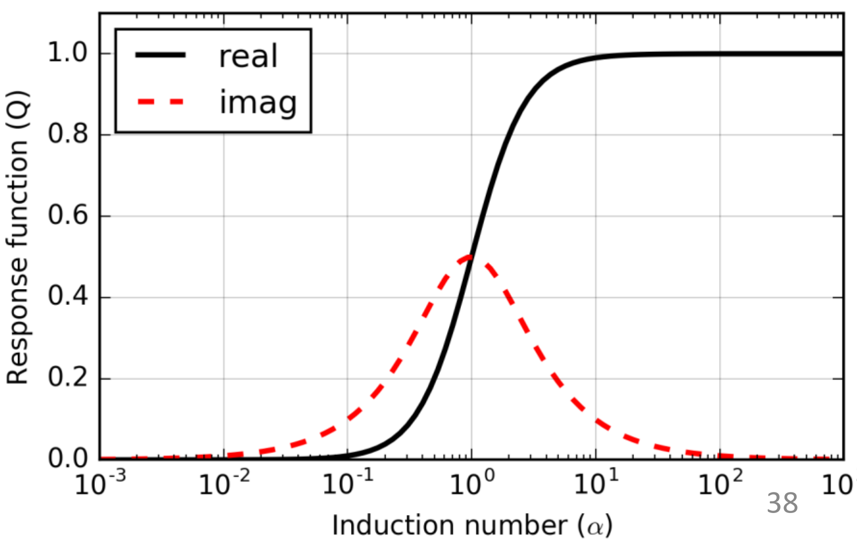


Magnetic field at the receiver

$$\frac{H^s}{H^p} = -\frac{M_{12}M_{23}}{M_{13}L}\underbrace{\left[\frac{\alpha^2 + \imath\alpha}{1+\alpha^2}\right]}_{Q}$$

Induction Number

- Depends on properties of target $\alpha = \frac{\omega L}{R}$

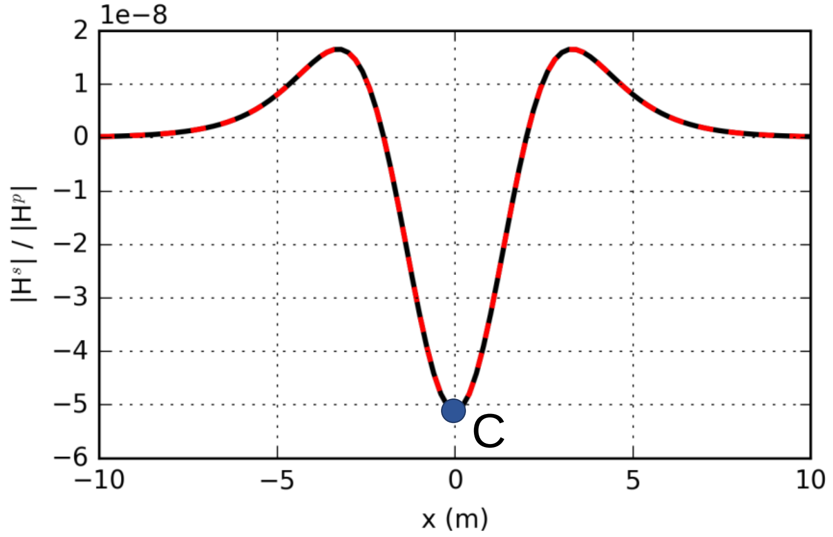


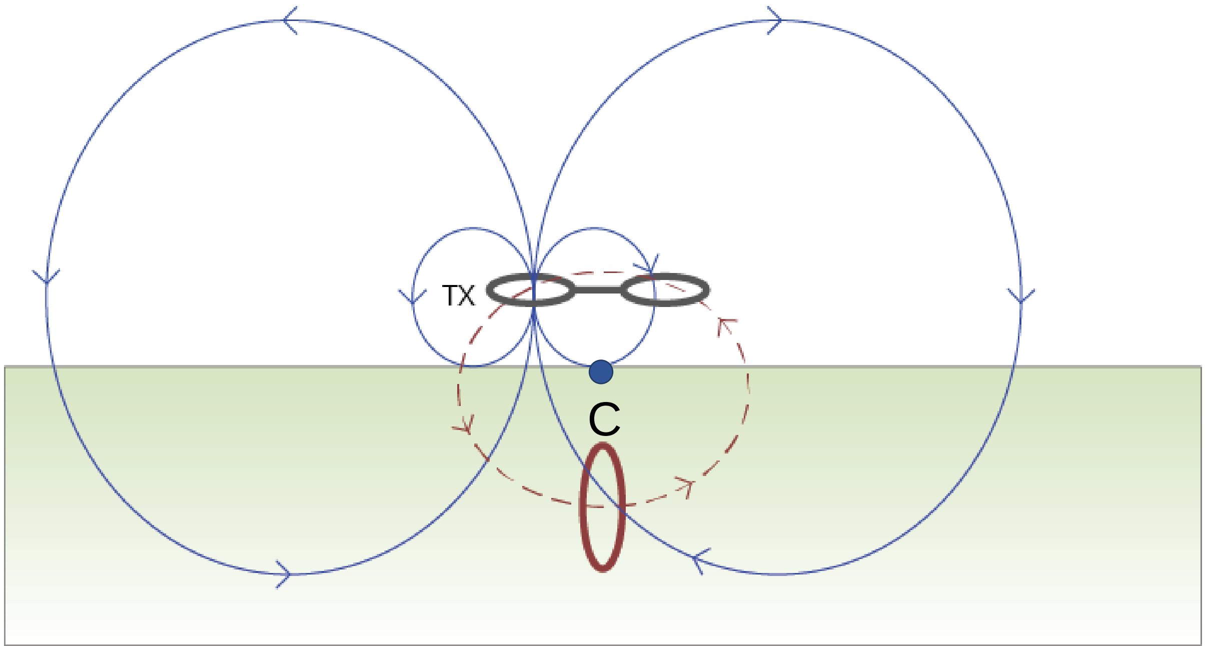
Coupling coefficient:

- Depends on loop geometry

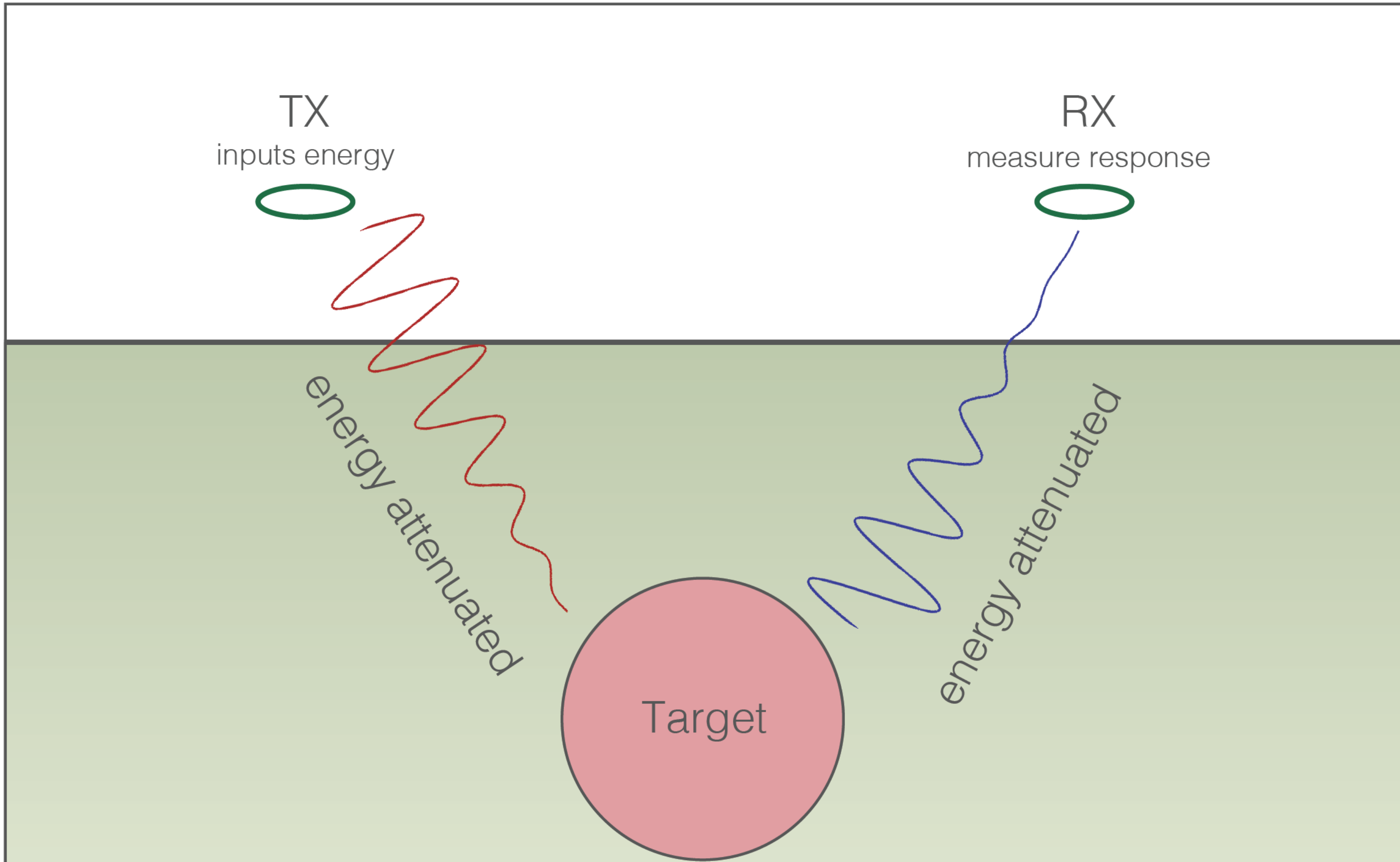
$$M_{12} = \frac{\mu_0}{4\pi}\oint\oint\frac{dl_1 \cdot dl_2}{|\mathbf{r} - \mathbf{r}'|^2}.$$

Response over target





Attenuation of EM Signal

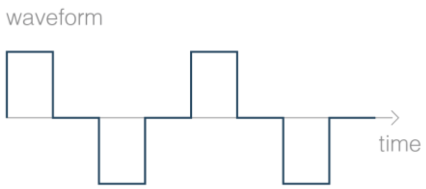


$$\delta \approx 500\sqrt{\frac{\rho}{f}}$$

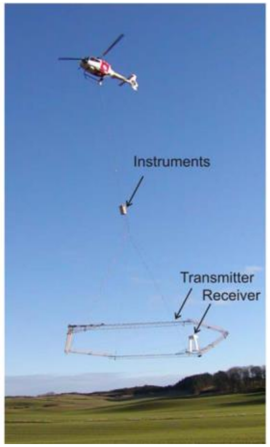
Data: Sounding Curve

Data obtained at a single location

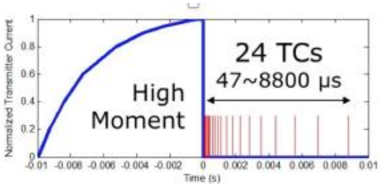
- Time



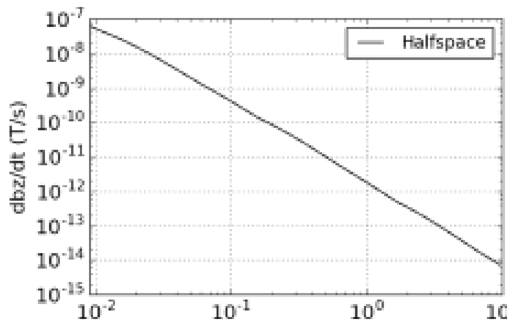
SkyTEM



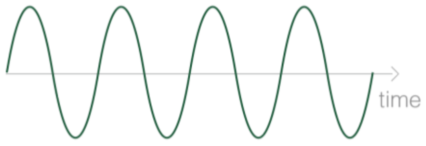
Sampling times



Sounding curve

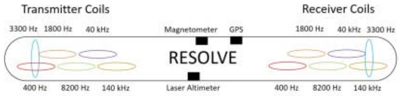


- Frequency

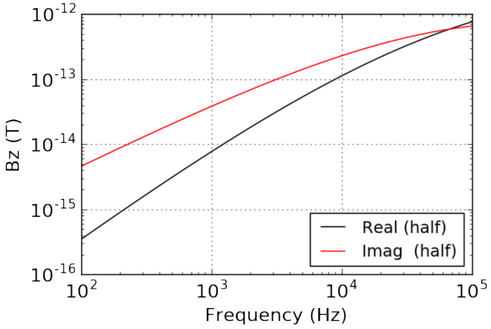


Resolve

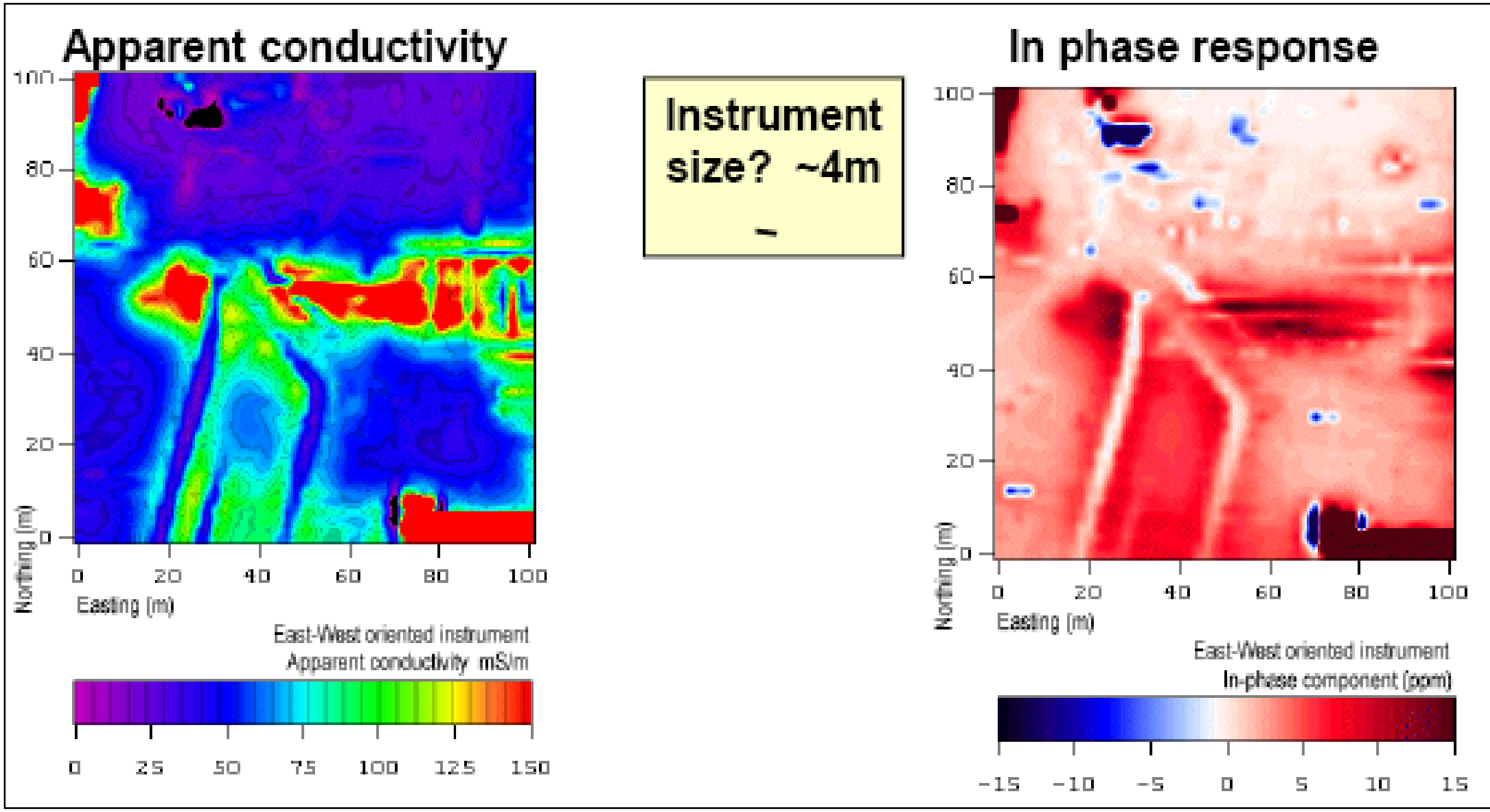
Sampling frequencies



Sounding curve



Apparent Conductivity and In-Phase Data



- **Apparent conductivity (mS/m):** lateral changes in conductivity
- **In-phase (ppm):** Large value highlights buried conductors

Unit Activities

- **Labs: (EM I)**
  - Monday, November 4th
  - Tuesday, November 5th
- **Labs: (EM II)**
  - Monday, November 18th
  - Tuesday, November 19th
- **TBL:**
  - Wednesday, November 15th
- **Quiz:**
  - Wednesday, November 15th