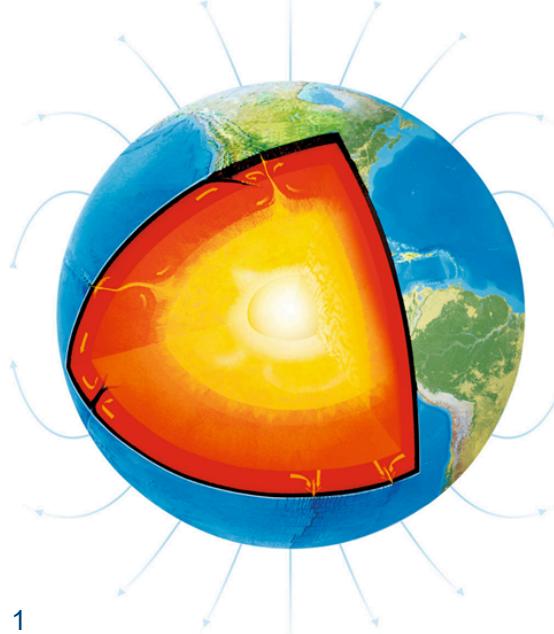


# Einführung in die Geophysik

## Teil 9: Induzierte Polarisation, Induktive Elektromagnetik

2. BSc Geophysik und Geoinformatik (BGIP)



*Thomas Günther*  
*(thomas.guenther@geophysik.tu-freiberg.de)*

# Previously on AnGy

1. ~~Gravimetric (1.5)~~
2. ~~Geomagnetik (2.5)~~
3. ~~Geelektrik+Inversion (3)~~
4. Induktive Elektromagnetik (1)
5. Georadar (1)
6. Seismik (3)

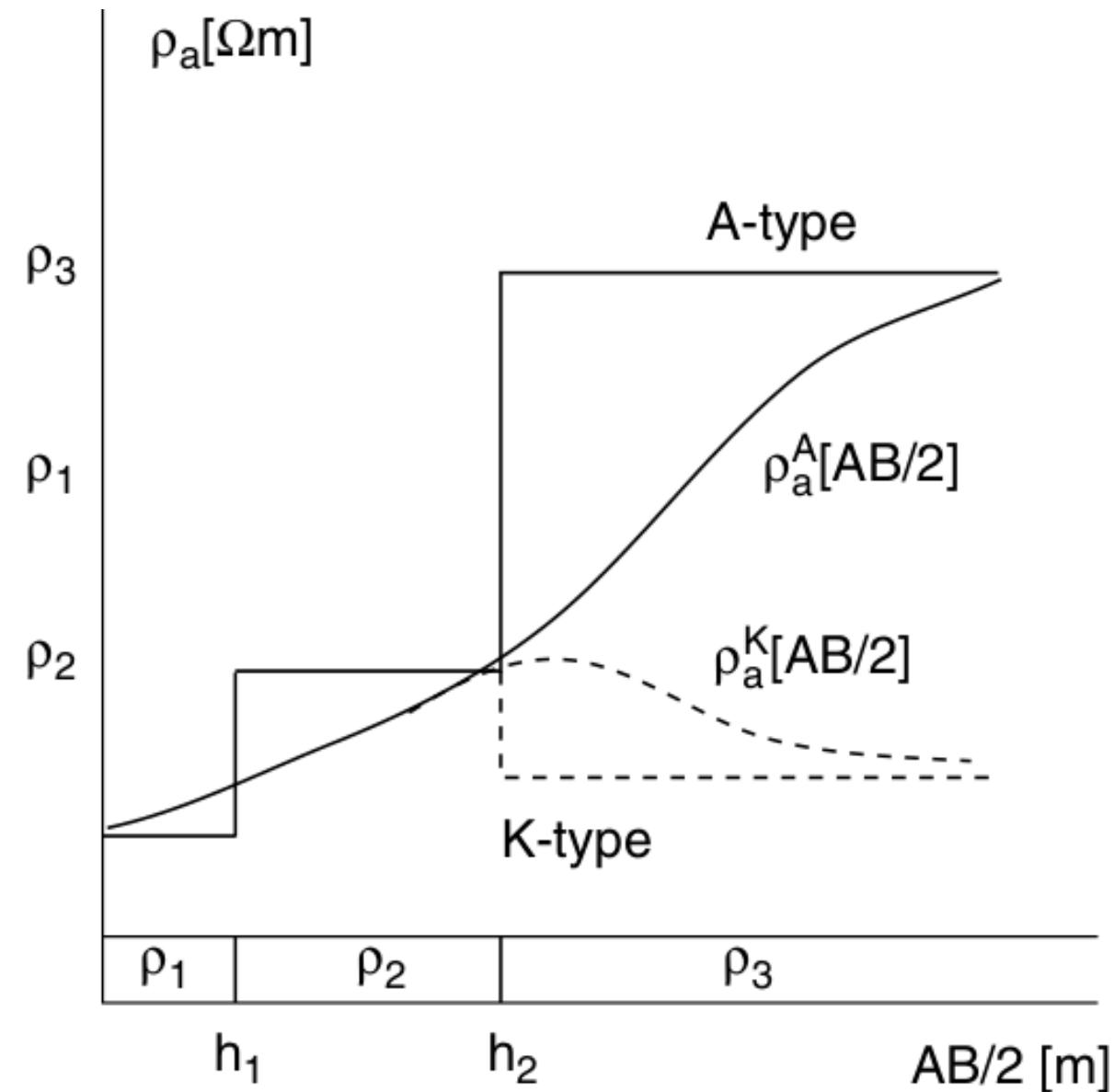
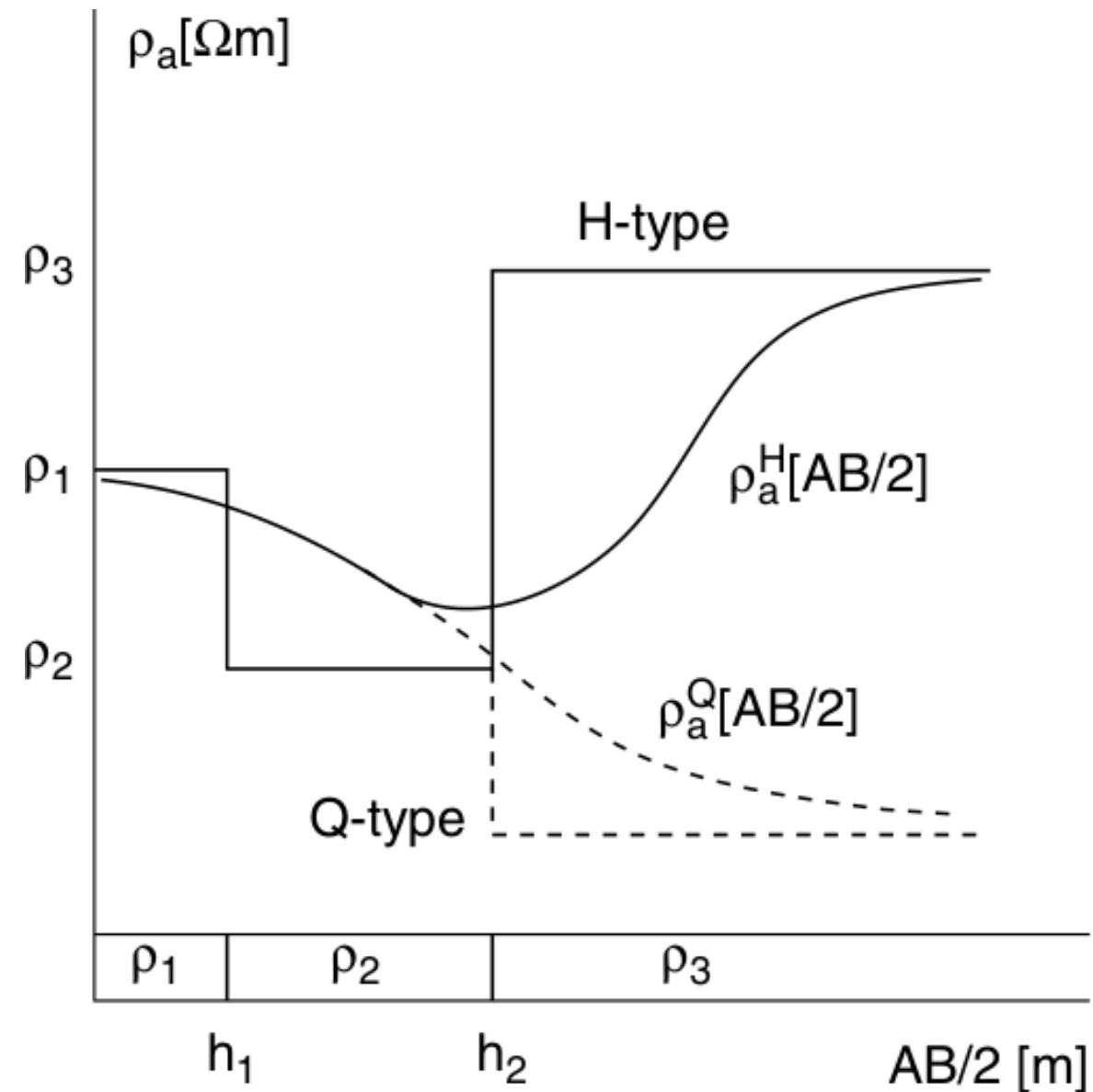
# Termine Praktikum

- 05.06. Geoelektrik-Messung
- 06.06. Auswertung Magnetik+Gravimetrie
- 13.06. Auswertung Geoelektrik
- 20.06. Georadar + EM38
- 27.06. Refraktions-Seismik
- 04.07. Auswertung EM + Seismik
- 11.07. Zusammenfassung

# Zusammenfassung Geoelektrik

- getrennte Stromeinspeisung & Spannungsmessung (4-Punkt)
- Verschiedene Mess-Strategien
  - Kartierung mit fester Anordnung entlang eines Profils
  - Tiefen-Sondierung mit vergrößernden Abständen (VES)
  - Kombination mit Multi-Elektroden-Gerät (2D/3D-ERT)
- einfaches & günstiges Verfahren (cm-km)
- breites Anwendungsfeld (Hydro, Ingenieur, Geologie, ...)

# Schlumberger sounding curves (Everett, 2013)

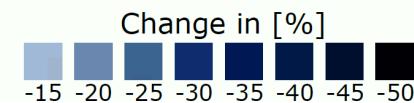
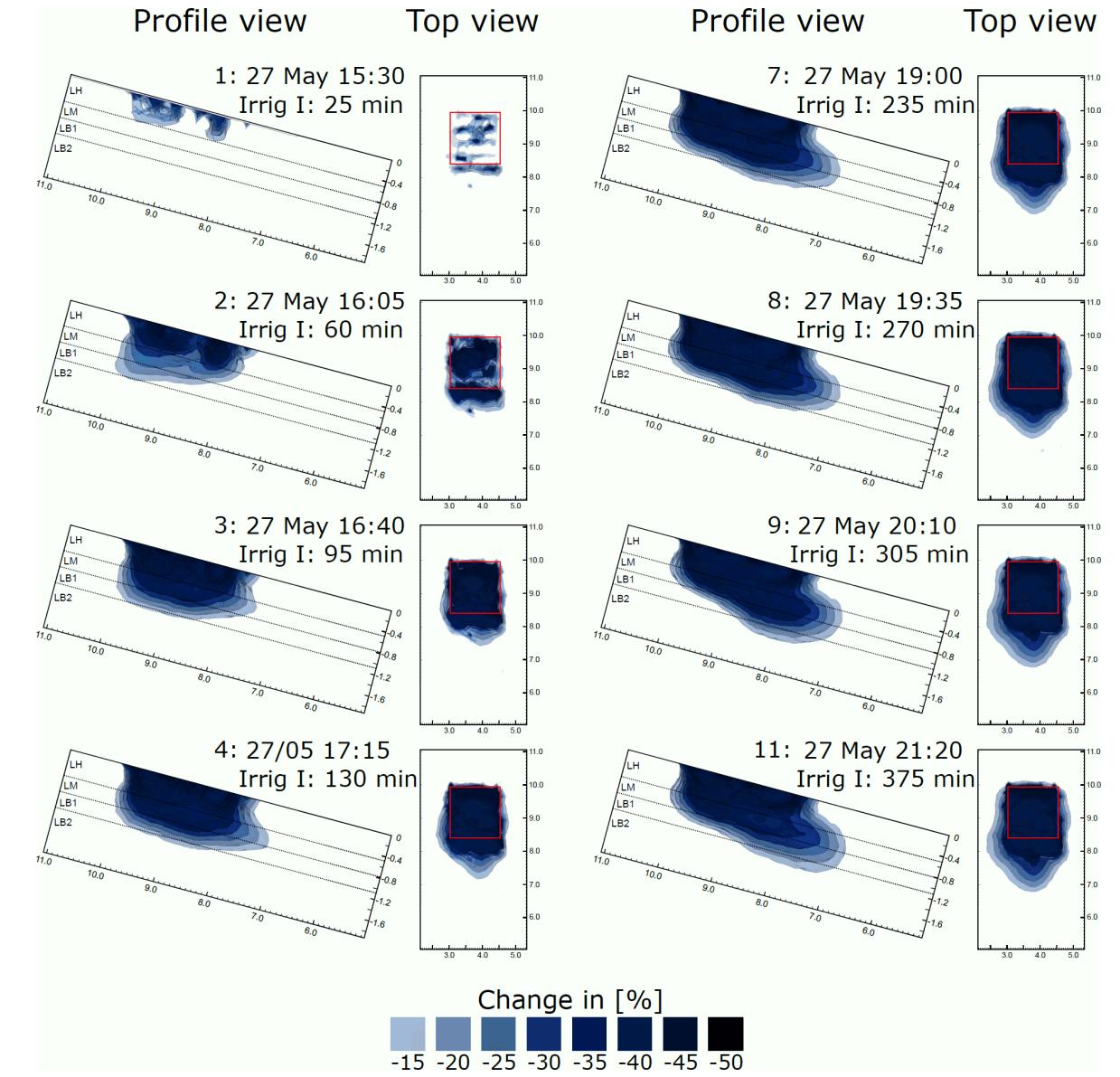
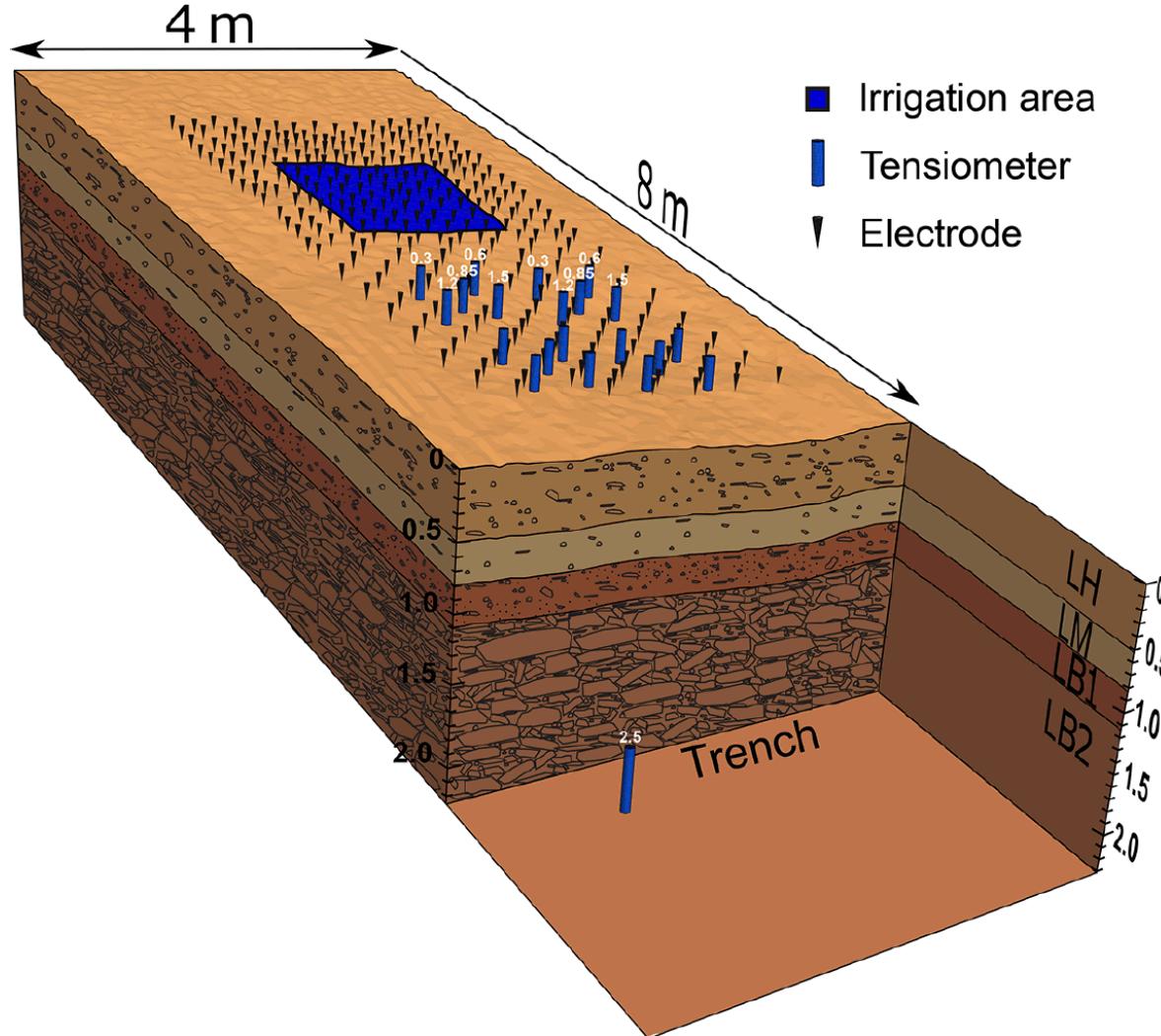


# ERT Monitoring

Zeitlich wiederholende (automatisiert) ERT-Messungen können Änderungen im Untergrund überwachen (“monitoren”) und damit dynamische Vorgänge abbilden

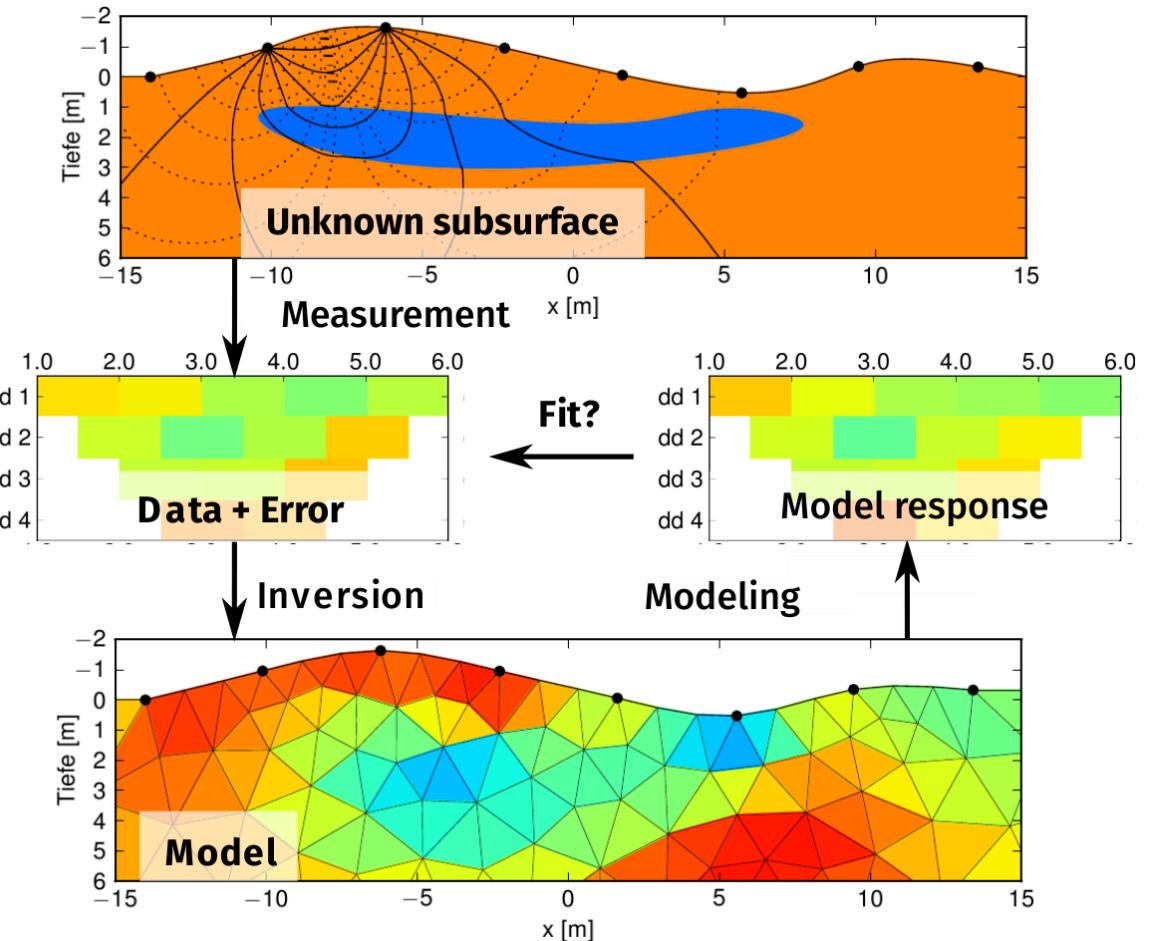
Beispiele: Tracerausbreitung, Infiltration, Salz-/Süßwasserdynamik, Durchfeuchtung, Abbau von Schadstoffen

# 4D Infiltration monitoring (Hübner et al. 2017)



# Geophysikalischer Workflow

1. Datenakquisition
2. Filter und Fehler
3. Parametrisierung
4. Inversion
5. Evaluierung
6. Postprocessing & Visualisierung
7. Interpretation



# Inversion - Methodik

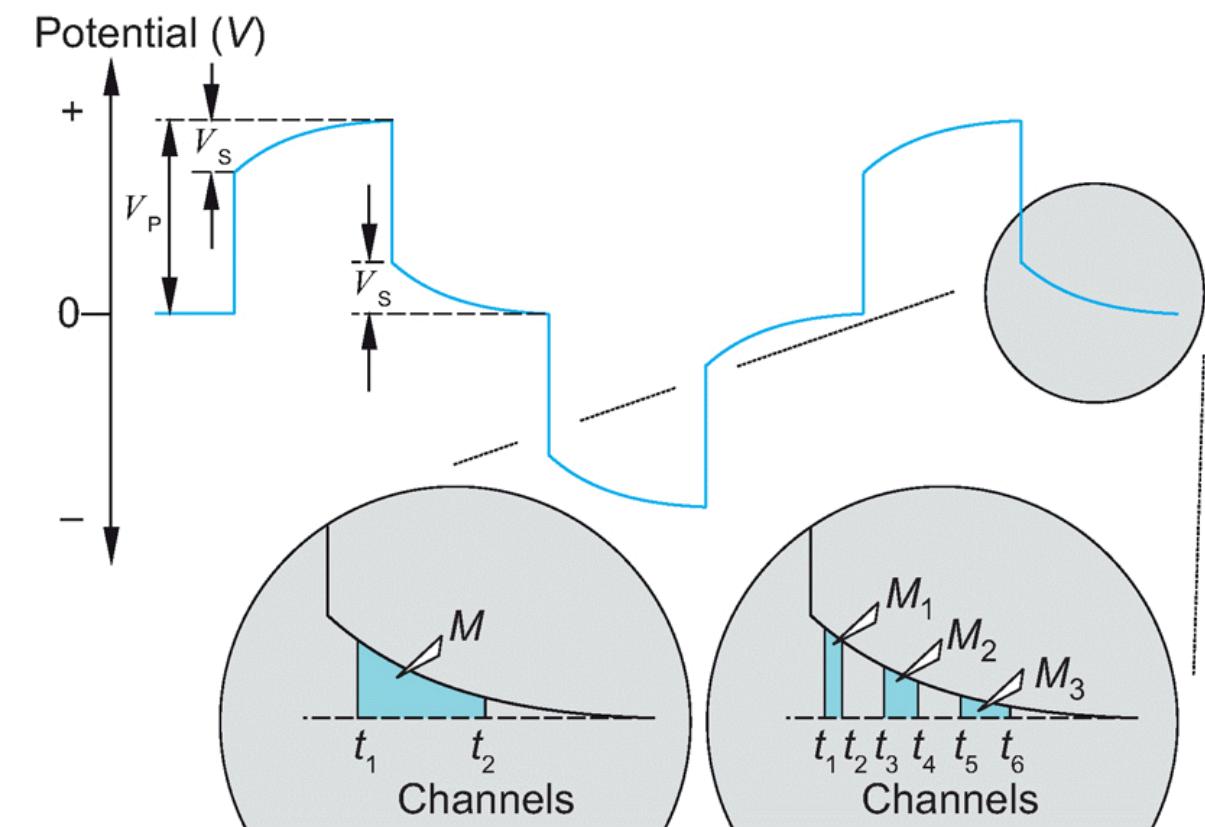
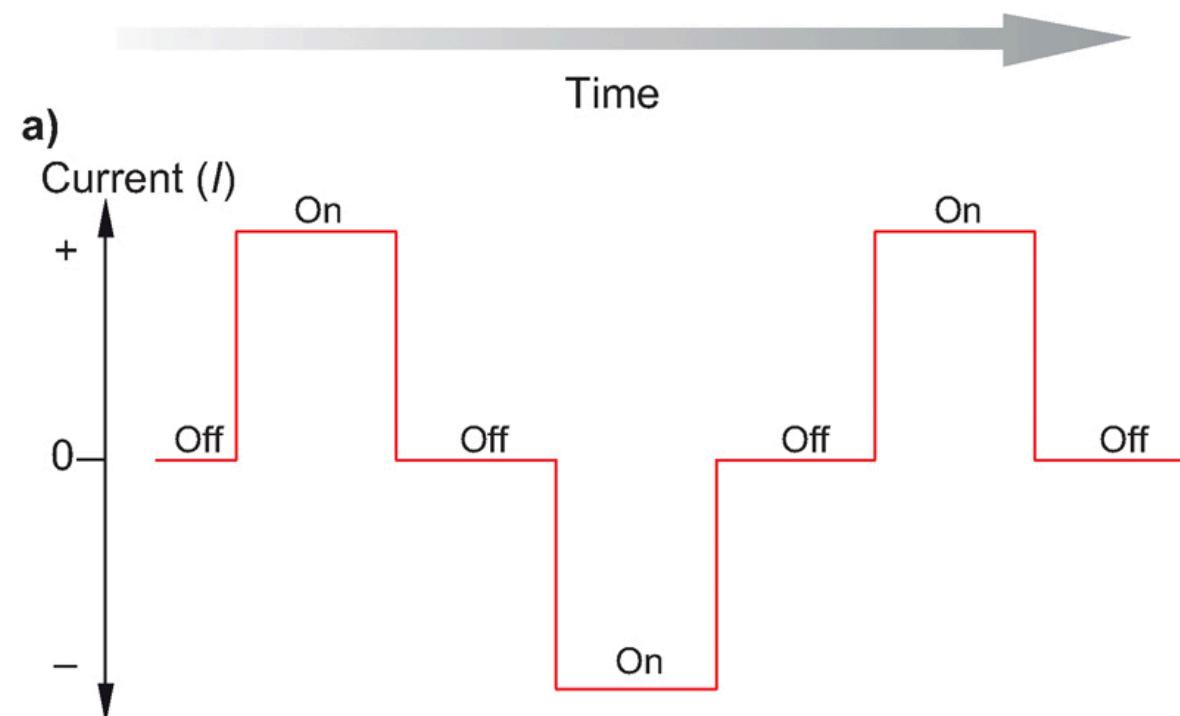
**Grundprinzip:** Methode der kleinsten Quadrate

Minimierung der Fehlerquadratsumme zwischen Daten & Modellantwort

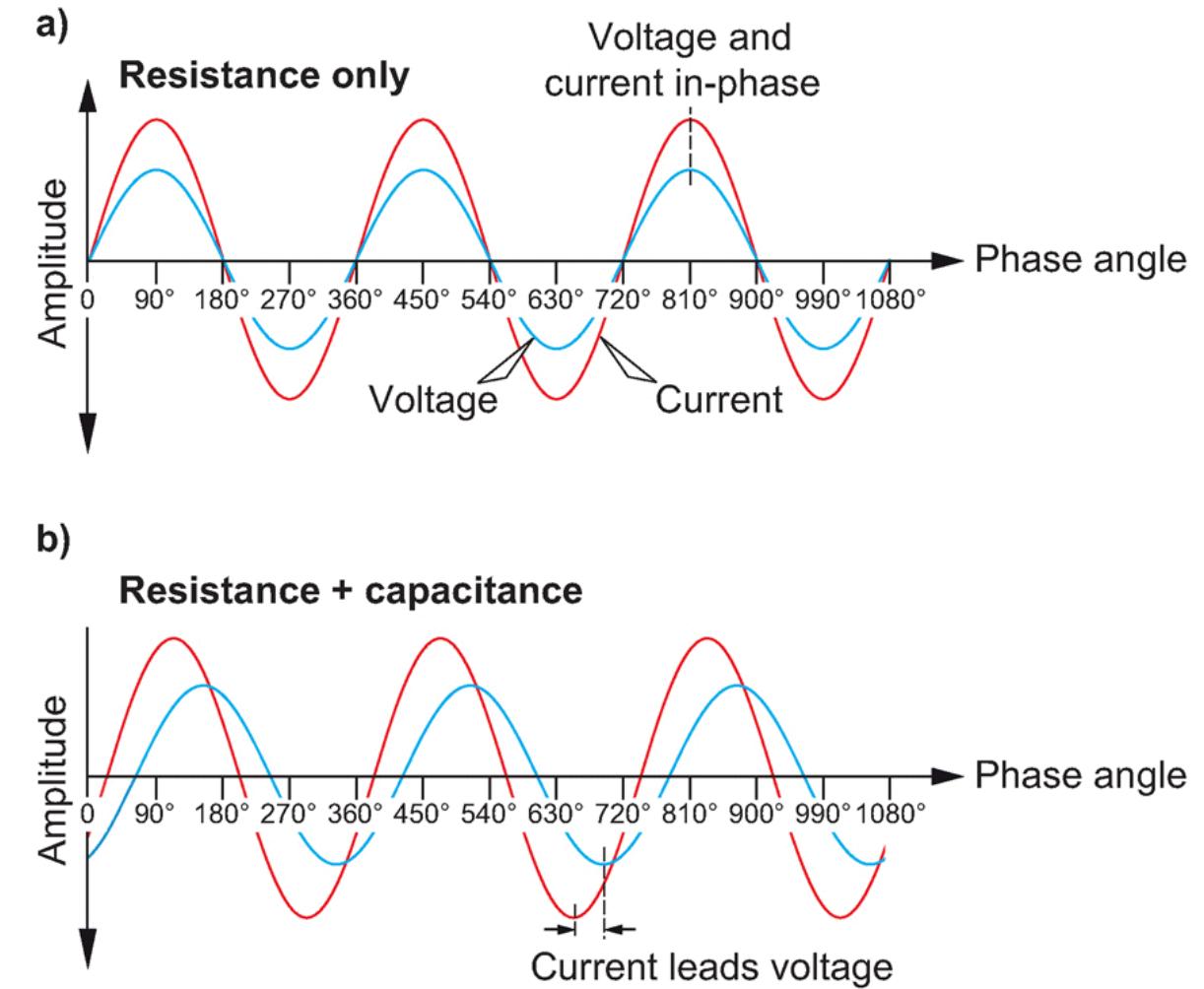
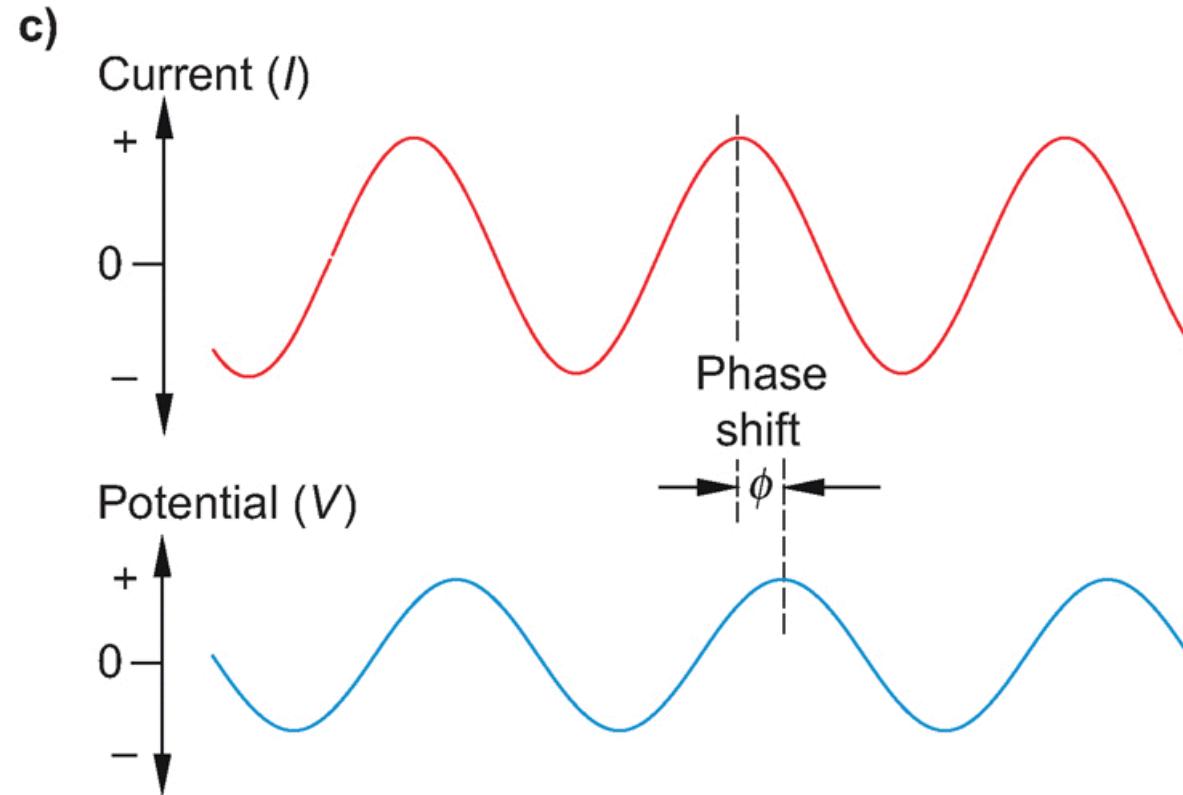
$$\Phi = \sum_i (d_i - f_i(m))^2 \rightarrow \min$$

$\Phi$  wird als Zielfunktion bezeichnet

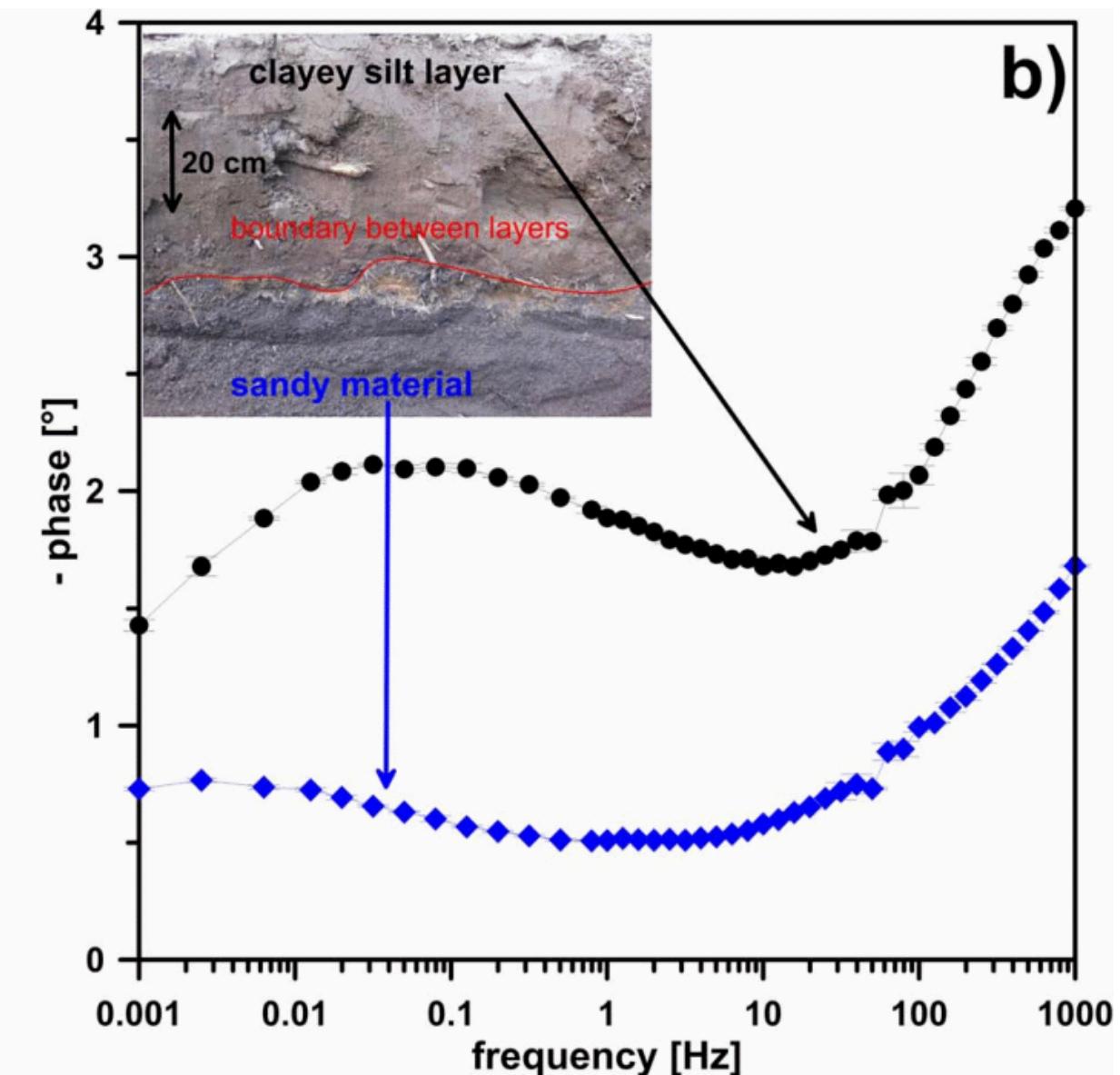
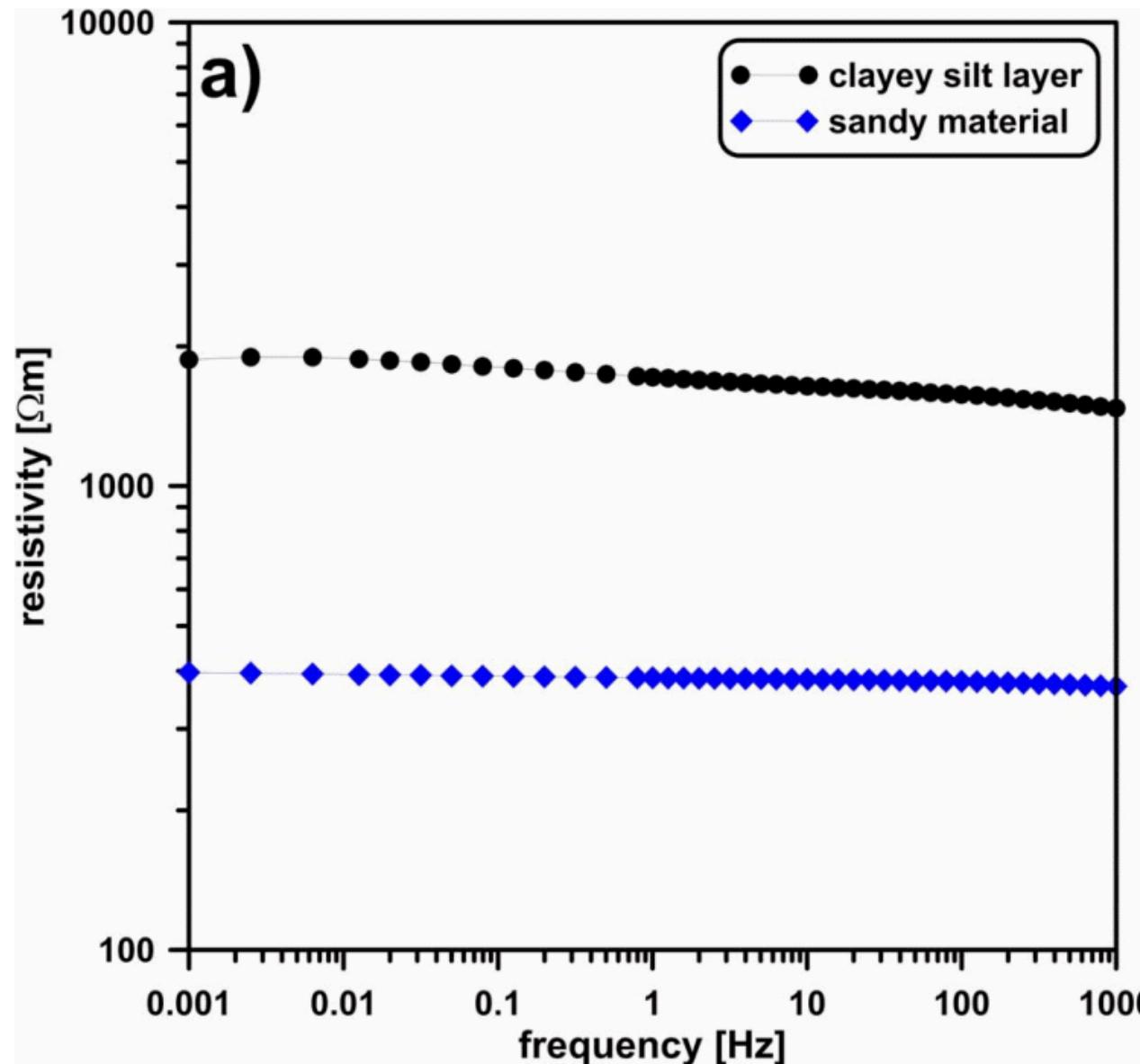
# Induzierte Polarisation



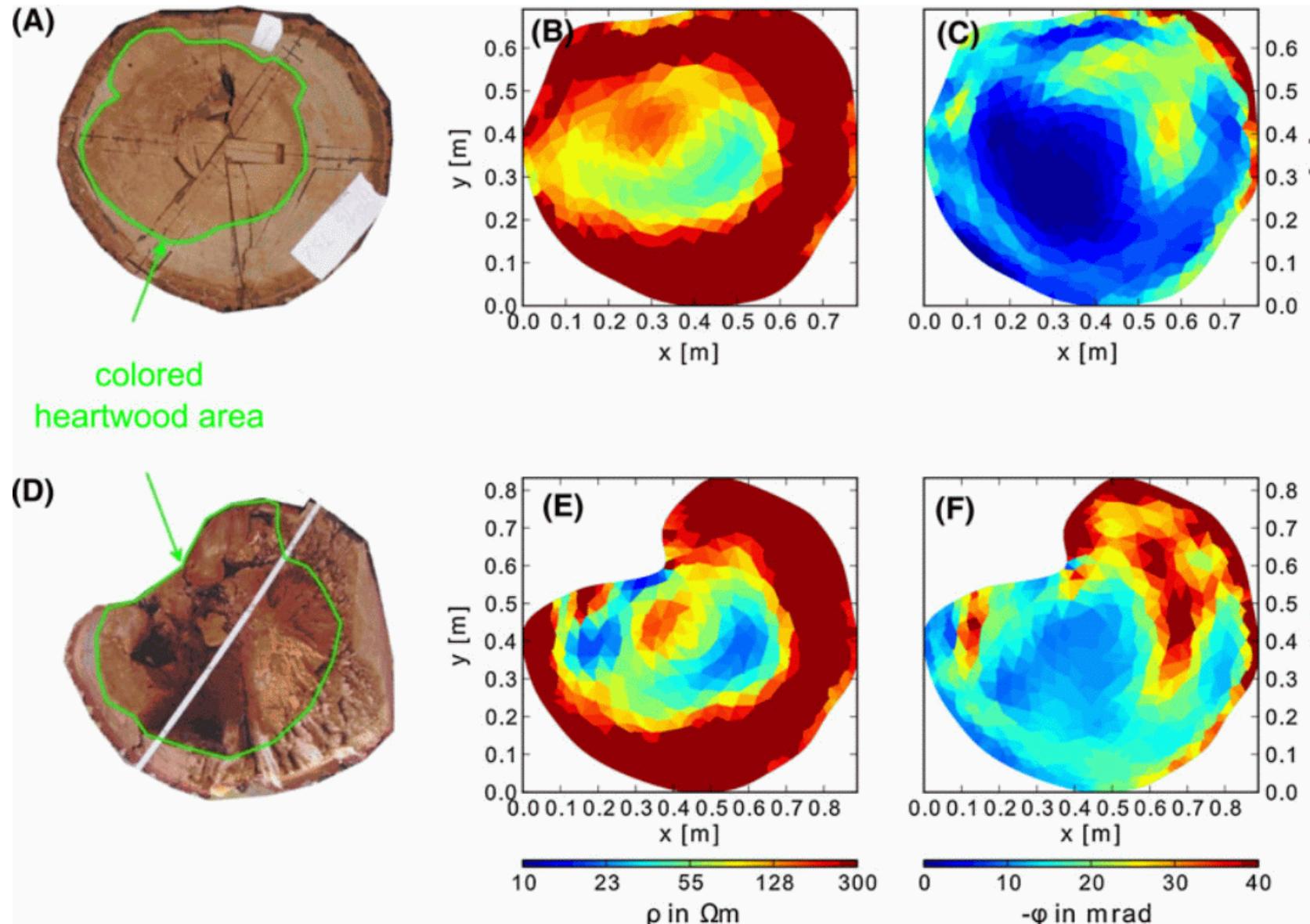
# Induzierte Polarisation



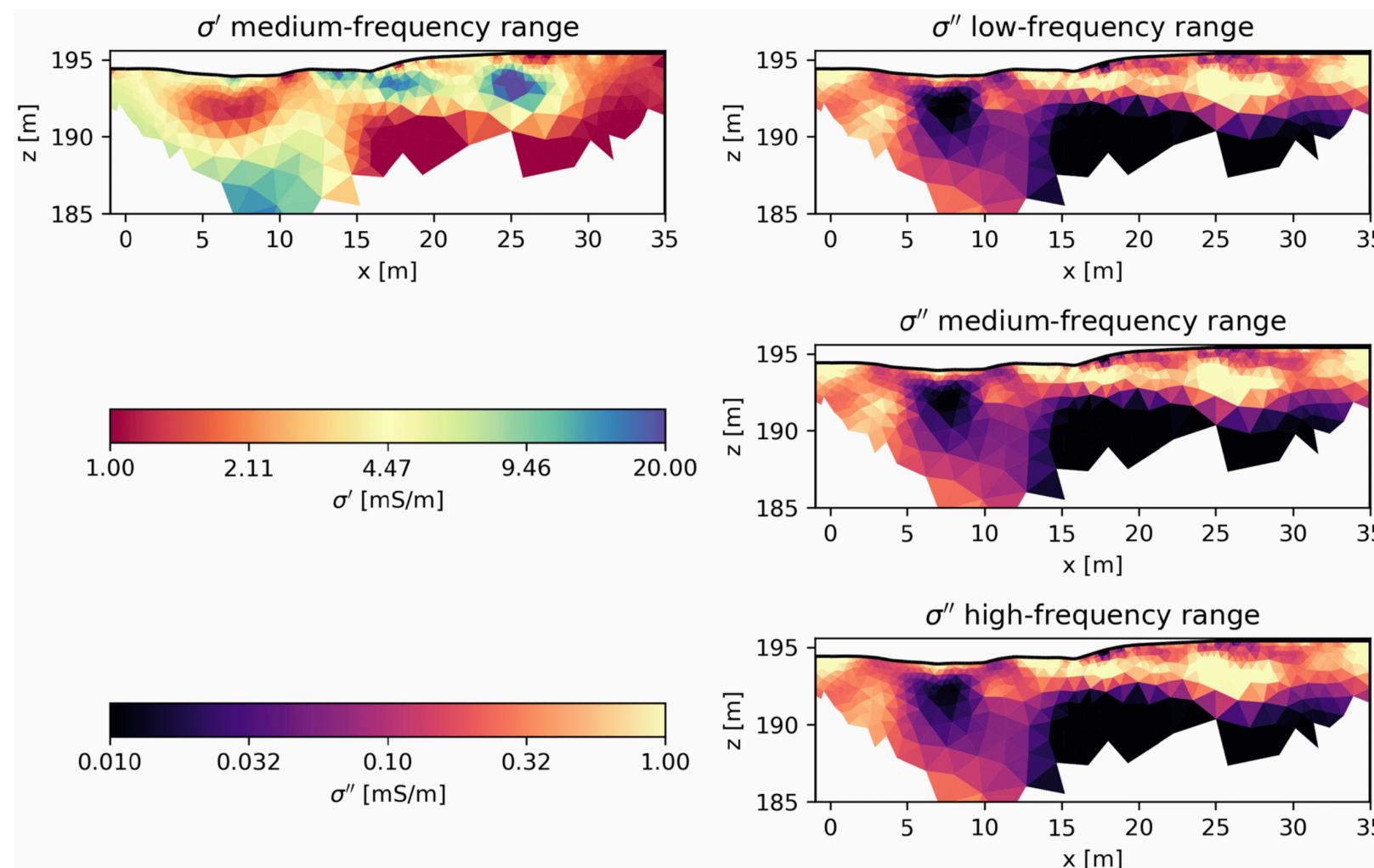
# Spektrale Induzierte Polarisation (SIP)



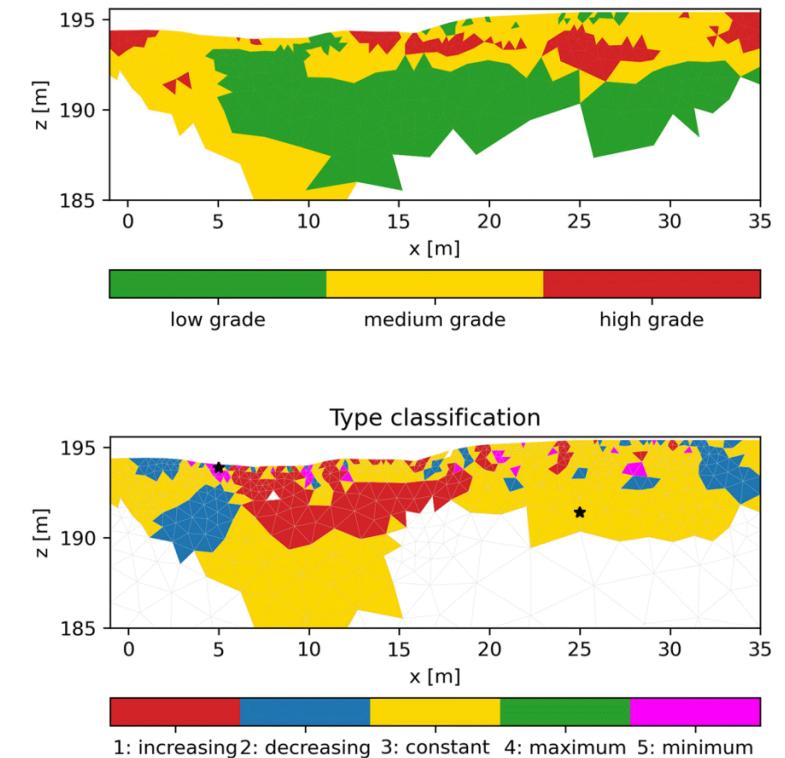
# IP Inversion (Martin&Günther, 2013)



# IP Inversion (Martin et al. 2021)



⇒ Mineral-Grad/Typ



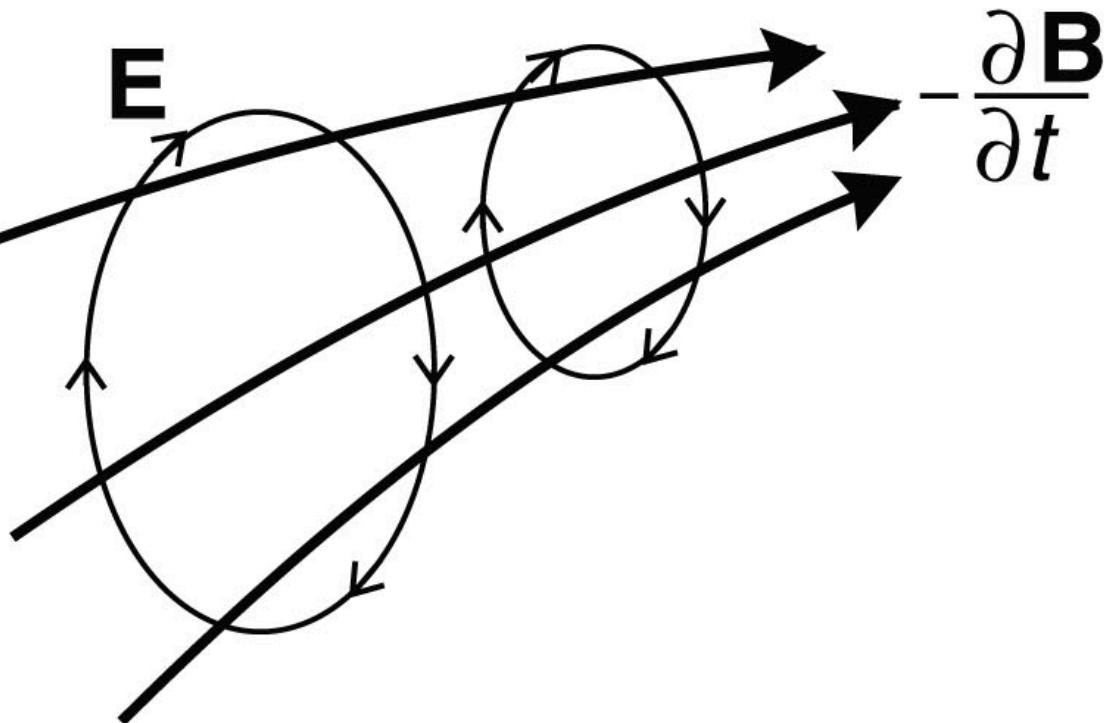
# Induktive Elektromagnetik

# Elektromagnetische Größen

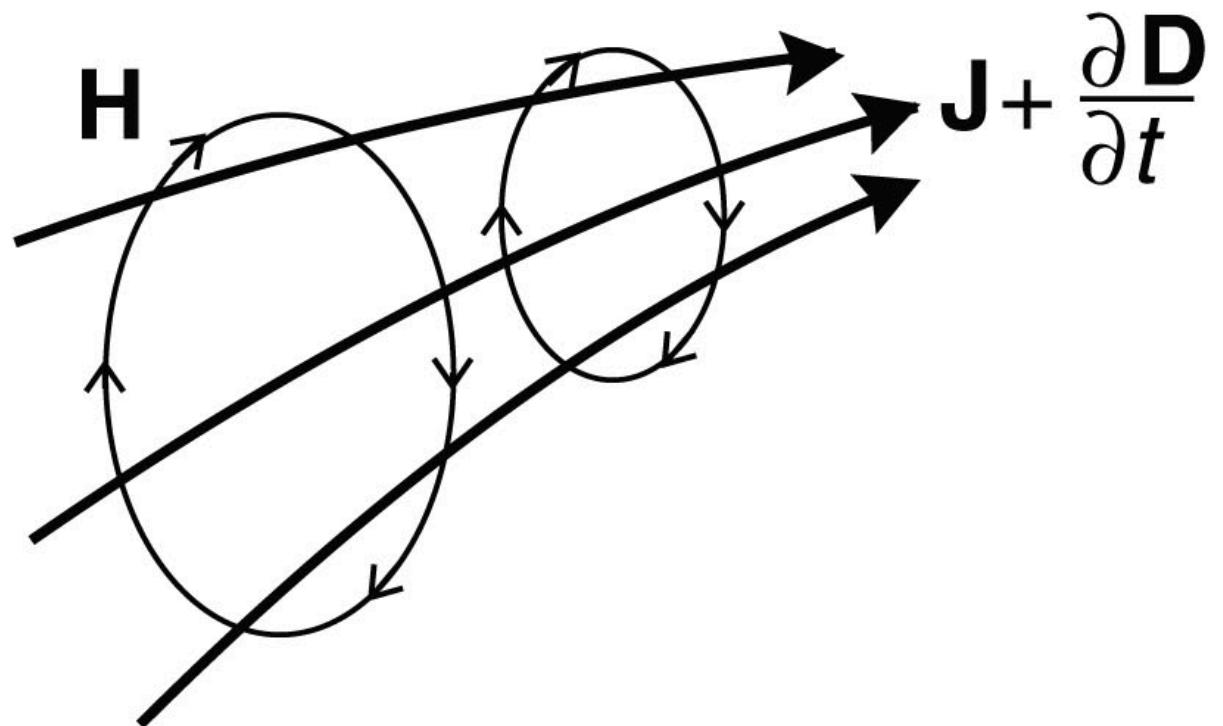
- magn. Feldstärke  $H$  [A/m]
- magn. Flussdichte  $B$  [Vs/m<sup>2</sup>]  
 $B = \mu H$  (oft “Magnetfeld”)
- magn. Permeabilität  $\mu$  [Vs/Am]  
 $\mu = \mu_0 \mu_r$  m.  $\mu_0 = 4\pi \cdot 10^{-7}$  Vs/Am
- mag. Suszeptibilität  $\chi_m = \mu_r - 1$
- magn. Fluss  $\Phi$  [Vs]
- spez. el. Widerstand  $\rho$  [ $\Omega$ m]
- elektr. Feldstärke  $E$  [V/m]
- dielektr. Verschiebung  $D$  [As/m<sup>2</sup>]  
 $D = \epsilon E$  (Hilfsfeld)
- elektr. Permittivität  $\epsilon$  [As/Vm]  
 $\epsilon = \epsilon_0 \epsilon_r$  m.  $\epsilon_0 = 8.854 \cdot 10^{-12}$  As/Vm
- el. Suszeptibilität  $\chi_e = \epsilon_r - 1$
- elektr. Stromdichte  $j$  [A/m<sup>2</sup>]
- el. Leitfähigkeit  $\sigma$  [S/m]

# Maxwell-Gleichungen

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



$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{j}$$



# Maxwell-Gleichungen - Quellen

Ladungsträger erzeugen eine elektrische Verschiebung

$$\nabla \cdot \mathbf{D} = \varrho$$

Das Magnetfeld ist frei von Quellen und Senken

$$\nabla \cdot \mathbf{B} = 0$$

# Amperesches Gesetz in der Geophysik

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{j}$$

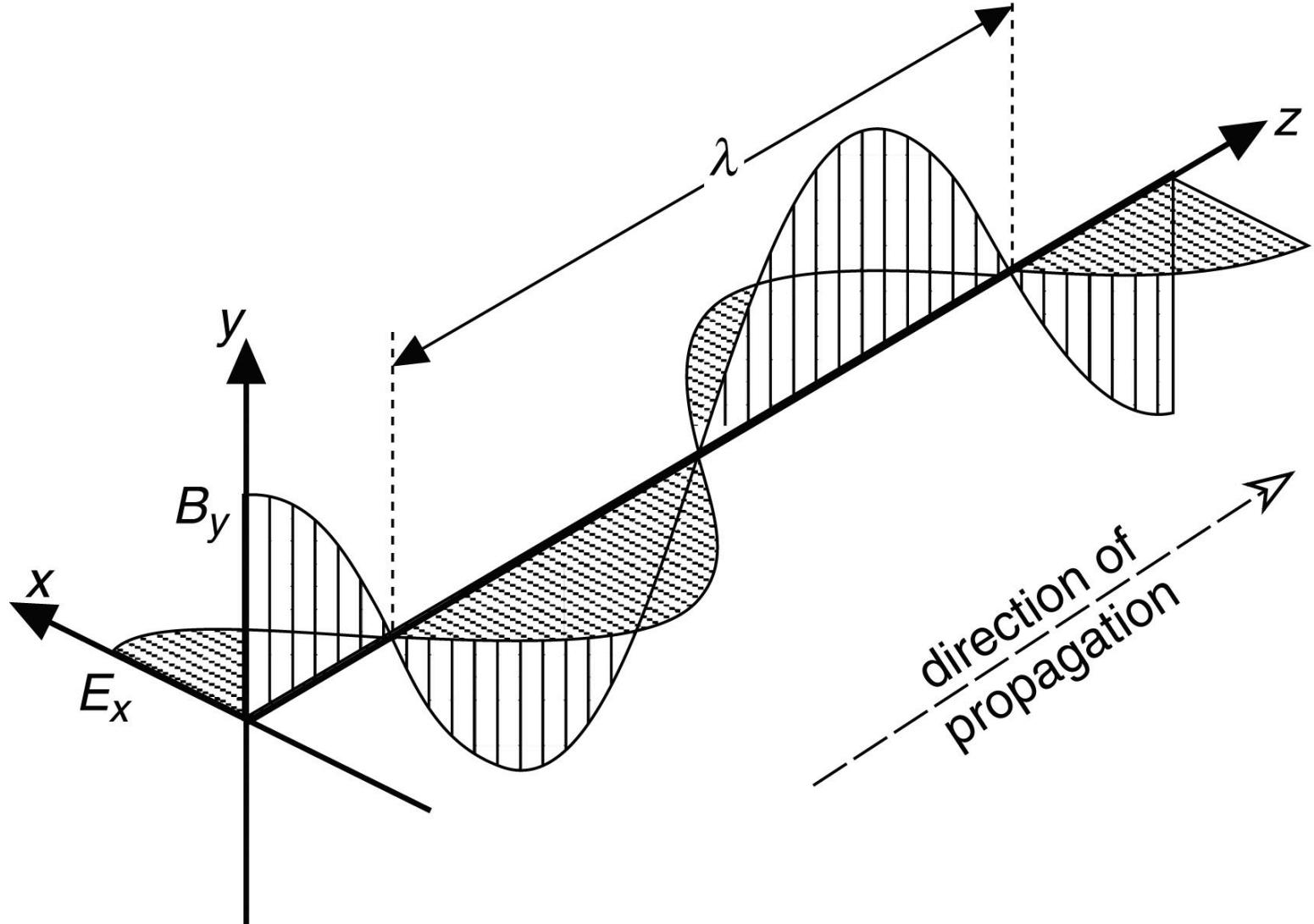
- Wellenausbreitung  $\nabla \times \mathbf{H} = \partial \mathbf{D} / \partial t$ : Georadar
- Induktion  $\nabla \times \mathbf{H} = \mathbf{j}$ ,  $\nabla \times \mathbf{E} = - \partial \mathbf{B} / \partial t$   
Magnetotellurik, EMF in Zeit- und Frequenzbereich
- Magnetostatik  $\nabla \times \mathbf{H} = \mathbf{j}$ ,  $\nabla \times \mathbf{E} = 0$

# Gleichungen und Methoden

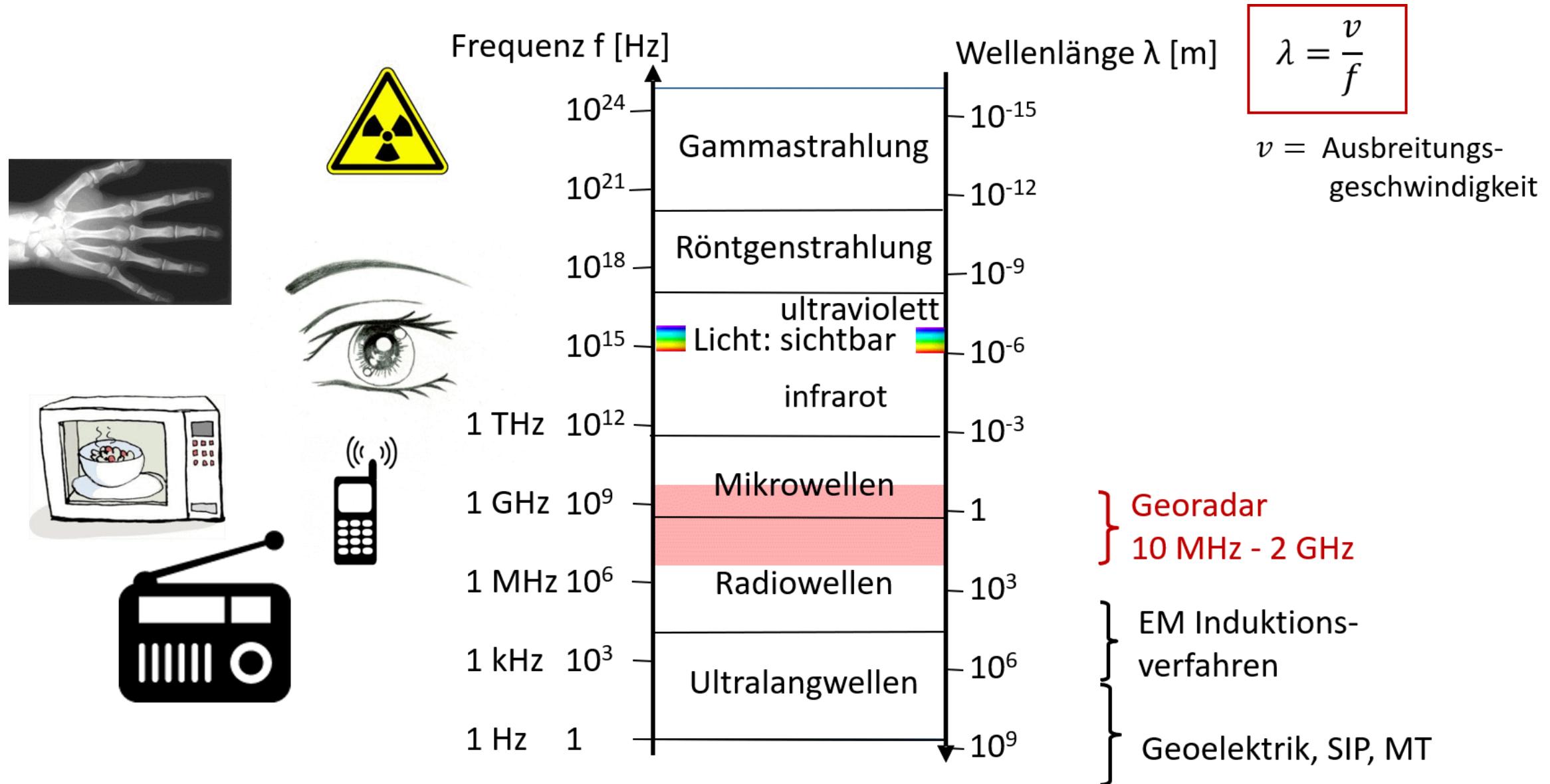
Vorgänge/Felder	$\nabla \times \mathbf{H}$	$\nabla \times \mathbf{E}$	Methoden
Stationär	$\mathbf{j}$	0	Geoelektrik
Quasistationär	$\mathbf{j}$	$-\partial\mathbf{B}/\partial t$	Induktion
Wellenvorgänge	$\partial\mathbf{D}/\partial t$	$-\partial\mathbf{B}/\partial t$	Georadar

# Elektromagnetische Wellen

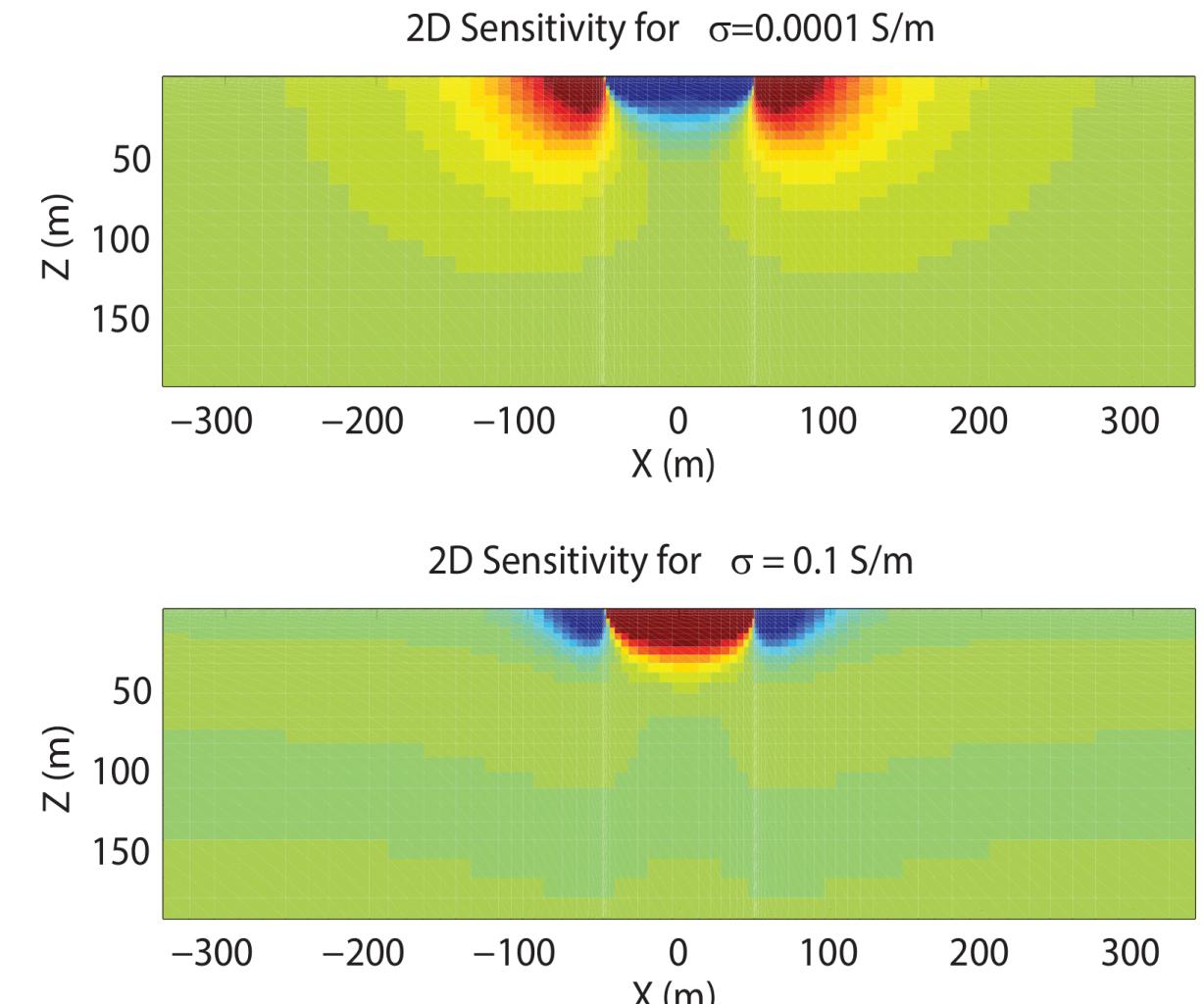
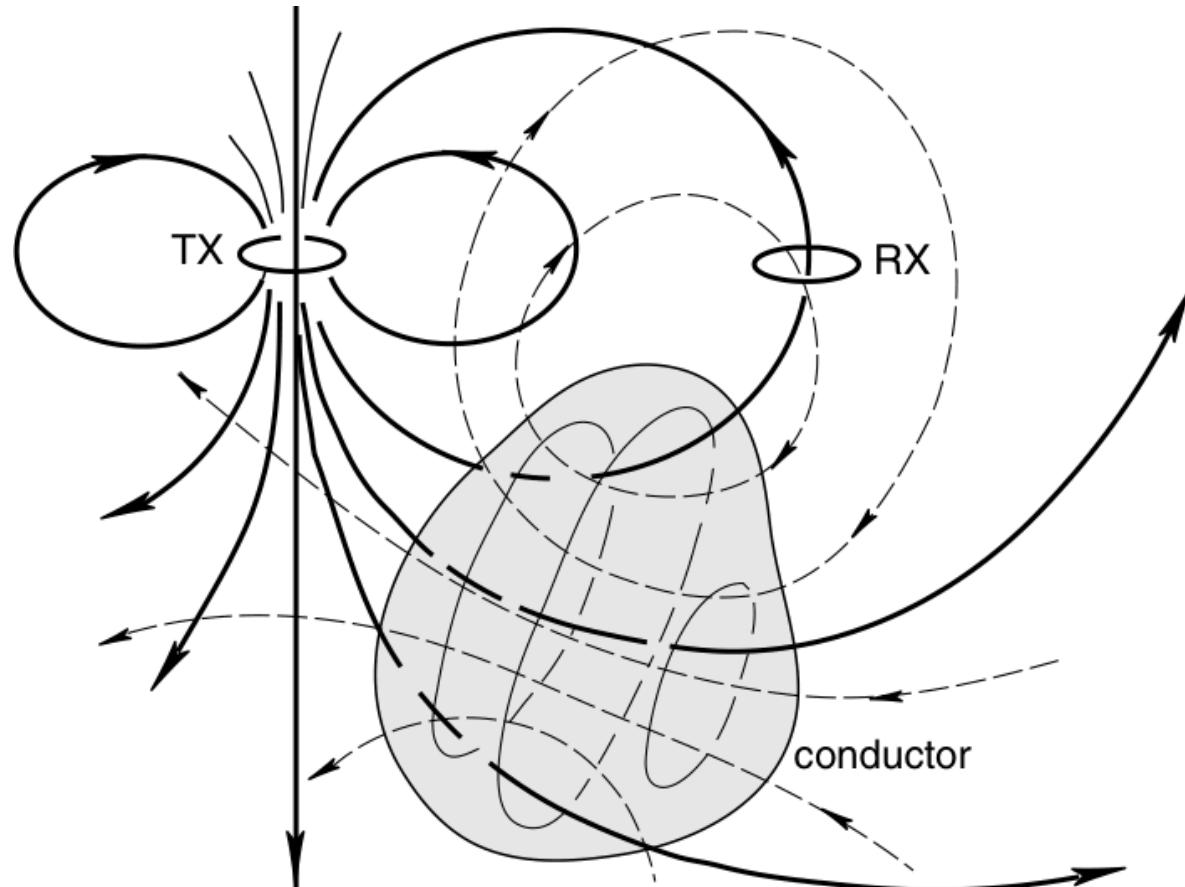
- $dD/dt$  dominiert  $\mathbf{j}$
- Wellenausbreitung
- $B$  und  $E$  um  $90^\circ$  phasenverschoben
- senkrecht zu Ausbreitung
- in der Erde sehr schnell gedämpft
- Induktion dominiert



# Elektromagnetisches Spektrum

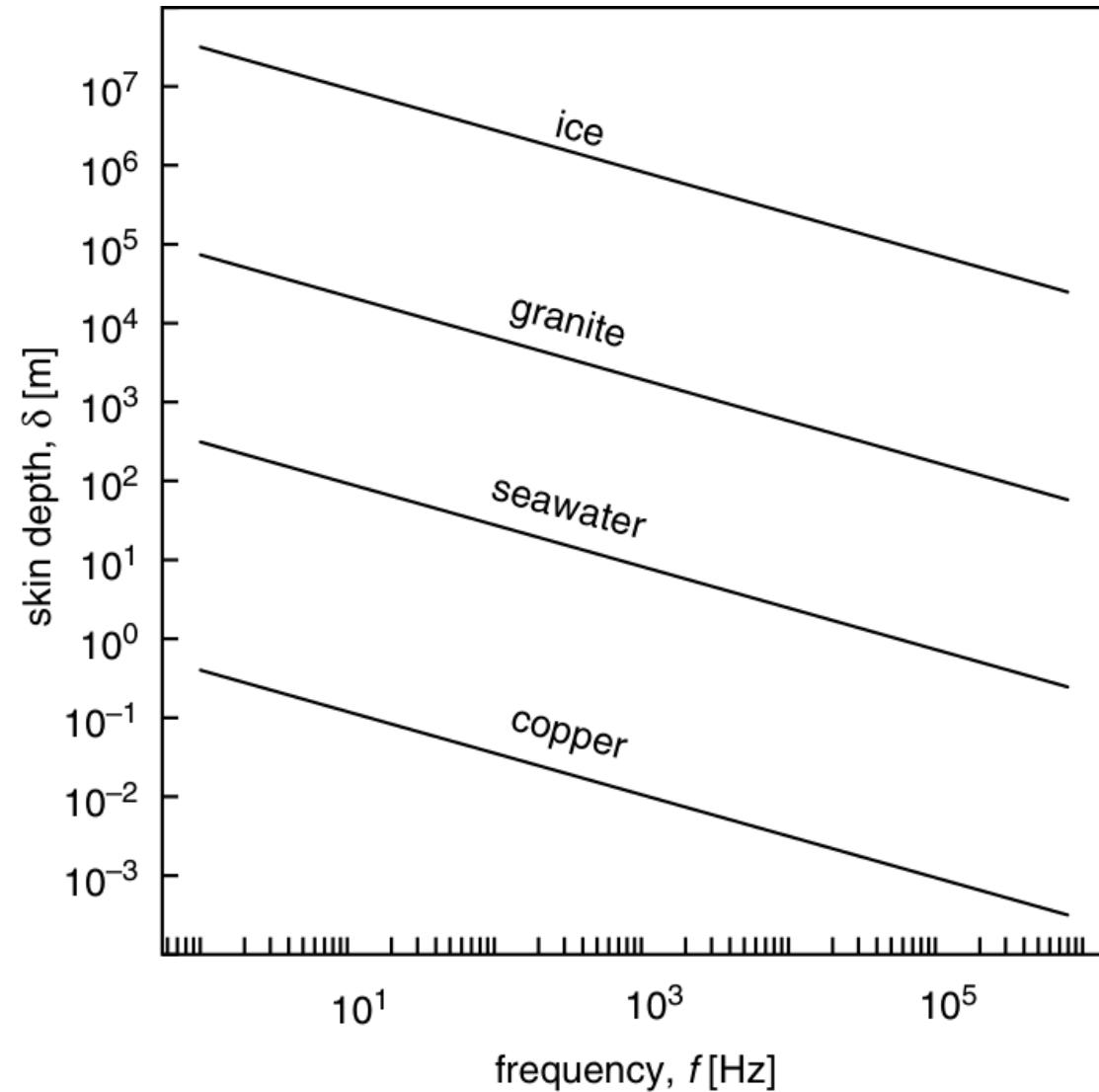
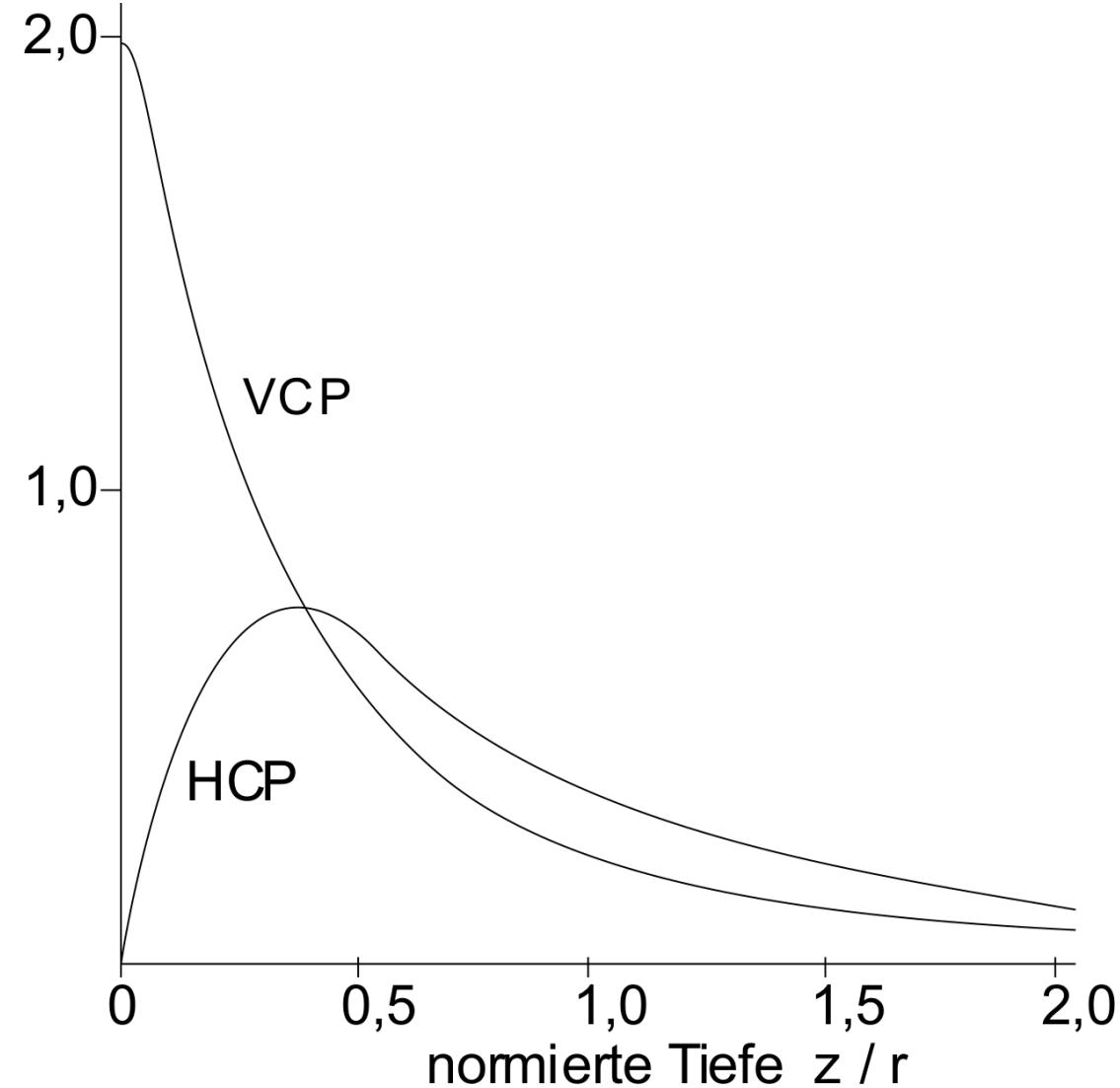


# Loop-loop methods



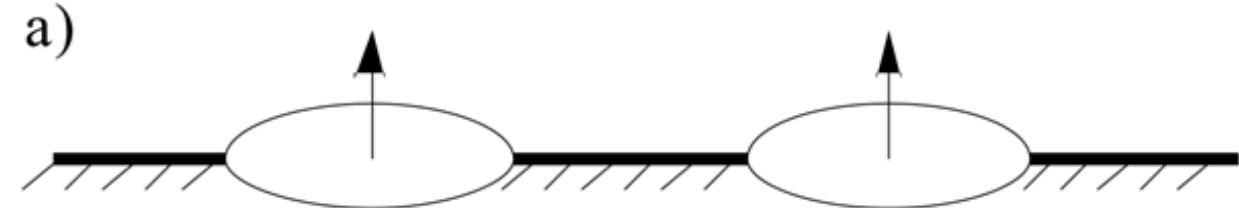
2D Sensitivität

# Empfindlichkeit und Skintiefe

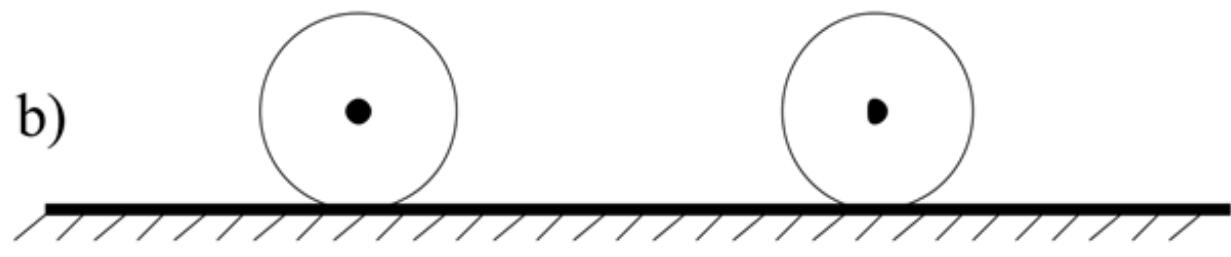


# Spulenanordnungen

**Sender**



**Empfänger**

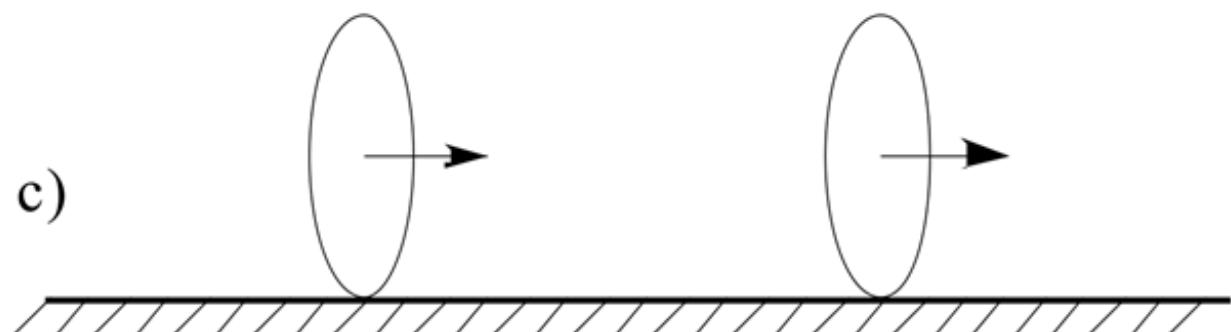


**Spulenachsen**

Vertikal,  
parallel

**Spulenebenen**

Horizontal,  
koplanar (HCP)



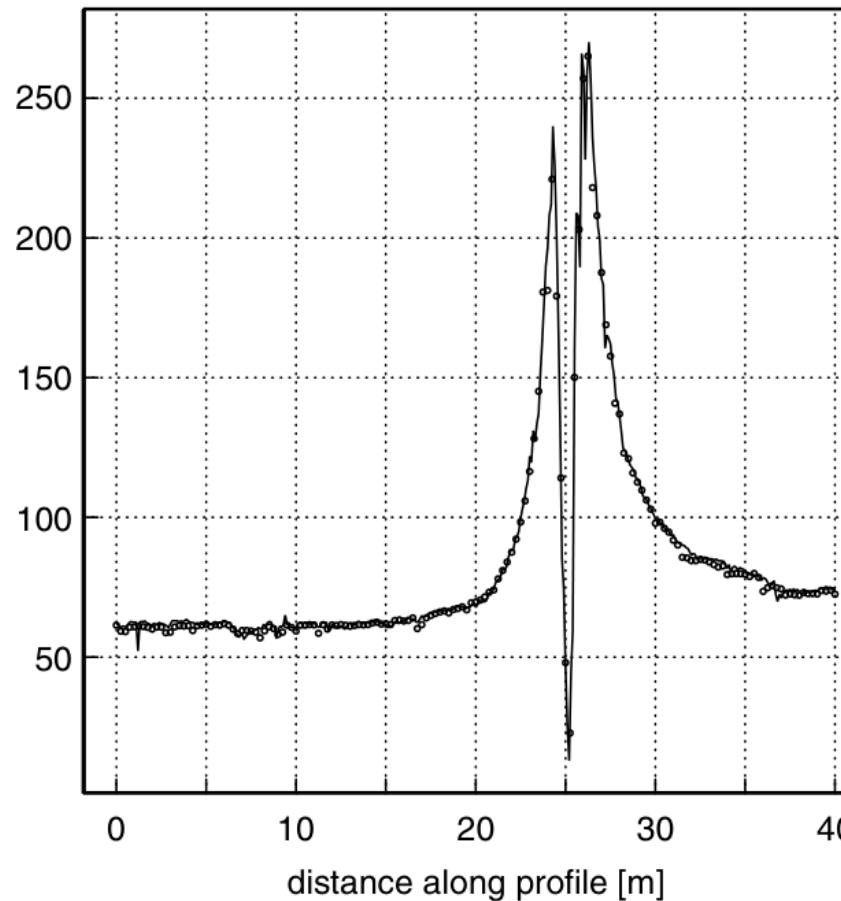
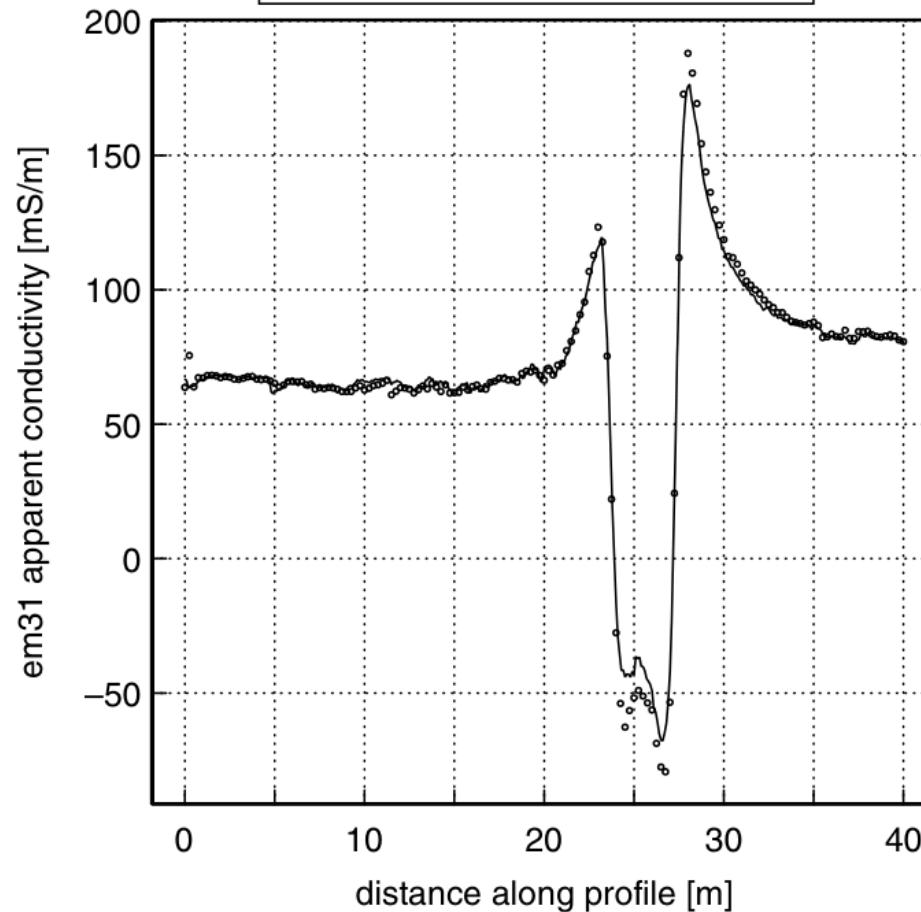
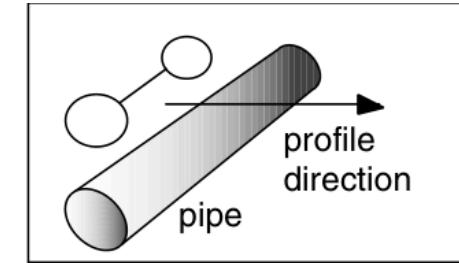
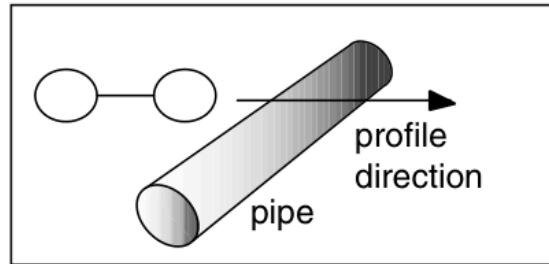
Horizontal,  
parallel

Vertikal,  
koplanar (VCP)

Horizontal,  
koaxial

Vertikal  
parallel (VCA)

# Leitungssuche mit Zweispulen-System

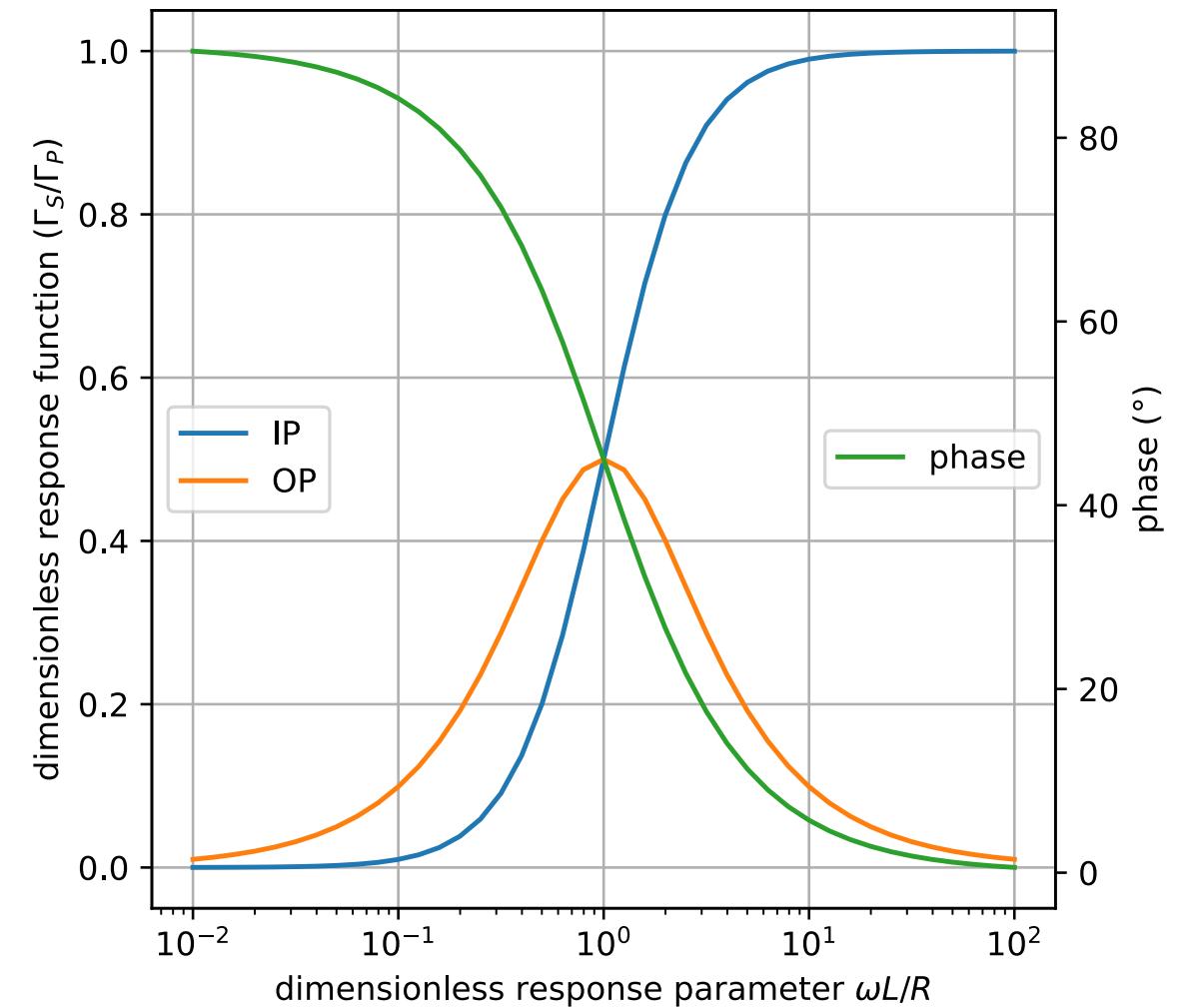


# Response function

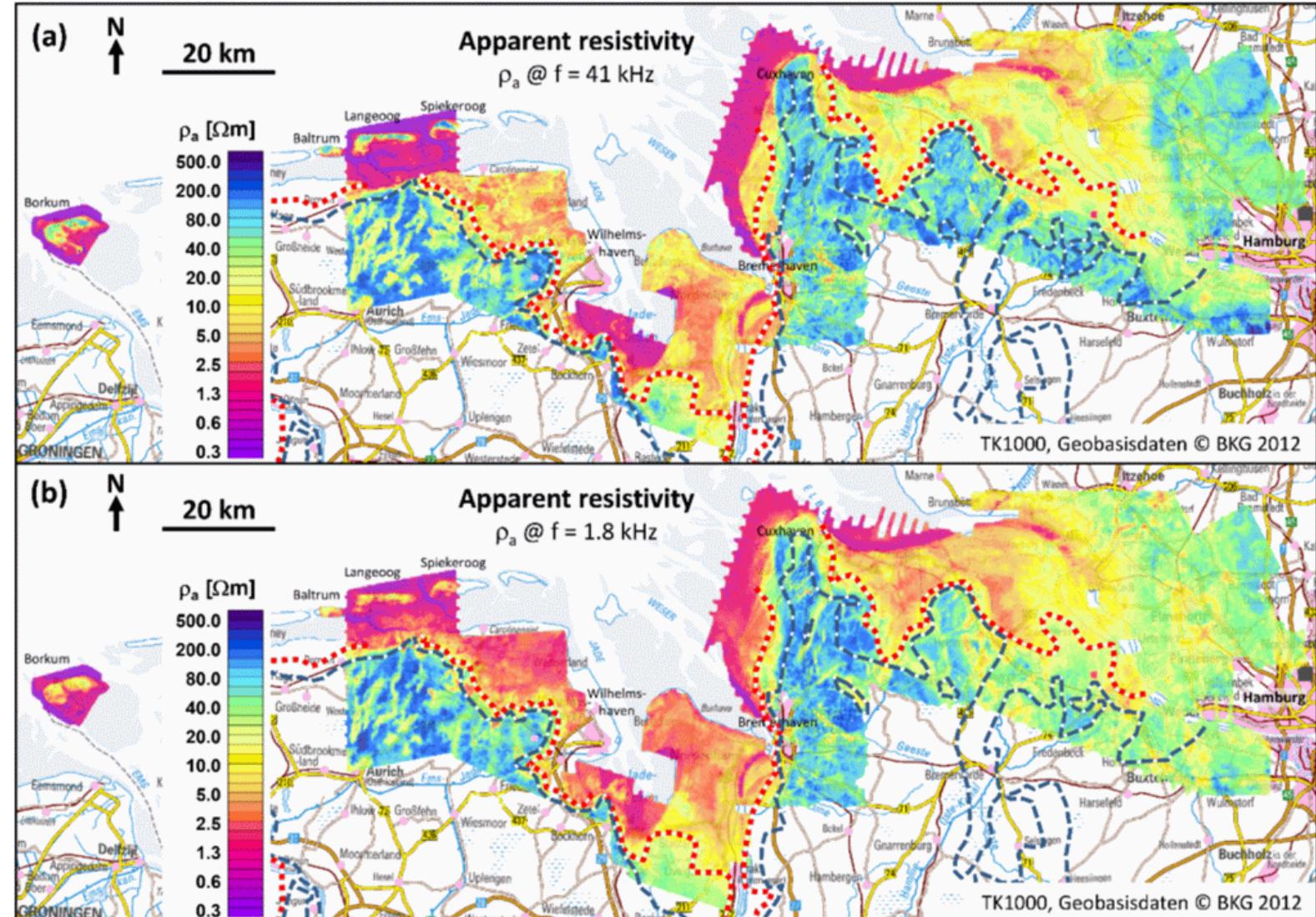
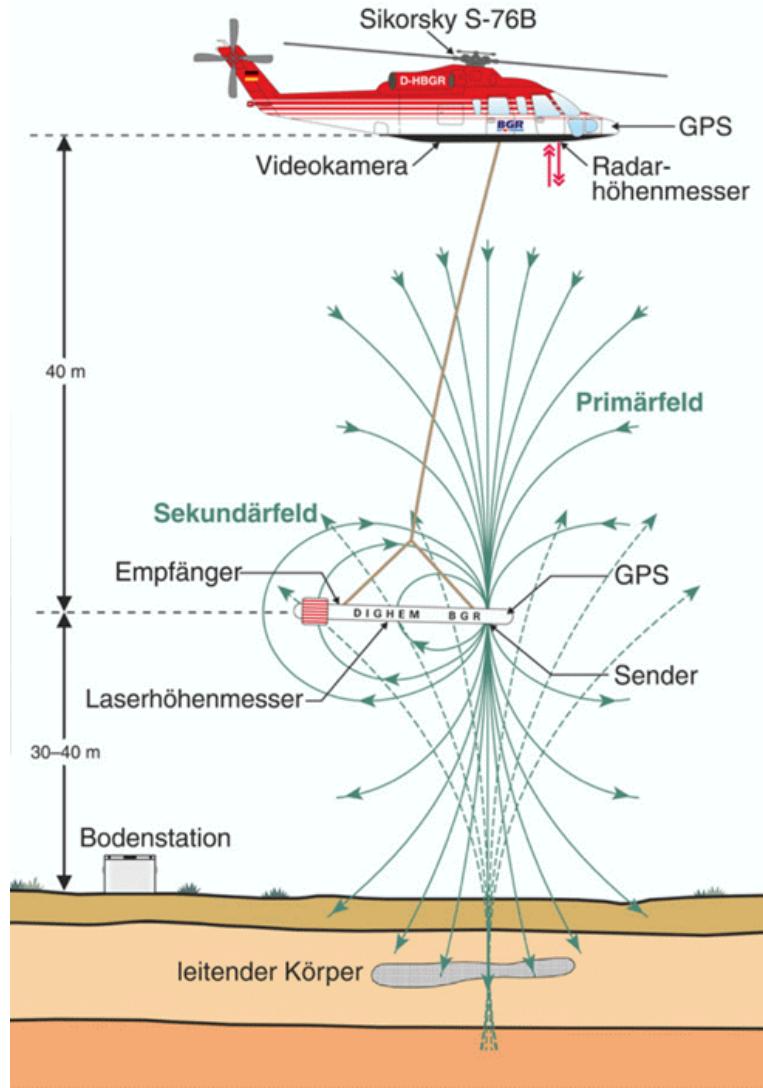
$$\frac{\Gamma_S}{\Gamma_P} = \kappa \frac{i\omega L/R}{1 + i\omega L/R}$$

$\omega \rightarrow 0$  secondary OP signal  
(resistive limit)

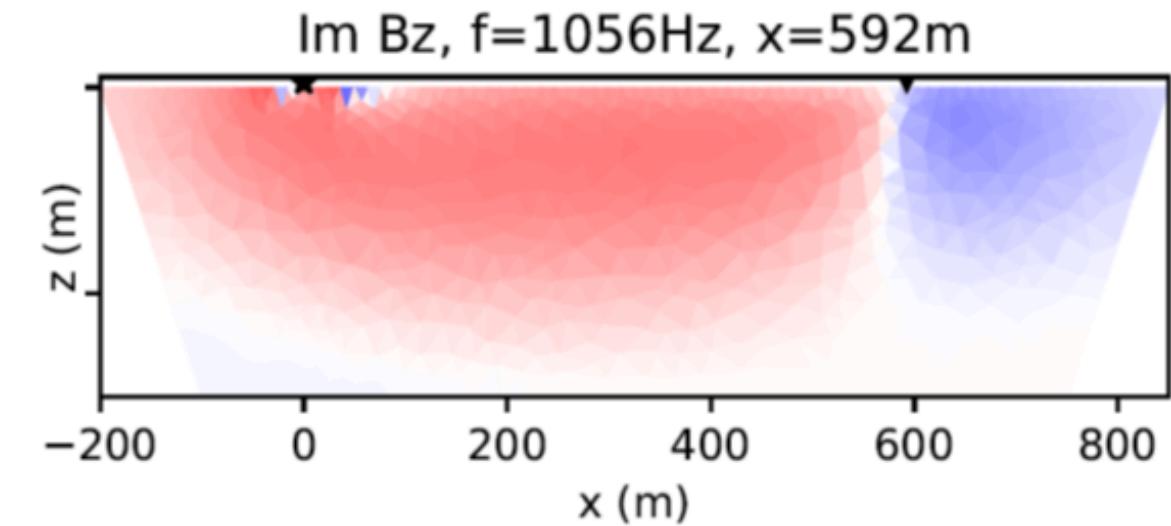
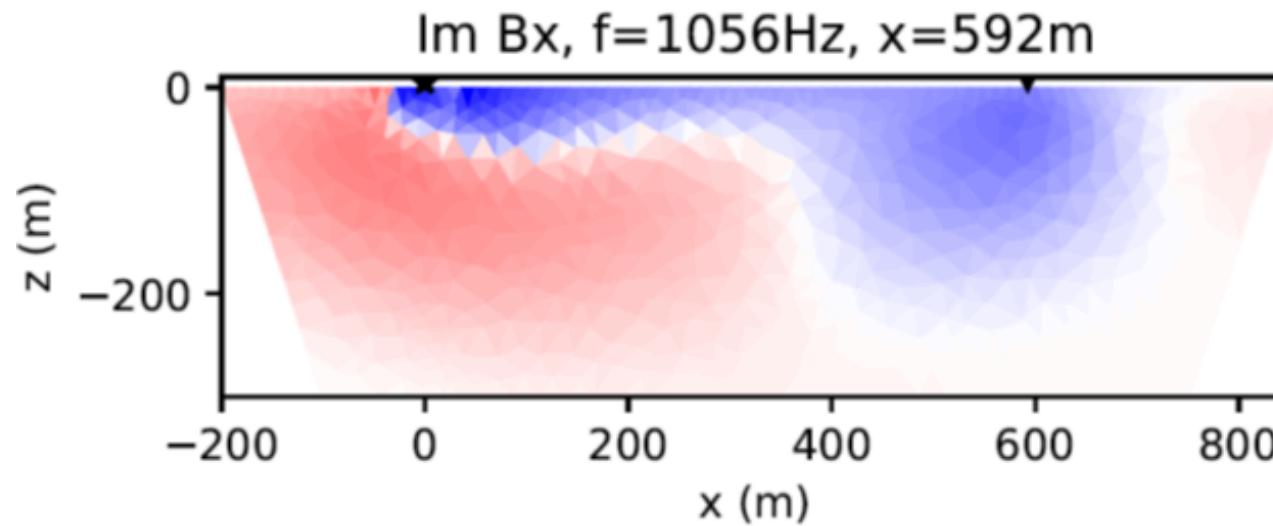
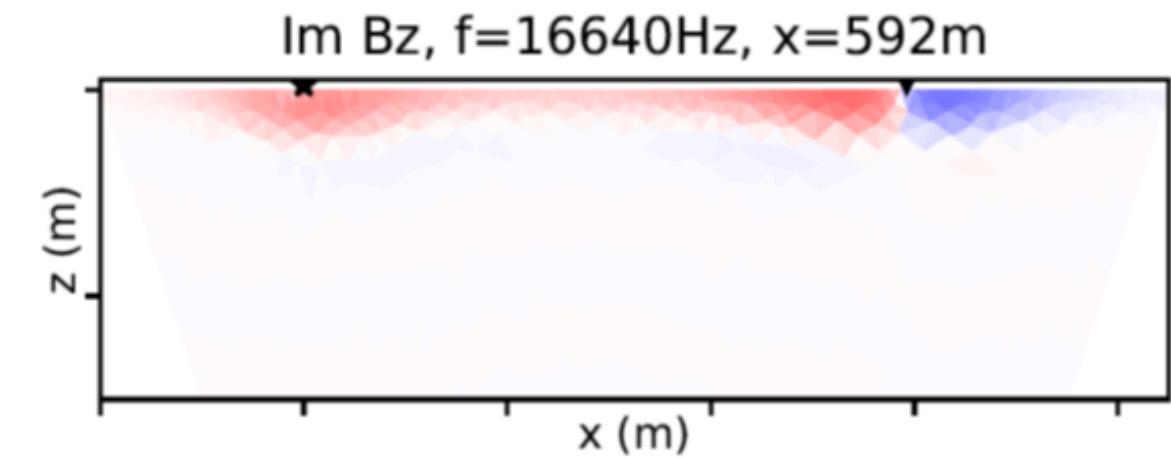
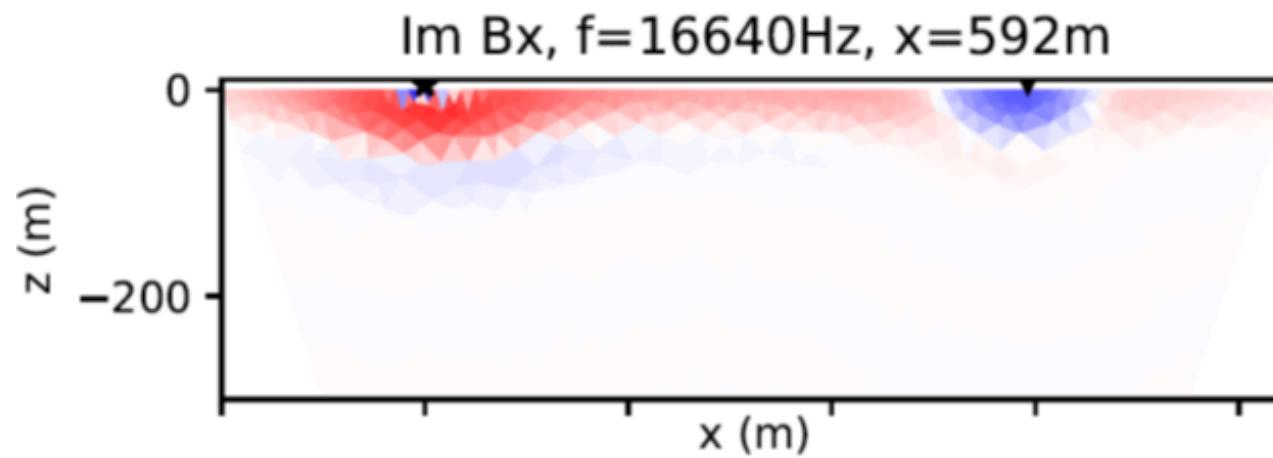
$\omega \rightarrow \infty$  secondary IP signal  
(inductive limit)



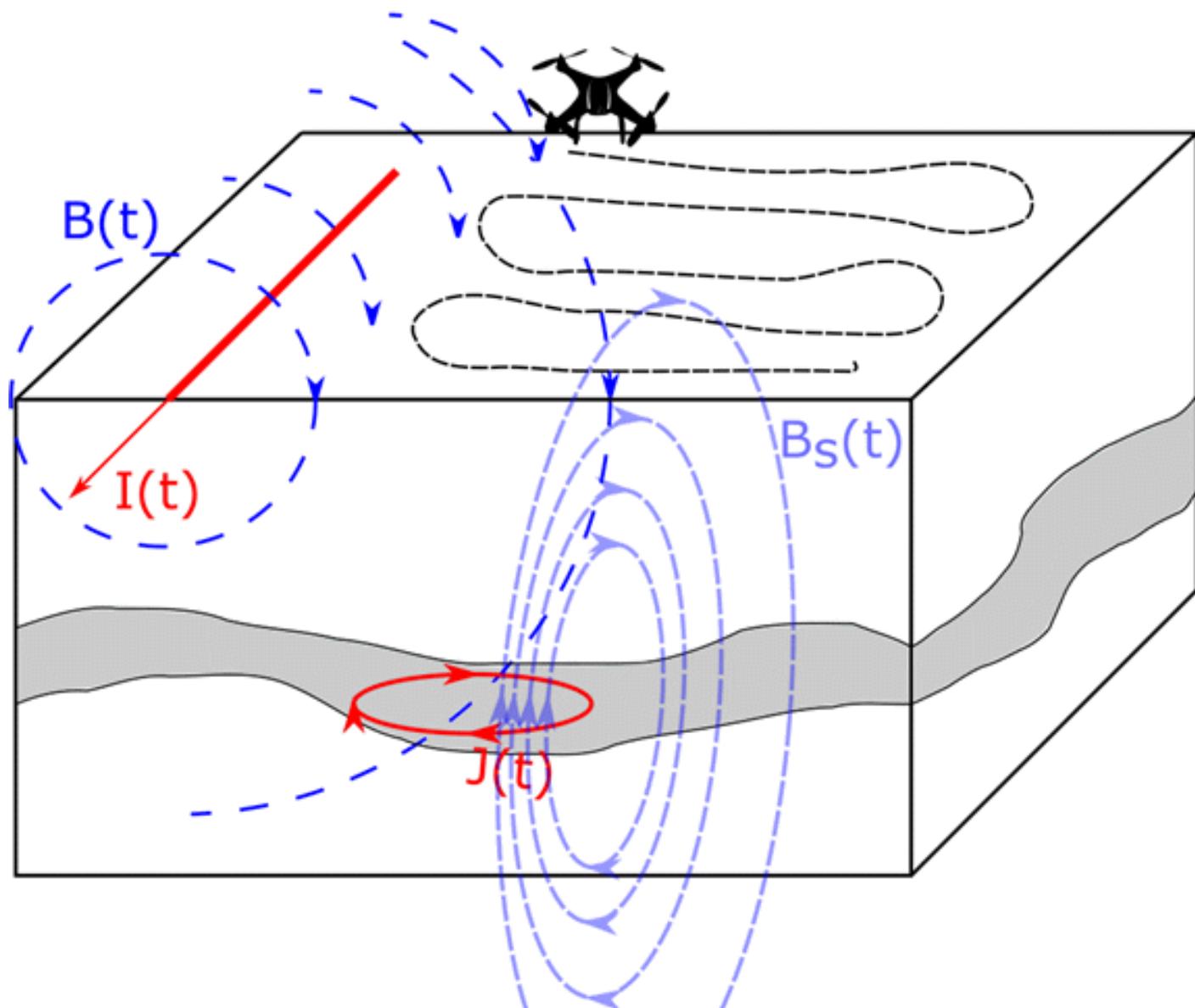
# Airborne Elektromagnetik



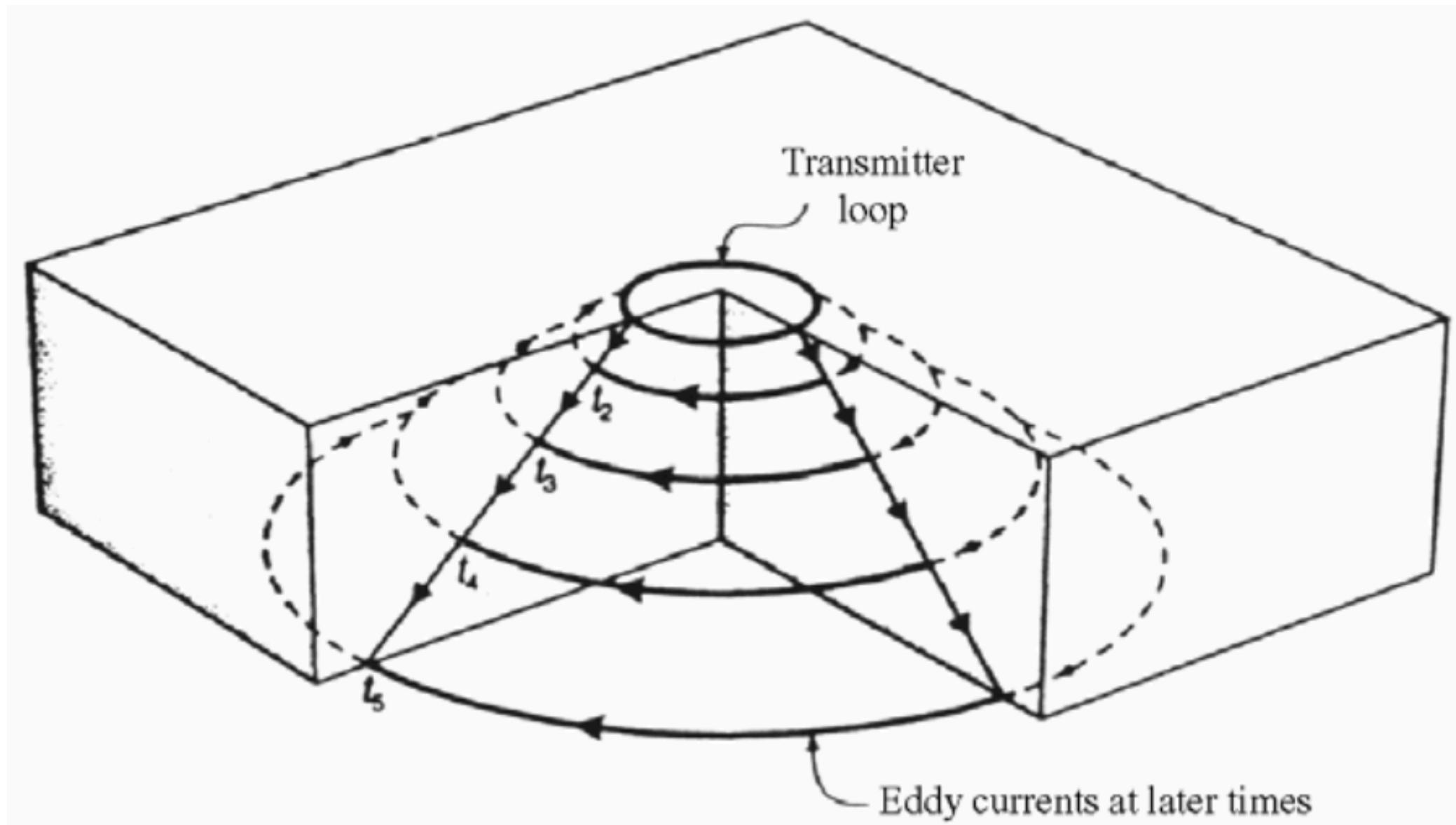
# CSEM sensitivity (Günther et al. 2021)



# Semi-airborne EM



# Transient-Elektromagnetik (TEM)



# TEM sensitivity

