Geophysics for Natural Risks and Resources
ENVIRONMENTAL and ENGINEERING GEOPHYSICS

ELECTRO-MAGNETIC
METHODS IN GEOPHYSICAL PROSPECTINGS

Outline

Geophysical methods for the subsoil prospecting

- Electrical methods (ERT Electrical Resistivity tomography)

- Electro-magnetic methods (FDEM, RADAR)

- Seismic Methods (refraction / reflection / surface waves)

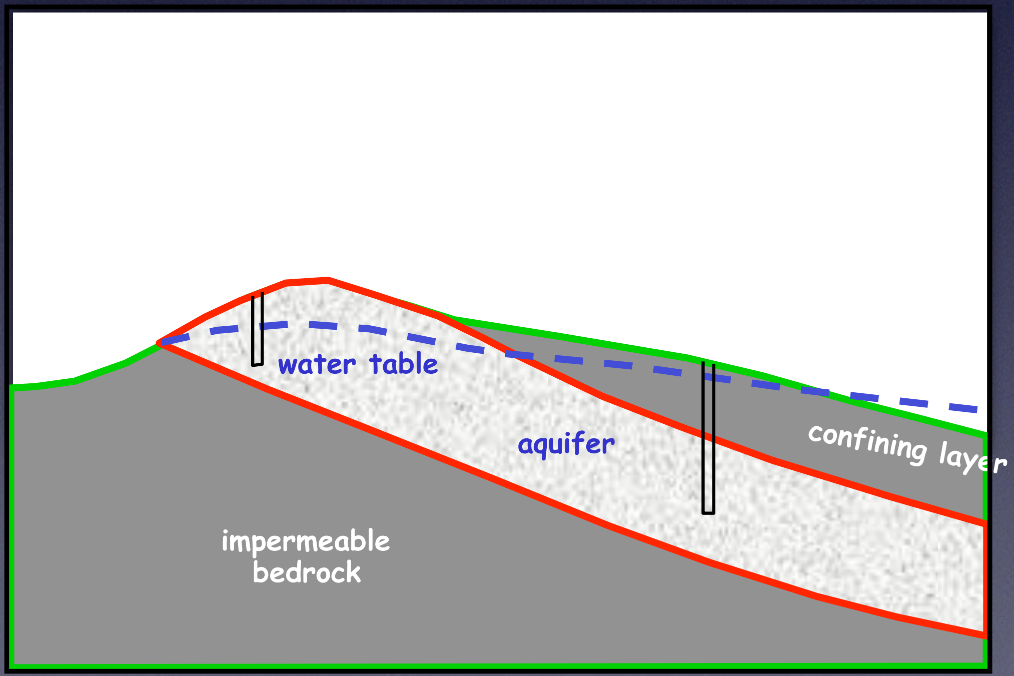
- case histories

Methods for geophysical prospecting

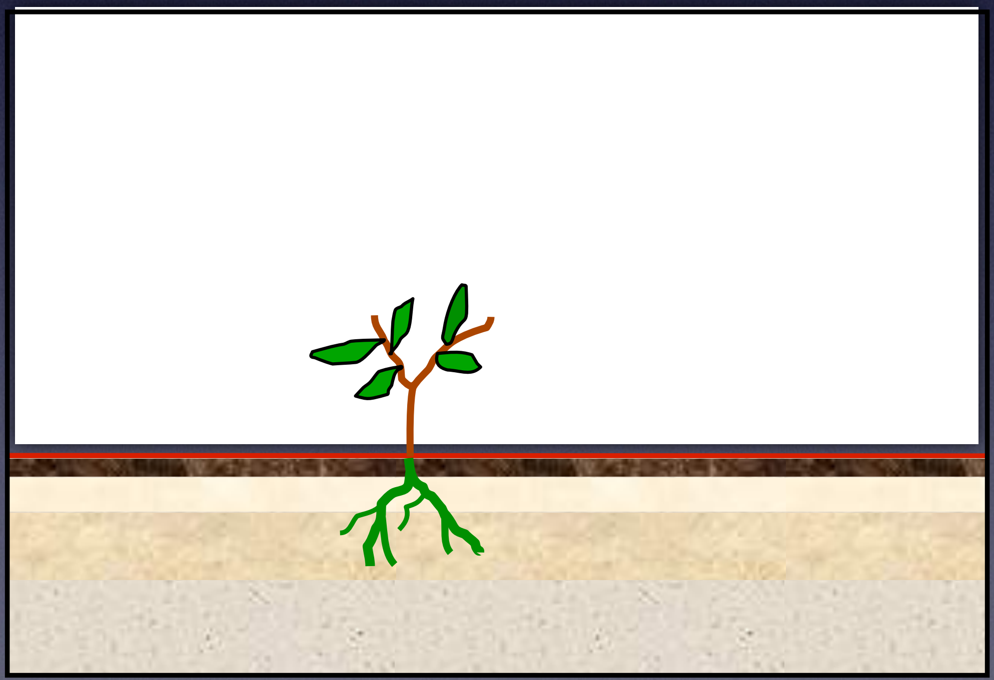
Method	Structure	Dynamic
Seismic	+ +	
Electro-Magnetic	+	++
DC resistivity methods	++	++
Ground Penetration Radar	++	+
Distributed Temp. Sensing		++
Magnetics	+	
Gravimetry	+	+
Spectral Induced Polarization	+	
Self Potential		+
Borehole logs	+ +	+

What geophysical methods can help define

- structure / texture (Seismic methods, EM methods, Electrical methods, Gravity methods, Radar etc)



large scale

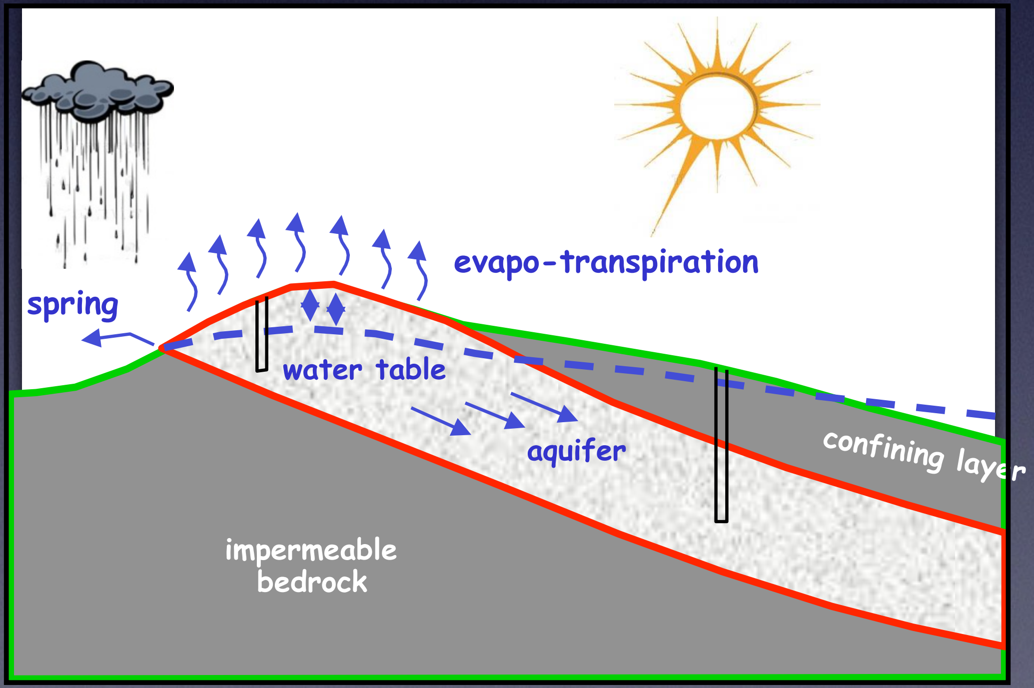


small scale

What geophysical methods can help define

- structure / texture (Seismic methods, EM methods, Electrical methods, Gravity methods, Radar etc)

- fluid-dynamics: e.g. time-lapse evolution of moisture content (DC resistivity methods, EM methods, GPR etc)



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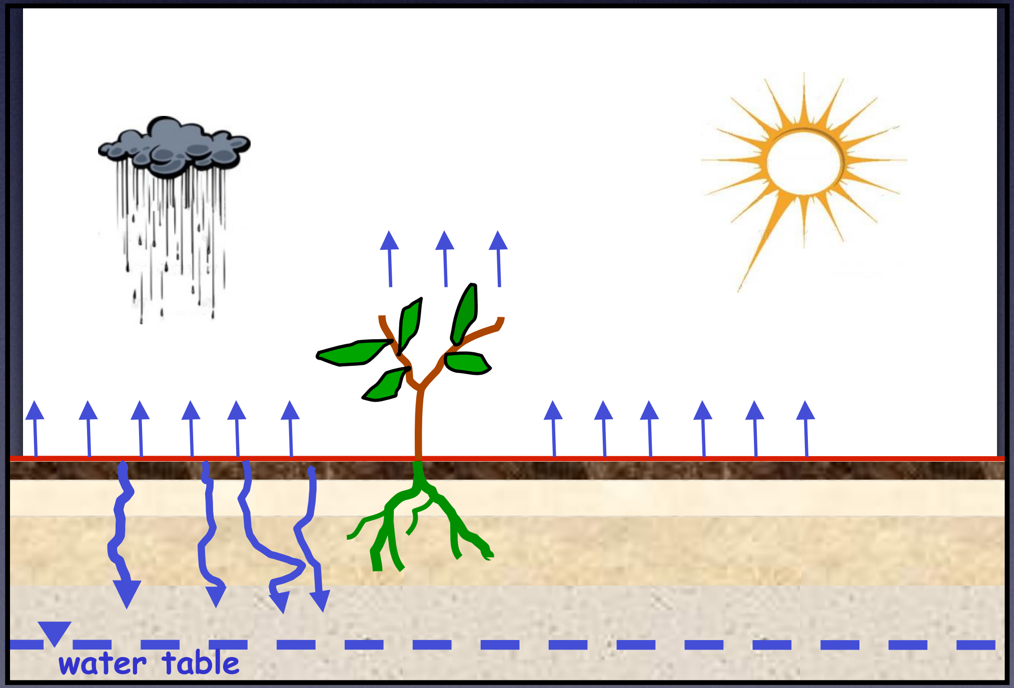


small scale

Physical Properties (P)

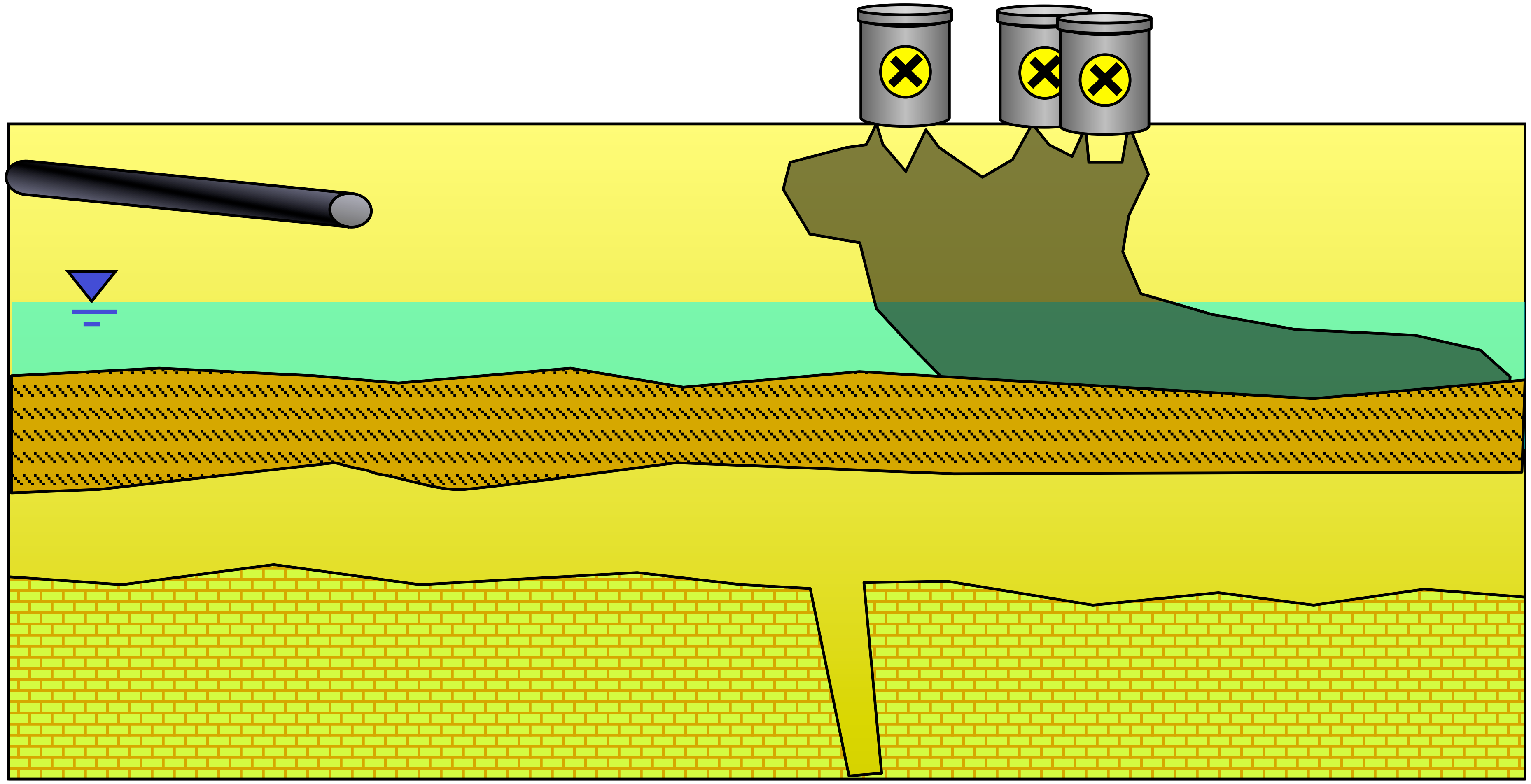
Seismic	Elastic moduli and density
Gravimetry	: Density
Magnetic meth.	Magnetic susceptibility
ERT meth.	Electrical resistivity
Electro-magnetic meth.	Electrical conductivity
Induced Polarization	Electrical complex conductivity
Spontaneous Potentials	Electrical conductivity
Ground penetrating Radar	Dielectric constant

EM METHODS

Electro-magnetic properties

APPLICATIONS:

- Mineral exploration
- Groundwater
- Mapping contaminants
- Landfill surveys
- Cavities
- Location of faults
- Geological mapping
- Archeological



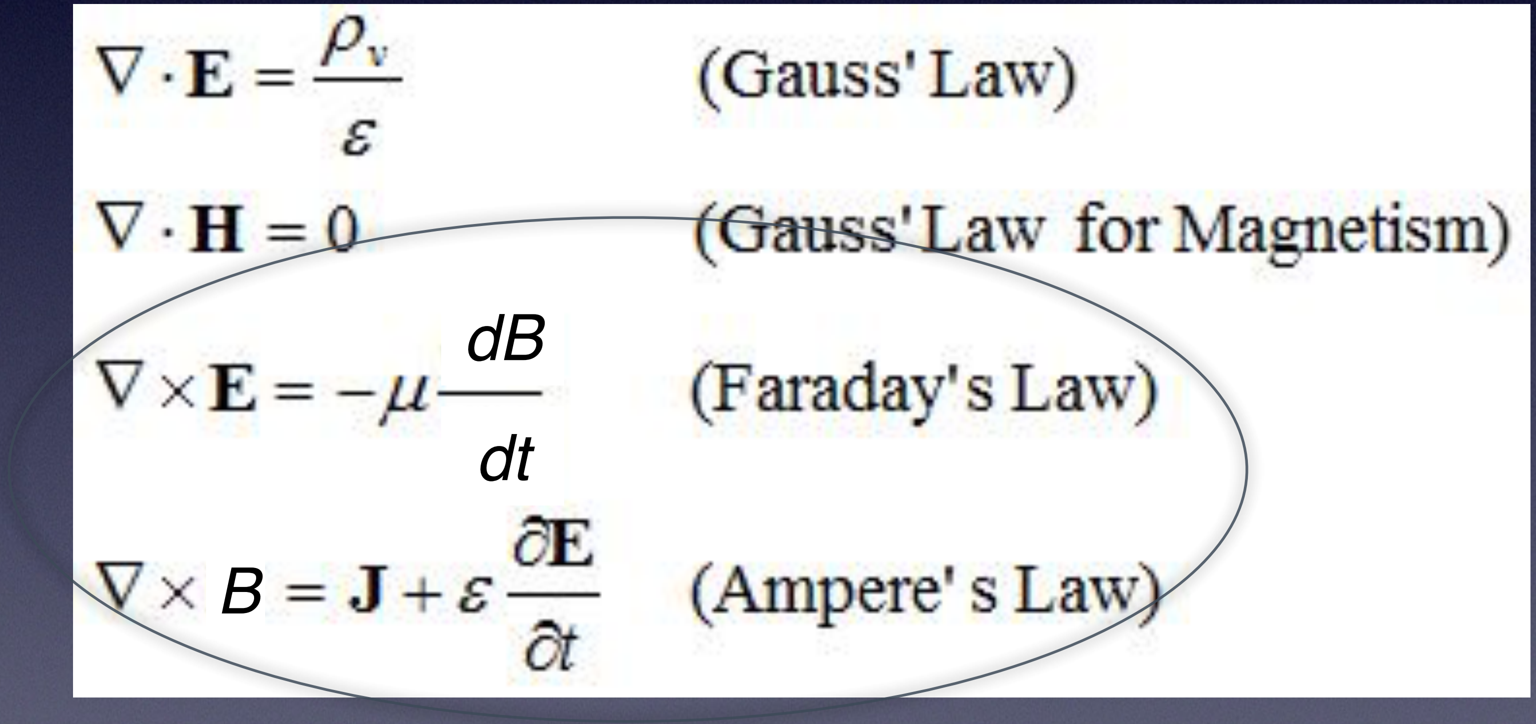
EM Methods

- Physical principles
- Acquisition methods
- Processing
- Case Histories

- Physical Principles

EM METHODS

Maxwell Equations



$\nabla \cdot \mathbf{E} = \frac{\rho_v}{\varepsilon}$ (Gauss' Law)

$\nabla \cdot \mathbf{H} = 0$ (Gauss' Law for Magnetism)

$\nabla \times \mathbf{E} = -\mu \frac{dB}{dt}$ (Faraday's Law)

$\nabla \times B = \mathbf{J} + \varepsilon \frac{\partial \mathbf{E}}{\partial t}$ (Ampere's Law)

link Electric Fields
and Magnetic Fields

Electro-magnetic methods

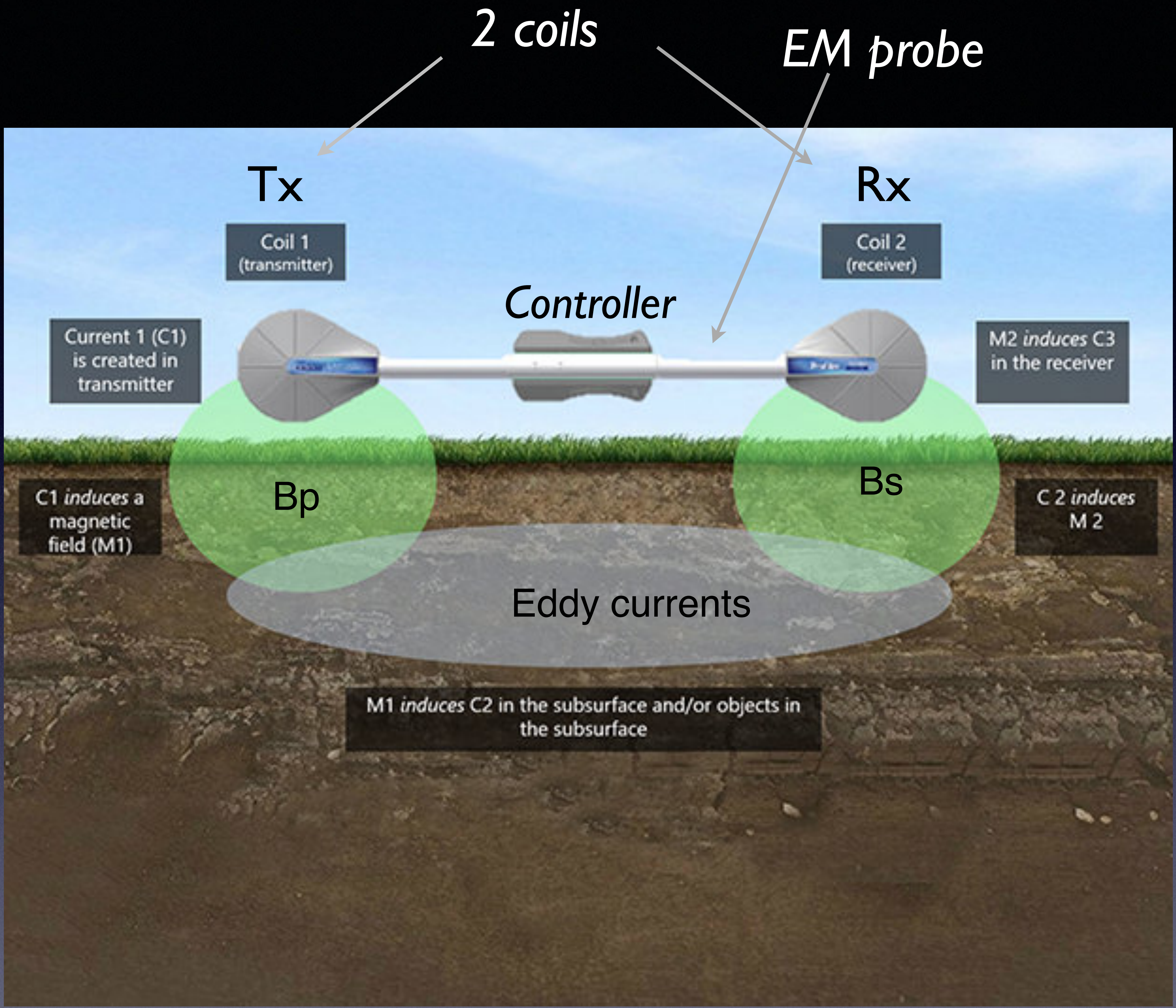
A current (variable in time *t)* in transmitter TX generates a primary magnetic field Bp

↓

in conductive subsoil, Bp varying in time generates *Eddy currents* which in turn generates a secondary magnetic field Bs

↓

Bs variable in time generates measurable currents in my receiver in Rx



The differences between the primary and secondary fields are related to the electrical properties of the subsoil !

Electro-magnetic methods

how an EM field propagate in the soil ?

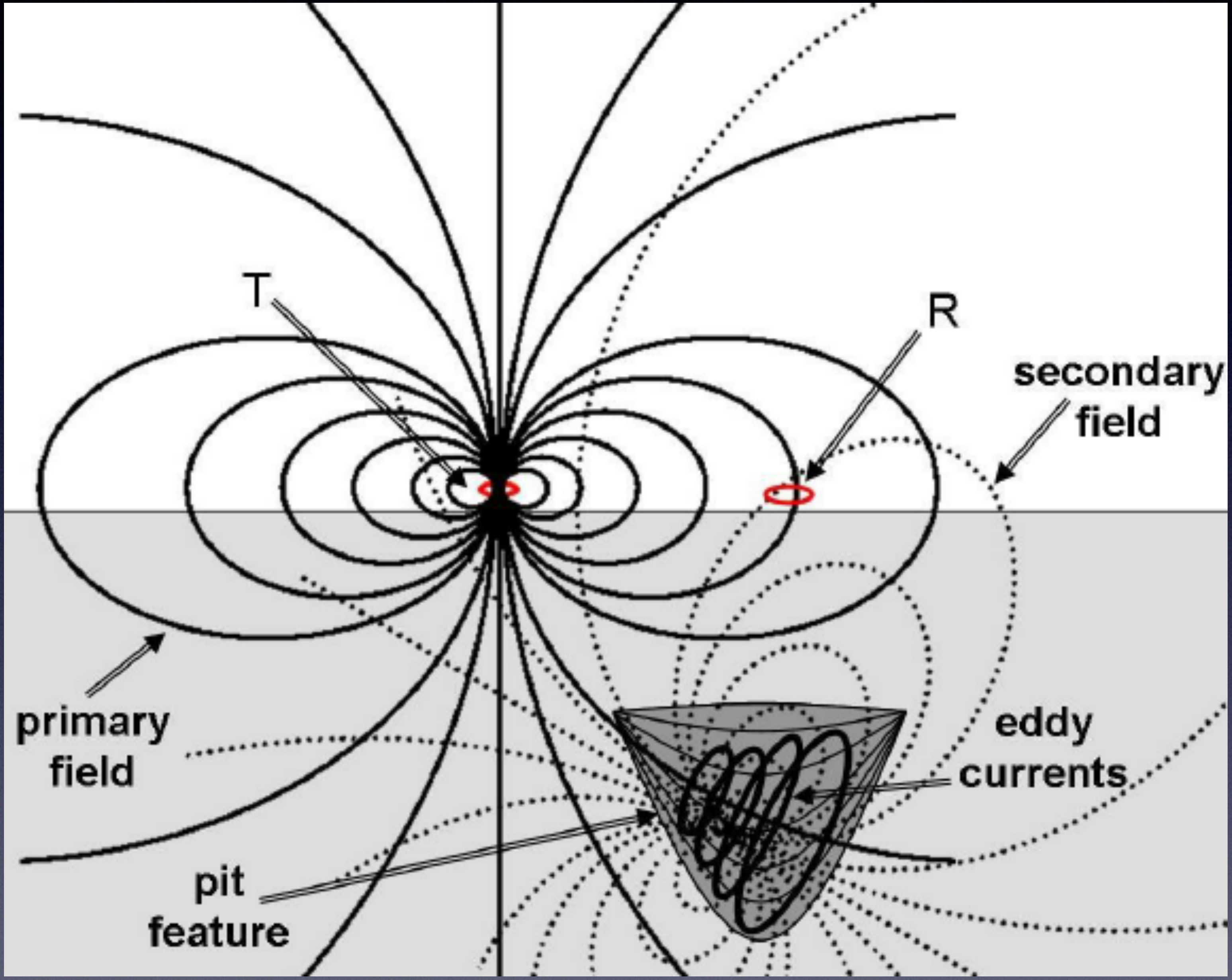
Faraday's law

1 $$EMF = -\frac{d\Phi}{dt}$$

Electro magnetic force = variable in time magnetic flux ϕ

2 $$EMF_{total} = \oint_{Circuit} \mathbf{E}\cdot\mathbf{dL}$$

Electro magnetic force = sum of the Electric field **E** around the length of the circuit **L**



3 $$\oint_{Circuit} \mathbf{E}\cdot\mathbf{dL} = \int_S \nabla\times\mathbf{E}\cdot\mathbf{dS} \quad \text{[Stokes' Theorem]}$$

Curl of **E** around surface ***S***

Electro-magnetic methods

1
$$EMF = -\frac{d\Phi}{dt}$$

3
$$\int_S \nabla \times \mathbf{E} \cdot d\mathbf{S} = -\frac{d}{dt}\int_S \mathbf{B}(t) \cdot d\mathbf{S} = \int_S \frac{-d\mathbf{B}(t)}{dt} \cdot d\mathbf{S}$$

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

FARADAY's LAW

Link
between field E and field B

∇x E= -dB/dt ← *III Maxwell law*
or Faraday's law

Electro-magnetic methods

Electric and Magnetic waves in EM fields

The electric displacement $\vec{D}$ and magnetic intensity $\vec{H}$ are related to the electric field E and magnetic field B

$$\vec{D} = \varepsilon\vec{E},$$

$$\vec{B} = \mu\vec{H}.$$

dielectric permittivity

magnetic permeability

The Ampere Law (IV maxwell) in free space is:

$$\nabla \times \vec{B} = \frac{1}{c^2}\frac{\partial\vec{E}}{\partial t},$$

$$\frac{1}{c^2} = \mu_0\varepsilon_0.$$

Light velocity

Free space

$$\nabla \text{x B} = \mu_0\varepsilon_0 \frac{\partial\vec{E}}{\partial t}$$

Electro-magnetic methods

Electric and Magnetic waves in EM fields

solving only for Electric field E:

Ampere law

iv) $$\nabla \times \vec{B} = \frac{1}{c^2}\frac{\partial \vec{E}}{\partial t},$$

Faradays law

iii) $$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t},$$

curl curl

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

$$\nabla \times \nabla \times \vec{E} = -\frac{1}{c^2}\frac{\partial^2 \vec{E}}{\partial t^2}.$$

$\nabla(\nabla E) - \nabla^2 E$

$$\nabla^2 \vec{E} - \frac{1}{c^2}\frac{\partial^2 \vec{E}}{\partial t^2} = 0.$$

Laplacian

Electric wave in EM field

Electro-magnetic methods

Electric and Magnetic waves in EM fields

Wave equation

solving only for Electric field E:

Curl

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

Div. null

Laplacian

$$\cancel{\nabla(\nabla E)} - \nabla^2 E = -\frac{1}{c^2}\frac{\partial^2 \vec{E}}{\partial t^2}.$$

$$\nabla^2 \vec{E} - \frac{1}{c^2}\frac{\partial^2 \vec{E}}{\partial t^2} = 0.$$

Conditions

$$\nabla \times \vec{B} = \frac{1}{c^2}\frac{\partial \vec{E}}{\partial t},$$

∇ E= 0

∇ B= 0

Divergences is null (Stationary)

Electro-magnetic methods

Electric and Magnetic waves in EM fields

Wave equation

solving only for Electric field E in conductors media

$$\nabla \times \vec{B} = \mu\sigma\vec{E} + \mu\varepsilon\frac{\partial \vec{E}}{\partial t},$$

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

Conditions

$$\nabla \times \vec{B} = \frac{1}{c^2}\frac{\partial \vec{E}}{\partial t},$$

∇ E= 0

∇ B= 0

Divergences
is null
(Stationary)

Laplacian

Div. null

$$\cancel{\nabla(\nabla \vec{E})} - \nabla \vec{E}^{\,2} = \nabla \; x \; -\frac{\partial}{\partial t}\left(\mu\sigma\vec{E} + \mu\varepsilon\frac{\partial \vec{E}}{\partial t} \right)$$

$$\nabla^2\vec{E} - \mu\sigma\frac{\partial \vec{E}}{\partial t} - \mu\varepsilon\frac{\partial^2 \vec{E}}{\partial t^2} = 0.$$

Wave Equation

Electro-magnetic methods

Electric and Magnetic waves in EM fields in conductors

iii and iv Maxwell Equations in conductors media become:

Electric conductivity

magnetic permeability

dielectric permittivity

$$\nabla \times \vec{B} = \mu\sigma\vec{E} + \mu\varepsilon\frac{\partial \vec{E}}{\partial t},$$

IV

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

III

same procedure of solving for E

$$\nabla^2\vec{E} - \mu\sigma\frac{\partial \vec{E}}{\partial t} - \mu\varepsilon\frac{\partial^2 \vec{E}}{\partial t^2} = 0.$$

WAVE EQUATION = PROPAGATION OF ELECTRIC FIELD IN CONDUCTORS

Electro-magnetic methods

Electric and Magnetic waves in EM fields in conductors as a wave equation

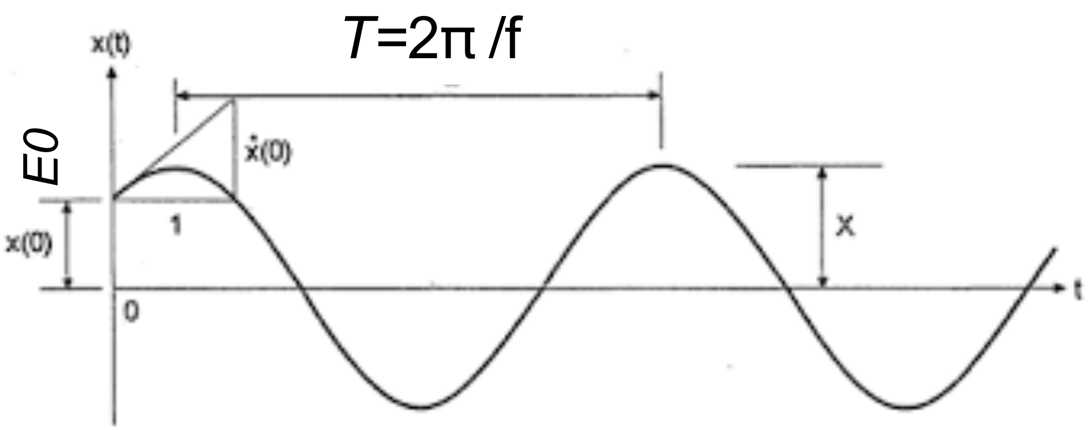
Magn. permeability

5) $$\nabla^2 E = \mu\sigma \frac{\partial E}{\partial t} + \mu\varepsilon \frac{\partial^2 E}{\partial t^2}$$

conductivity

dielectric permeability

Solution of 5)
(complex notation)



$$\vec{E} = \vec{E}_0 e^{i(\vec{k}\cdot\vec{r}-\omega t)}.$$

wave equation
function of
frequency!

frequency ω

wave Vector K

$$e^{ix} = \cos x + i \sin x$$

Solution of wave equation

$$\boxed{A(t) = A_{\max} \cos(2\pi f t + \phi)}$$

Displacement

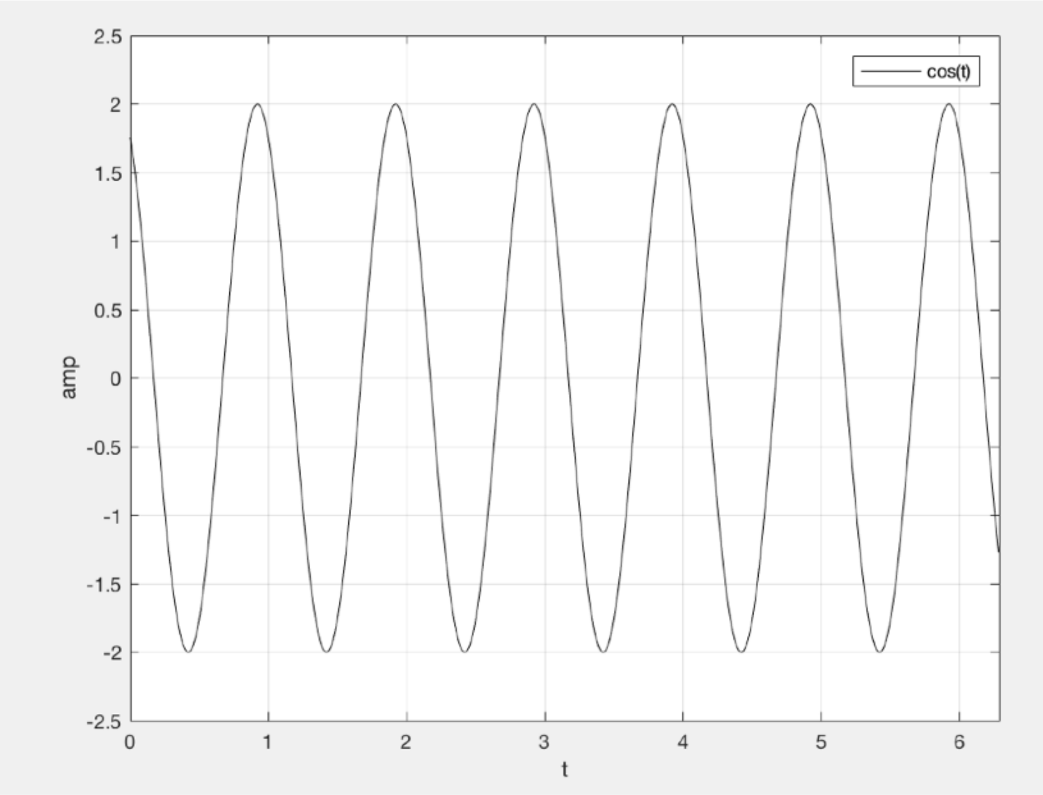
Frequency

Phase

```
clear all
close all
clc

Dm=2 % Spostamento Massimo
f=1  % frequenza in Hz
fi=0.5 % sfasamento
t = 0:0.01:(2*pi); % vettore tempo

D=Dm*(cos(2*pi*f*t+fi)); % equazione d'onda 1D
%plot
plot(t,D,'k'); hold on;
axis([0 2*pi -2.5 2.5])
legend('cos(t)','Location','NorthEast')
xlabel 't'
ylabel 'amp'
grid on
```



Electro-magnetic methods

Electric and Magnetic waves in EM fields in conductors

$$\nabla^2 E = \mu\sigma\frac{\partial E}{\partial t} + \cancel{\mu\varepsilon\frac{\partial^2 E}{\partial t^2}}$$

if $\sigma \gg \omega\varepsilon$ *So called GOOD CONDUCTOR CASE*

$$\mu\varepsilon\frac{\partial^2 E}{\partial t^2} \Longrightarrow 0$$

Electro-magnetic methods

Electric and Magnetic waves in EM fields in conductors

$$\nabla^2 E = \cancel{\mu\sigma \frac{\partial E}{\partial t}} + \mu\varepsilon \frac{\partial^2 E}{\partial t^2}$$

if $\sigma \ll \omega\varepsilon$, *So called DIELECTRIC CASE*

$$\mu\sigma \frac{\partial E}{\partial t} \quad \Rightarrow \quad 0$$

Electro-magnetic methods

Electric and Magnetic waves in EM fields in conductors as a wave equation

$$\nabla^2 E = \mu\sigma \frac{\partial E}{\partial t} + \mu\varepsilon \frac{\partial^2 E}{\partial t^2}$$

if $\sigma \gg \omega\varepsilon$

Conductor case

if $\sigma \ll \omega\varepsilon,$

Dielectric case

I cannot modify the electric properties of the soil (σ, ε)

but I can change the frequency (ω) in the generation of the EM field...

Electro-magnetic methods

Electric and Magnetic waves in EM fields in conductors

LOW FREQUENCY EM METHOD

(e.g. K Hz) Kiloherz

$$\text{if } \sigma \gg \omega\varepsilon$$

$$\nabla^2 E = \mu\sigma\frac{\partial E}{\partial t}$$

CONDUCTION CURRENTS

I CAN RETRIEVE conductivity σ OF THE SOIL

Electro-magnetic methods

Electric and Magnetic waves in EM fields in conductors

HIGH FREQUENCY EM METHOD

(e.g. *M Hz*)
Megaherz

if $\sigma \ll \omega\varepsilon$,

$$\nabla^2 E = \mu\varepsilon \frac{\partial^2 E}{\partial t^2}$$

DISPLACEMENT CURRENTS

I CAN STUDY THE PROPAGATION OF EM WAVES

Electro-magnetic methods

Electric and Magnetic waves in EM fields in conductors

LOW FREQUENCY EM METHOD (e.g. K Hz)

$$\text{if } \sigma \gg \omega\varepsilon$$

$$\nabla^2 E = \mu\sigma\frac{\partial E}{\partial t}$$

EM METHODS

FDEM, TDEM, etc.

Electro-magnetic methods

Electric and Magnetic waves in EM fields in conductors

HIGH FREQUENCY EM METHOD (e.g. M Hz)

if $\sigma \ll \omega\varepsilon$,

$$\nabla^2 E = \mu\varepsilon \frac{\partial^2 E}{\partial t^2}$$

RADAR METHODS

GEORADAR, GPR, etc.

∇x E= -dB/dt

∇x B= με(dE/Dt)

Physical principles
Maxwell's equations

SMALL LOOPS SYSTEMS: moving-source dual-coil system

Two small coils separated by a constant distance

A transmitter coil, in which an a.c. is sent creates a primary EM field which propagated above and below ground and eddy currents are generated (flow of magnetic field) . These currents generate a secondary field detected by the receiver coil

conduction current

wave propagation

$$\nabla^2 E = \mu\sigma\frac{\partial E}{\partial t} + \mu\varepsilon\frac{\partial^2 E}{\partial t^2}$$

conduction currents

displacement currents

μ	magnetic permeability
σ	electric conductivity
ε	dielectric permittivity

LOW FREQUENCY:

the second term is much smaller than the first, and the regime is called *inductive,* with the diffusion of fields

$$\nabla^2 E = \mu\sigma\frac{\partial E}{\partial t}$$

HIGH FREQUENCY:

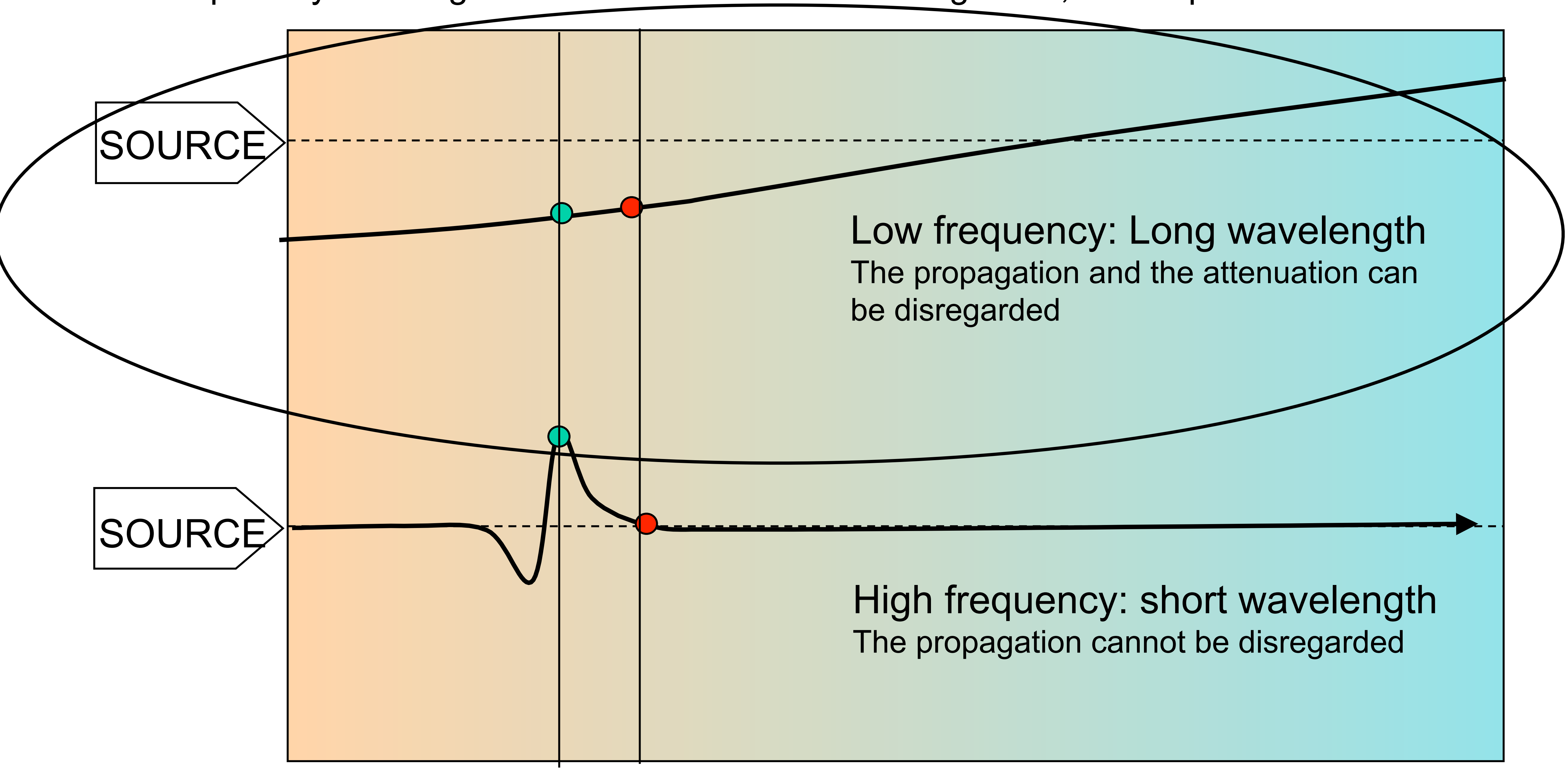
the first term become negligible and the propagation is important

$$\nabla^2 E = \mu\varepsilon\frac{\partial^2 E}{\partial t^2}$$

EM METHODS

Propagation of an electromagnetic wave

A primary field is generated and the sent into the ground, the response is measured



Low frequency: Long wavelength

The propagation and the attenuation can be disregarded

High frequency: short wavelength

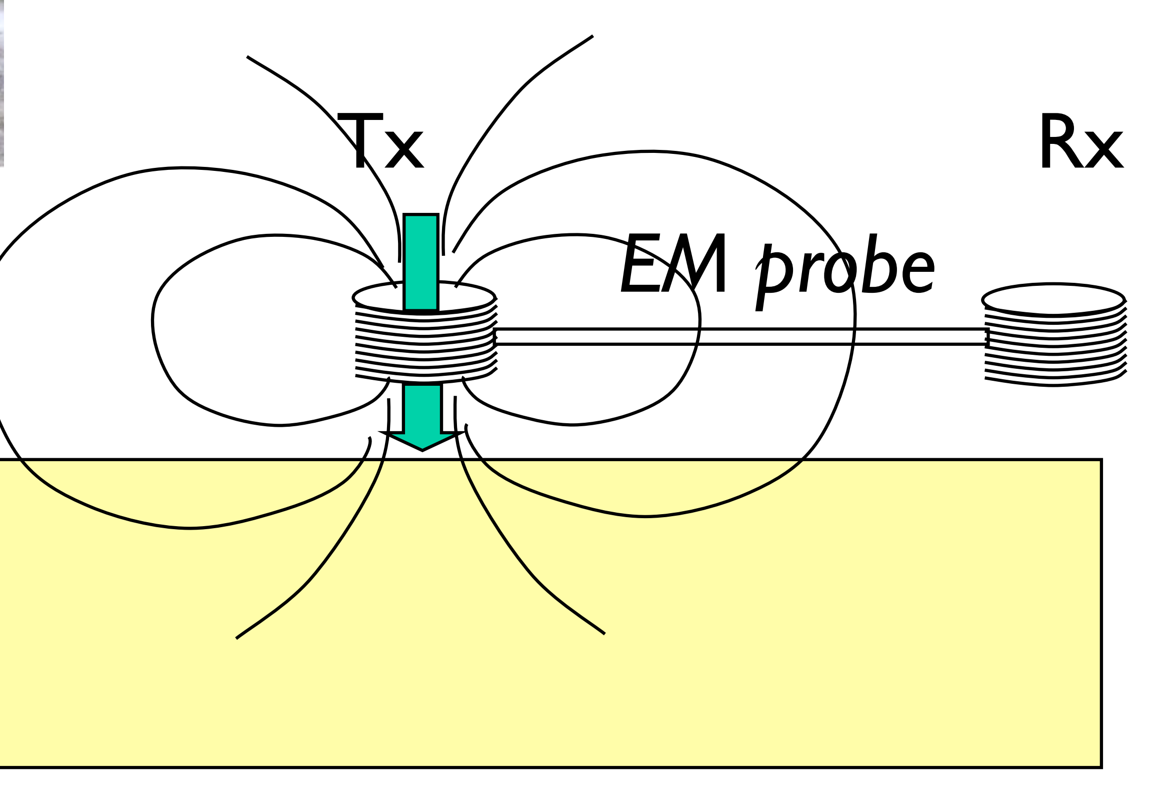
The propagation cannot be disregarded

Electro-magnetic methods

EM METHODS

FDEM

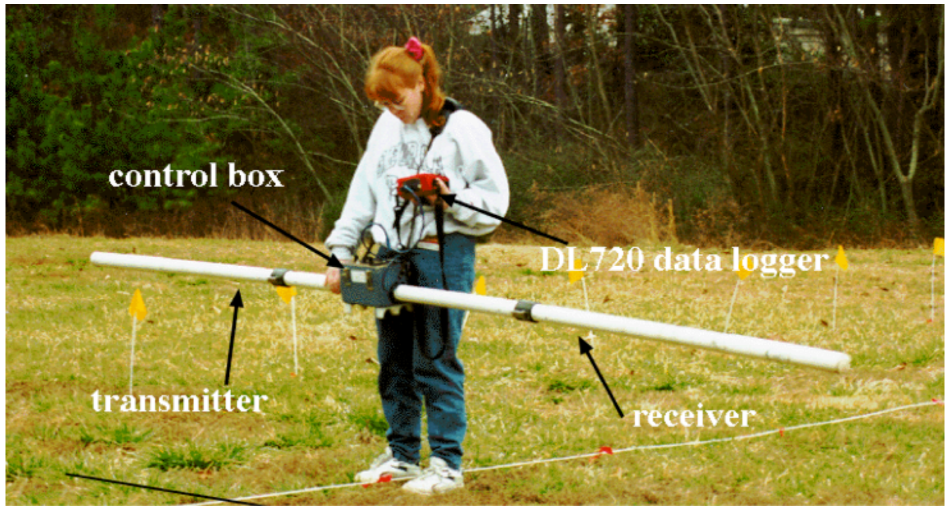
2 coils



Frequency Domain ELECTRO MAGNETOMETER

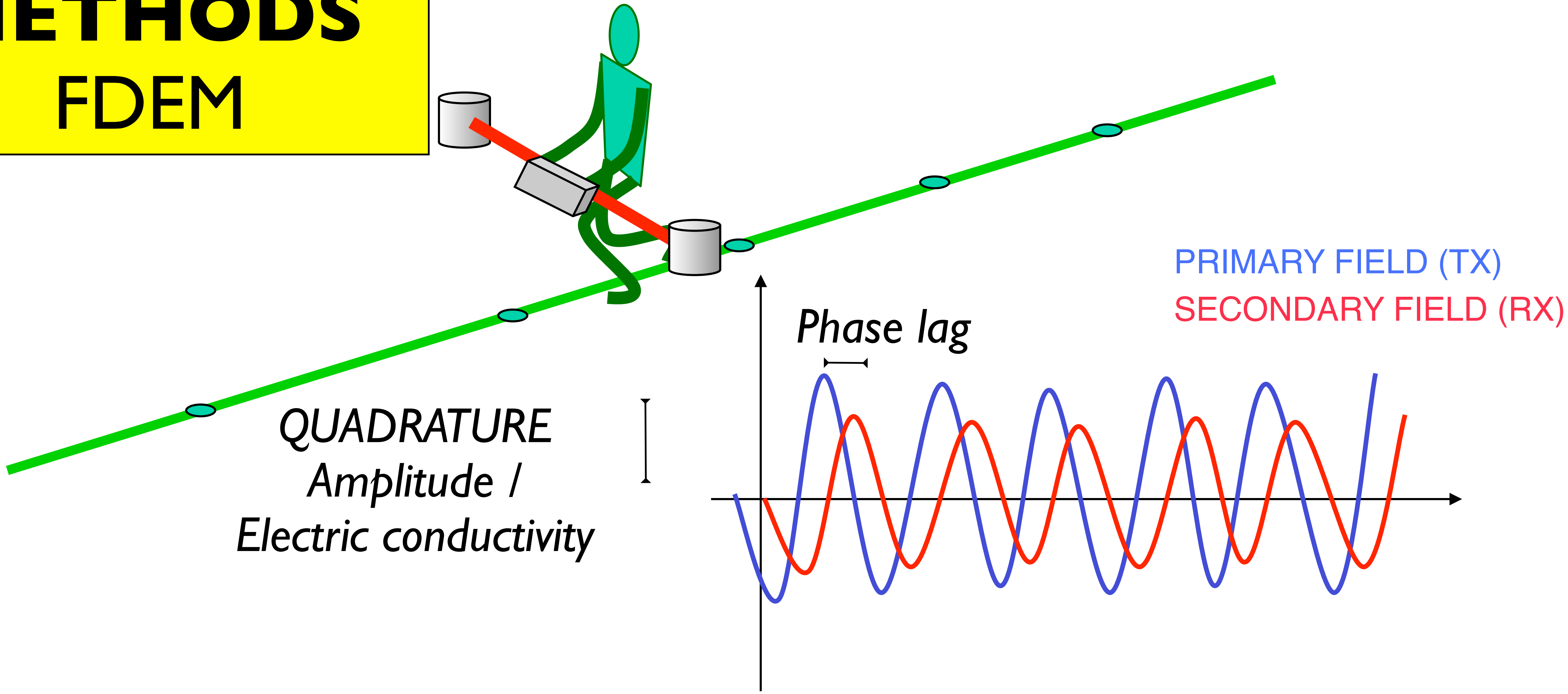
There are two types of electromagnetic (EM) survey:

- FDEM, frequency domain, measures the amplitude and phase of an EM induced field (shallow part, environmental/civil use)



- TDEM, based on the time domain, measures the decay time of an electromagnetic pulse induced by a transmitter (deep part, mine use).

EM METHODS
FDEM



Relation between primary, secondary and resultant field: two values measured at each station

- Real (in-phase)
- Imaginary (quadrature, out-of-phase)

PHASE

AMPLITUDE

Amplitude
Phase lag

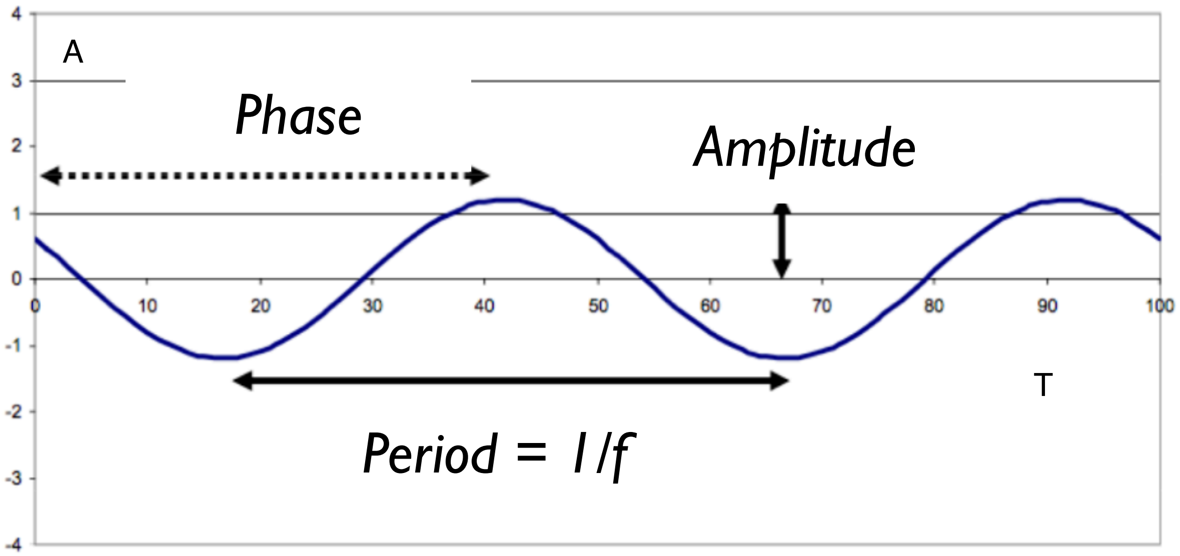
Electro-magnetic methods

Electro-magnetic waves are complex signals

Sinusoidal wave

$$A_c \cos(2\pi f_c t + \phi)$$

Amplitude Frequency Phase



$$A(t) = A_{\max} \cos(2\pi f t + \phi)$$

Eq. Wave

$\phi = -2\pi f t_{\max}$	phase (when arrive the maximum?)
$T = 1/f$	Period (how much last the motion?)
$f = 1/T$	Frequency (how much oscillation?)
$\omega = 2\pi f = 2\pi / T$	Pulsation

$$\vec{E} = \vec{E}_0 e^{i(\vec{k}\cdot\vec{r}-\omega t)}.$$

Eulerian Expression
EM wave

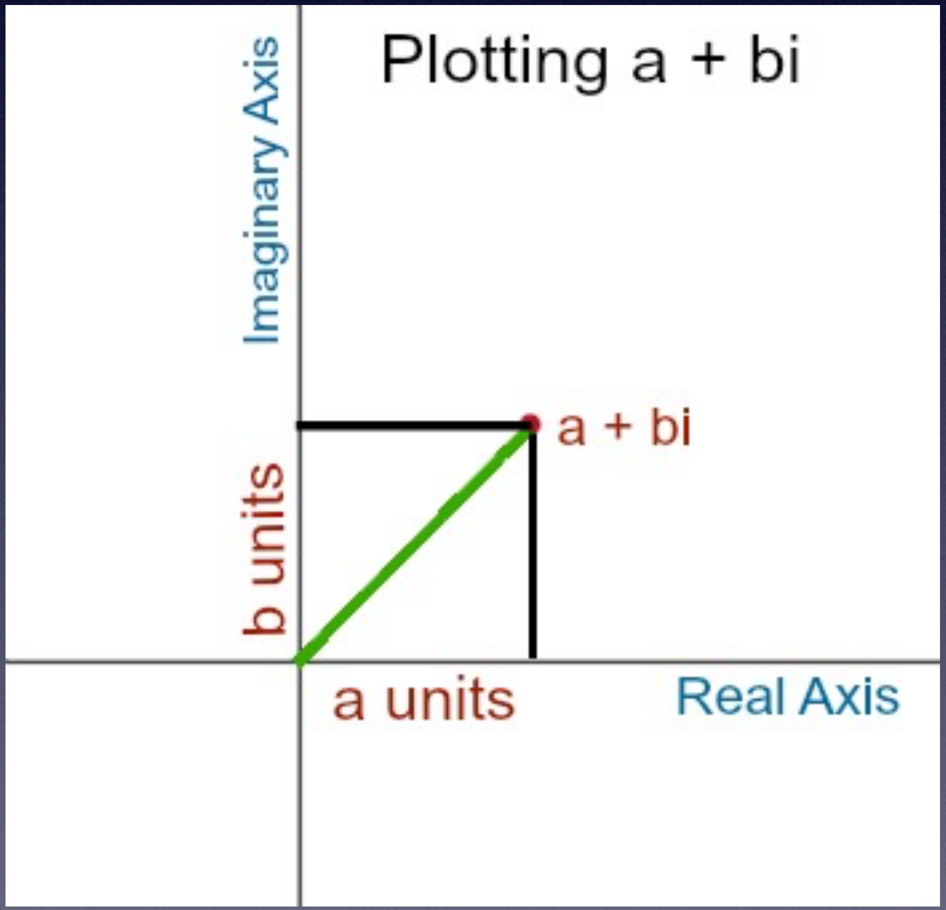
Electro-magnetic methods

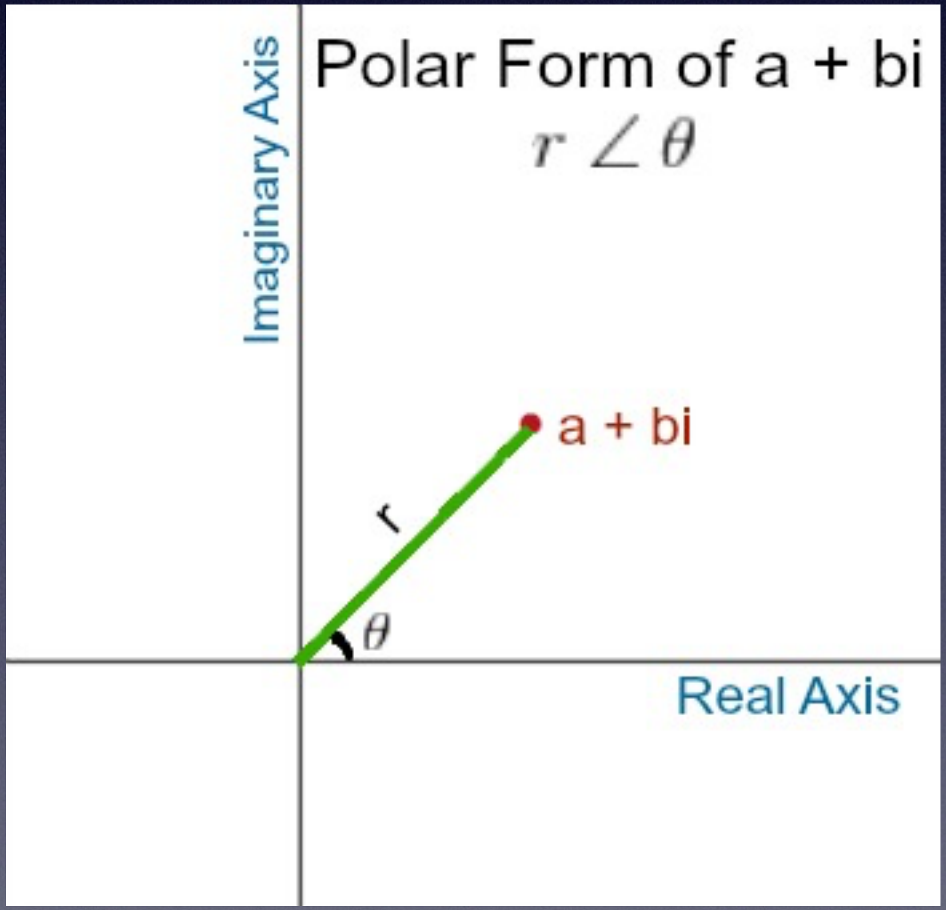
Electro-magnetic waves are complex signals

Complex numbers have a real and imaginary part

$$Nc = a+ib$$

a,b Real numbers   *Imaginary unit $i=\sqrt{-1}$*





Plotted in polar form the complex vector has length r and angle θ with the real axis

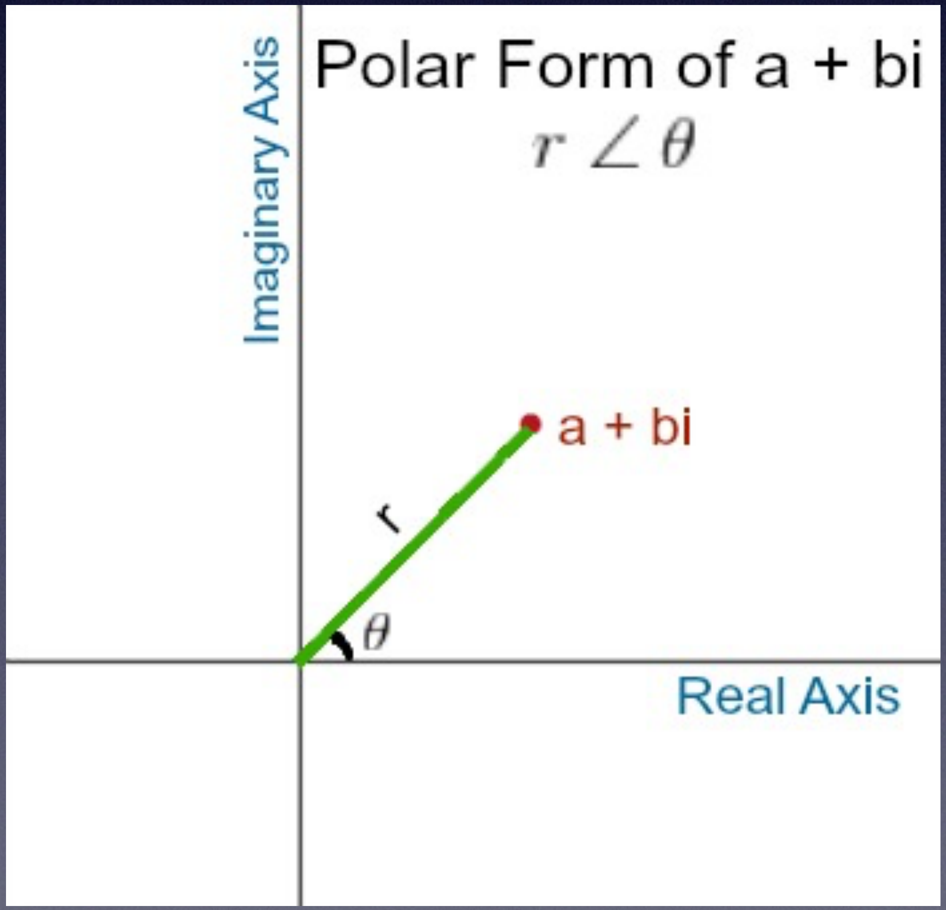
Electro-magnetic methods

Electro-magnetic waves are complex signals

Complex numbers have a real and imaginary part

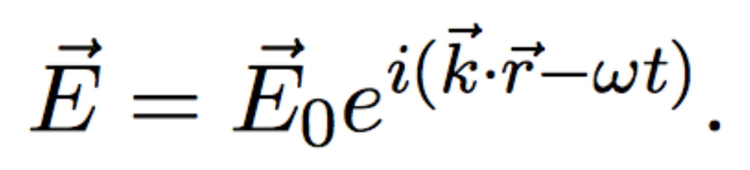
$$Nc = a+ib$$

a,b Real numbers *Imaginary unit* $i=\sqrt{-1}$



In Euler's notation

$$a + bi = re^{i\theta}$$



$$\vec{E} = \vec{E}_0 e^{i(\vec{k}\cdot\vec{r}-\omega t)}.$$

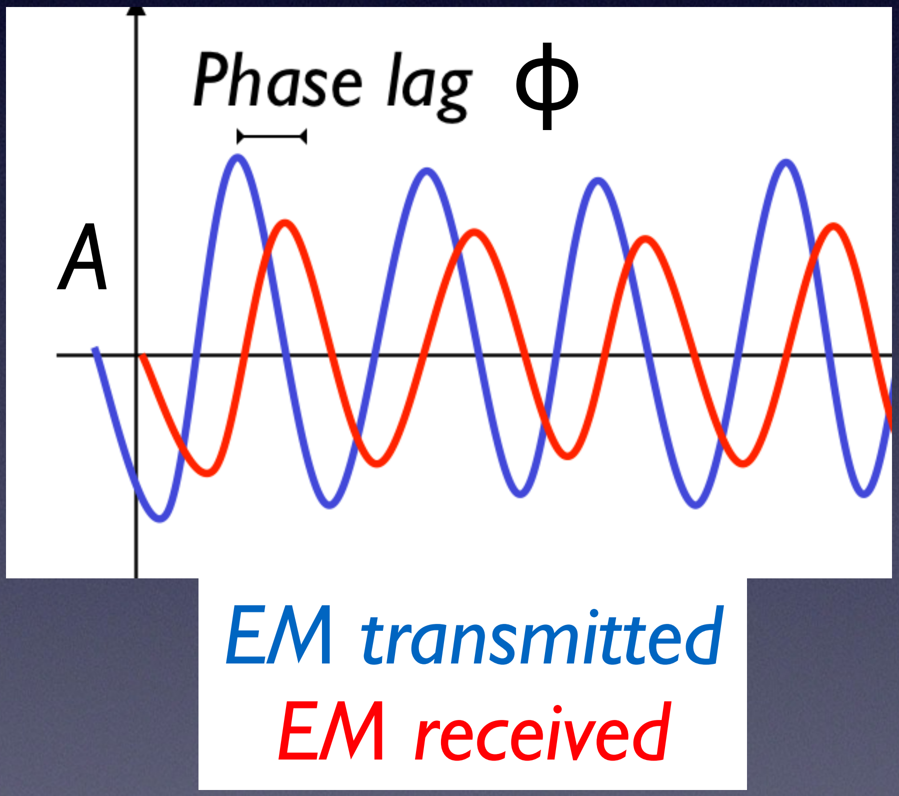
Electro-magnetic methods

Electro-magnetic waves are complex signals

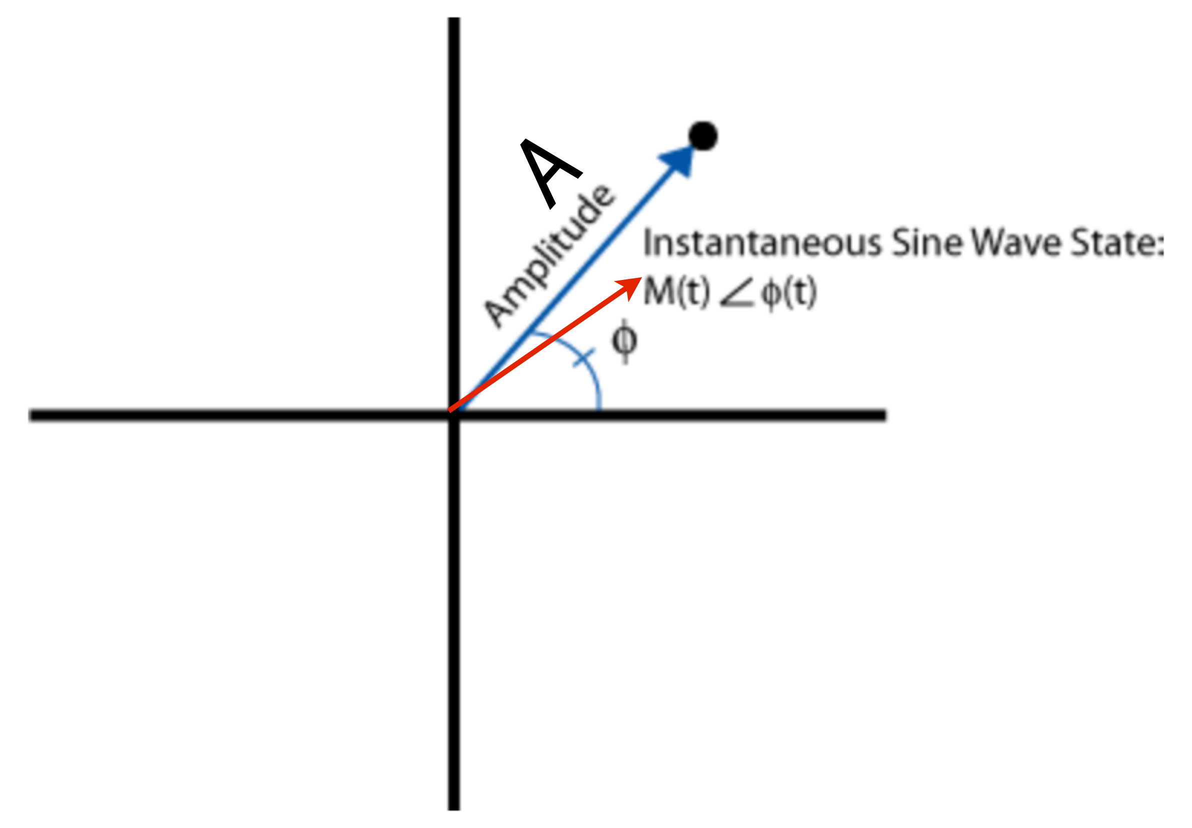
Sinusoidal wave

$$A_c \cos(2\pi f_c t + \phi)$$

Amplitude Frequency Phase



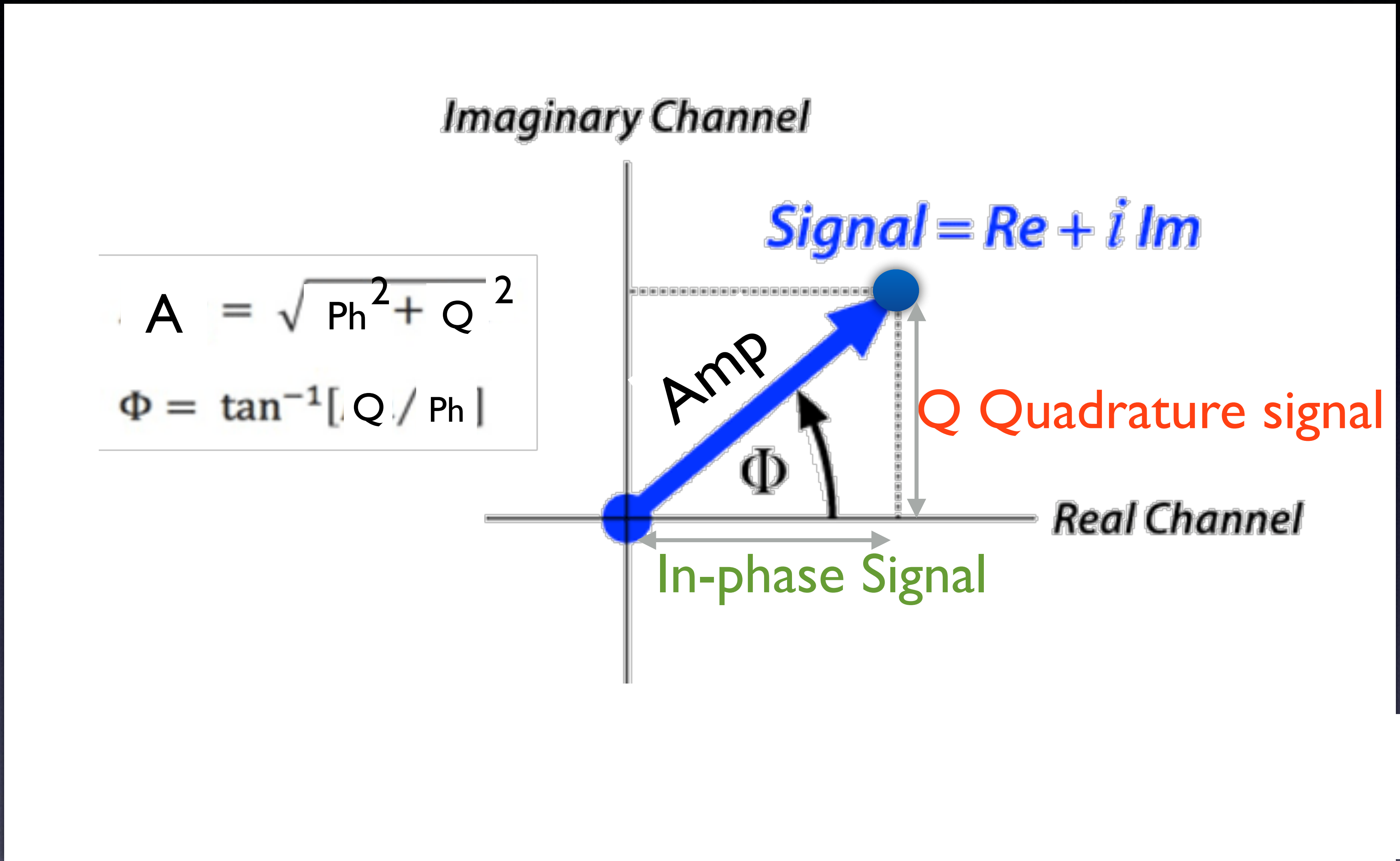
Vector on a Complex plain



EM wave as a complex vector

Electro-magnetic methods

Electro-magnetic waves are complex signals



$$A = \sqrt{Ph^2 + Q^2}$$

$$\Phi = \tan^{-1}[Q / Ph]$$

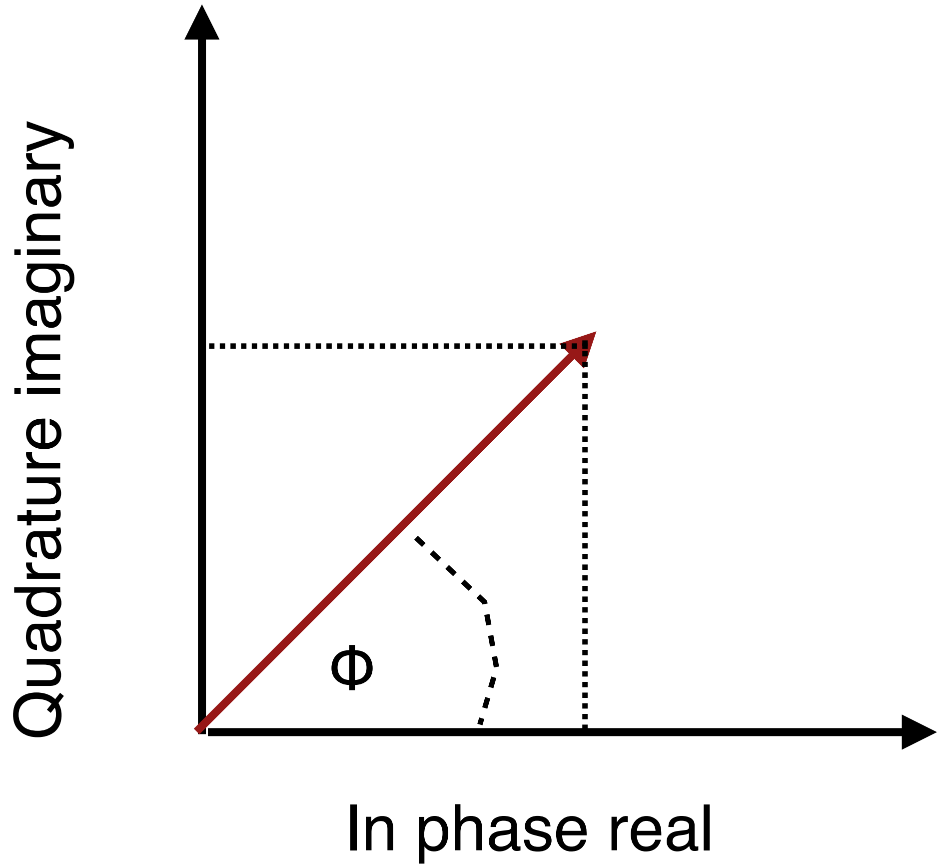
FDEM equipment record both the parts of the field signal, the one in phase with the transmitter (called the 'in-phase' component) and the other orthogonal (90° out of phase, called the 'quadrature').

$$\nabla^2 E = \mu\sigma \frac{\partial E}{\partial t}$$

In-phase ratio of the secondary to primary magnetic field, usually expressed in parts per thousand (ppt), is related to the magnetic susceptibility. The Quadrature is related to the ground apparent conductivity and usually expressed in mS/m.

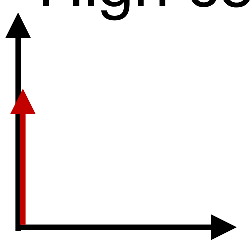
This value is an integrated number depending on ancillary of soil properties such as bulk density, salinity, soil structure, moisture content, ionic composition, etc

Electro-magnetic methods



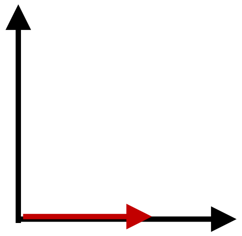
High conductivity = High quadrature

High conductivity = Φ ➡ π/2



Low conductivity = Low quadrature

Low conductivity = Φ ➡ 0



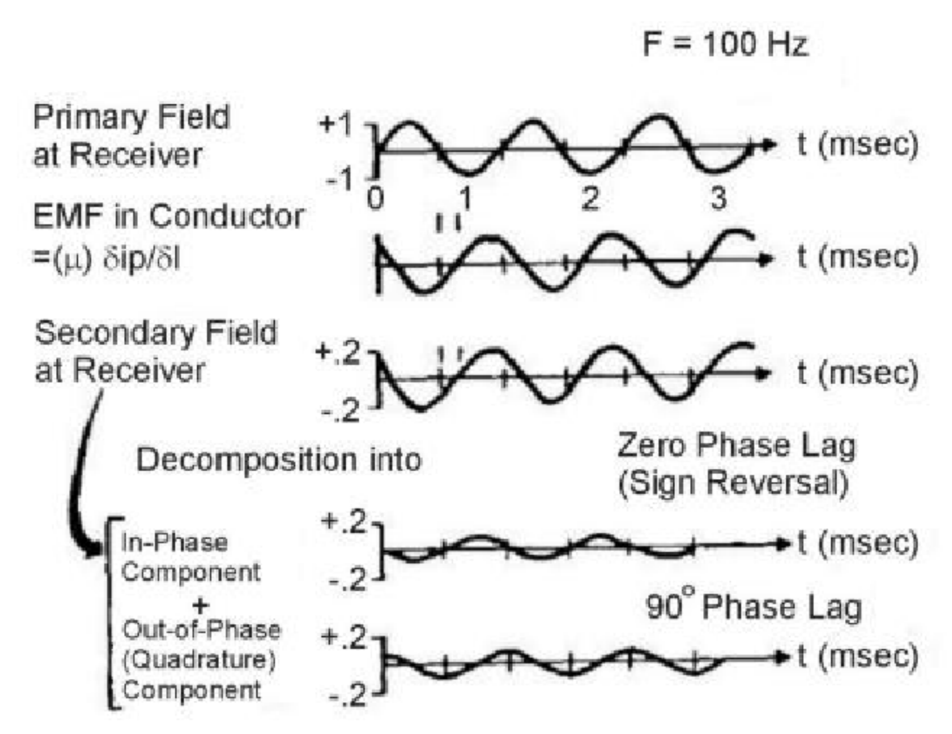
EM METHODS
FDEM

In phase Part → *magnetic susceptibility*

Quadrature Part → *electric conductivity*

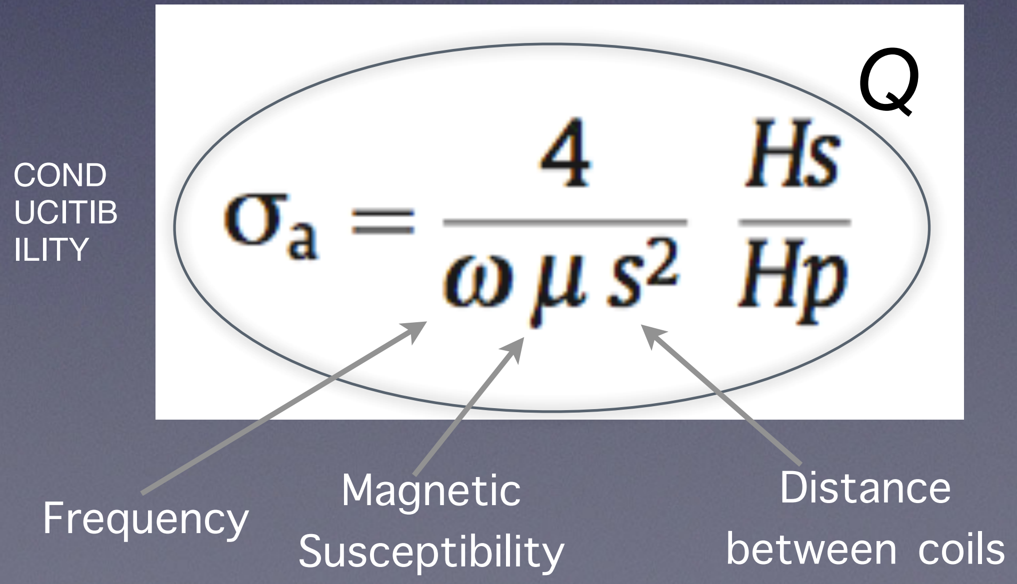
EM METHODS

FDEM



Hp = primary Em field intensity

Hs = secondary Em field intensity



COND
UCITIB
ILITY

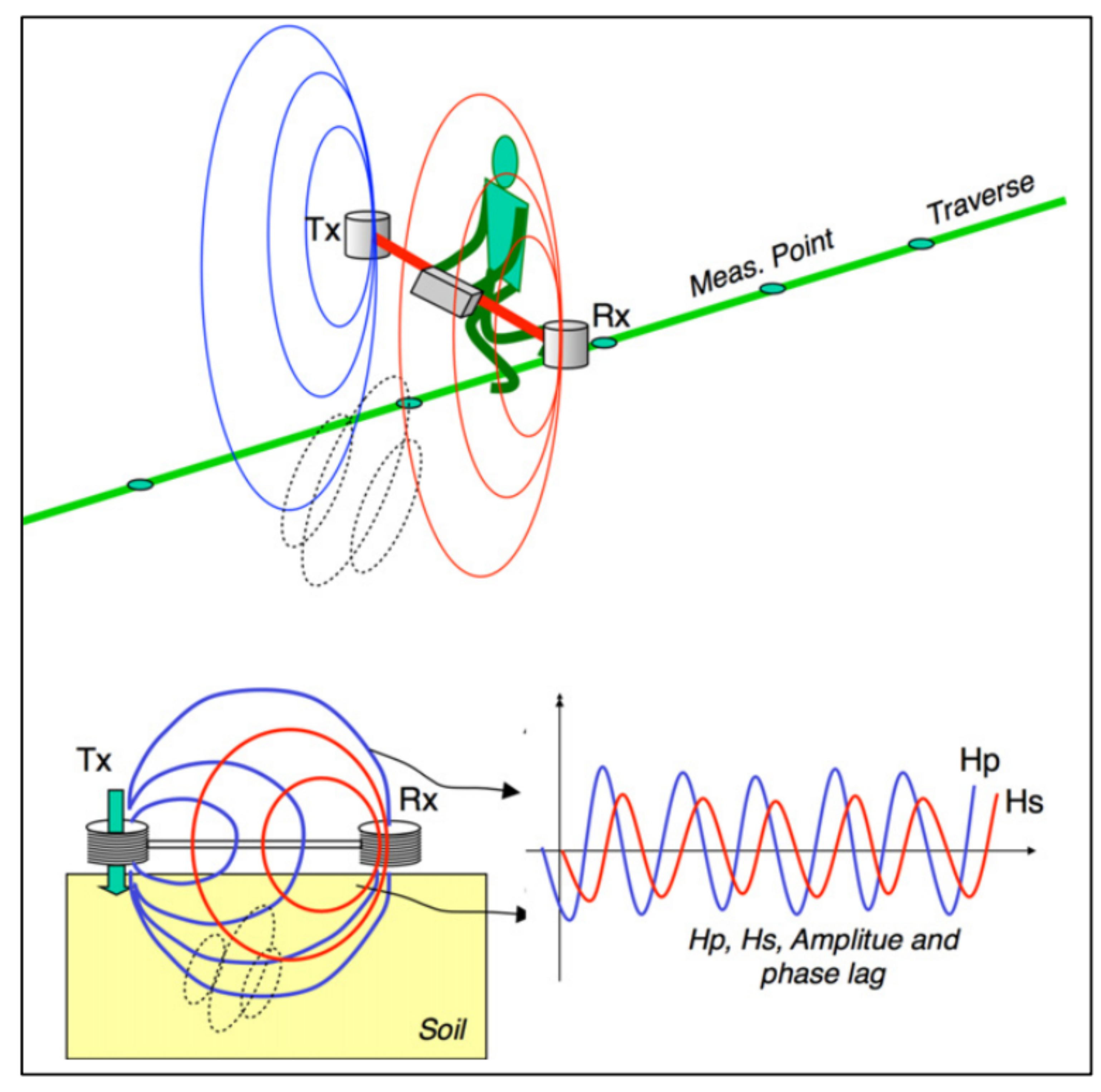
$$\sigma_a = \frac{4}{\omega \mu s^2} \frac{Hs}{Hp}$$

Q

Frequency

Magnetic Susceptibility

Distance between coils



EM METHODS
FDEM

LOW INDUCTION NUMBER condition

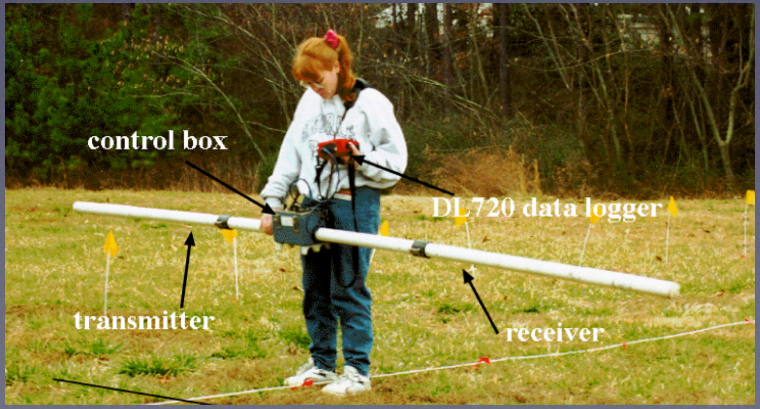
$$2\pi f \ll 2/\mu_0\sigma s^2$$

$$\sigma_a = \frac{4}{\omega\,\mu_0 s^2}\,\frac{Hs^{Q}}{Hp}$$

$4\pi.10^{-7}$ H.m^{-1}, SI units

App. Conductivity

$$\sigma_a = \text{cost}\ \left(\frac{Hs}{Hp}\right)^{Q}$$



EM METHODS

FDEM

$$\sigma_a = \frac{4}{\omega\,\mu_0 s^2}\,{\frac{Hs}{Hp}}^{Q}$$

≠ ω

≠s

≠ depth of investigation

Multi-frequencies probe

Or

Probe with different coils distances

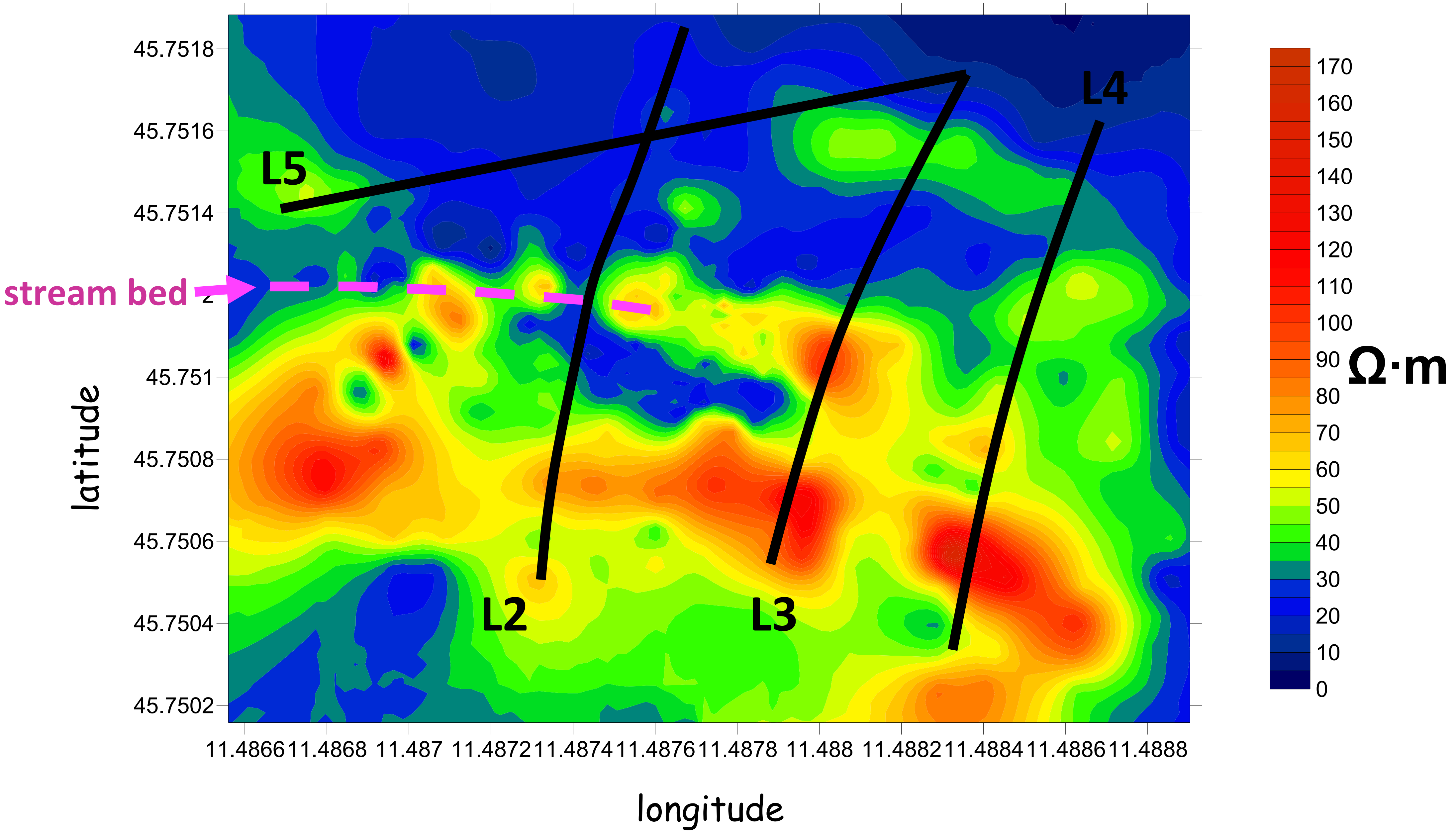
<u>CONDUCTIVITY SUBSOIL MAP</u>

Conductivity / Resistivity MAP

$\sigma = 1/\rho$

Frequency-domain EM

Resistivity map obtained using a GF Instrument CMD 1 sonde:
max investigation depth = 0.75 m



EM METHODS
FDEM

Campi Elettro-magnetici si attenuano con la distanza, posso abbassare la frequenza ω per andare più in profondità, quanto ?

LOW INDUCTION NUMBER

Devo rispettare la condizione

$$2\pi f \ll 2/\mu_0 \sigma s^2$$

Skin Depth *d*

$$d = \sqrt{\frac{2}{\omega \mu_0 \sigma}}$$

Distanza per cui il campo Hp si riduce di 1/e ← *Euler number 2,7*
(massima profondità di indagine)

Advantages of FDEM

- No need of galvanic contact
- Less sensible to surface conditions
- Quick for wider area
- Can be used in land or water
- Can be used in borehole

Cons of FDEM (respect to DC ERT methods)

- Dynamic range is less (1-1000 ohm m) in Quick resistive soils no current can be put in, for conductive soil not-linear effects are possible

- Depth of penetration is limited (but for separated coils system or big TDEM methods)

- Not easy the quantitative interpretation

Dipole-source methods

- Measurements tolls called twin-coil or slingram systems

- Tx and Rx are coils (about 1m diameter) linked by a cable which carries a reference signal in order to compensate the effect of the primary field. By this means, the system subsequently responds only to the secondary fields

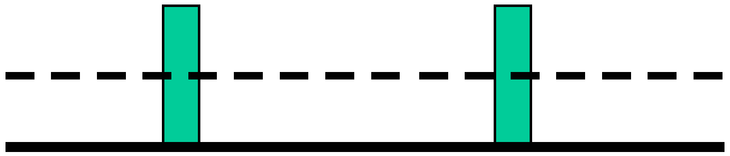
- A decomposer spilt the secondary field into real and imaginary components (display the result as a percentage of the primary field)

Loop configurations

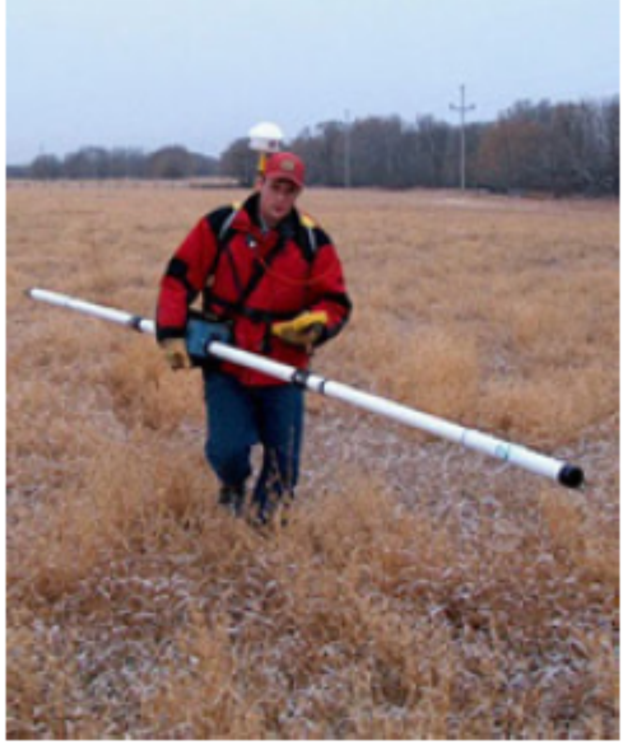
- HCP (horizontal co-planer)

- VCP (vertical co-planer)

- VCA (vertical Coaxial)



- Others



EM31 (Geonics), 9.8 kHz, *s*=3.66 m

EM34 (Geonics), 6.4 kHz for *s*=10 m

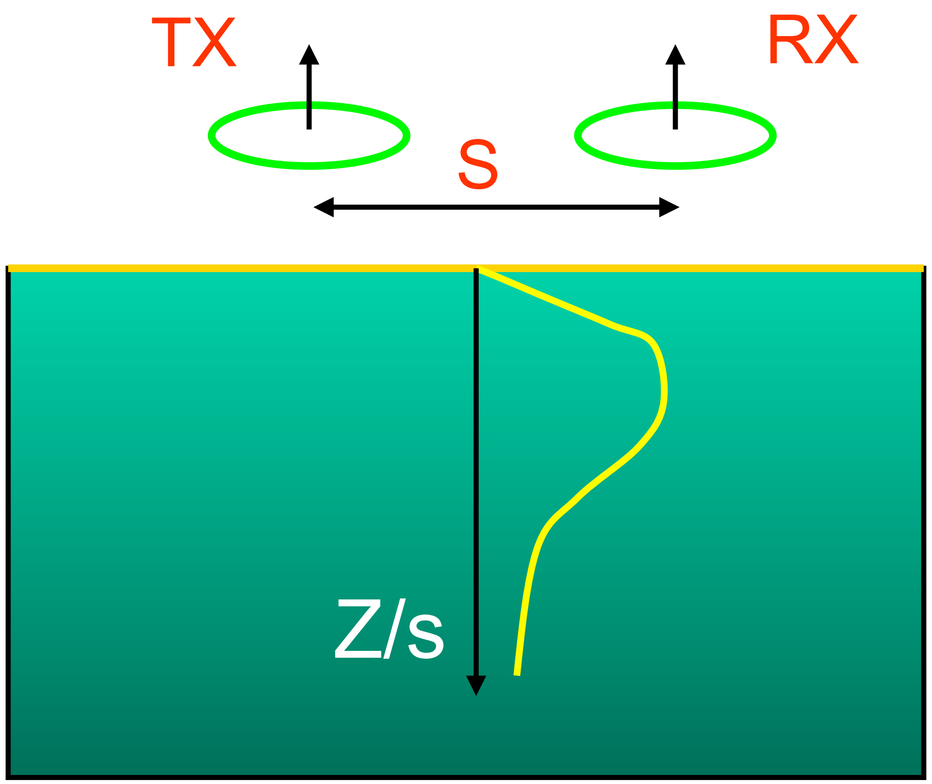
1.6 kHz for *s*=20 m

0.4 kHz for *s*=40 m

EM38 (Geonics), 14.6 kHz, *s*=1 m

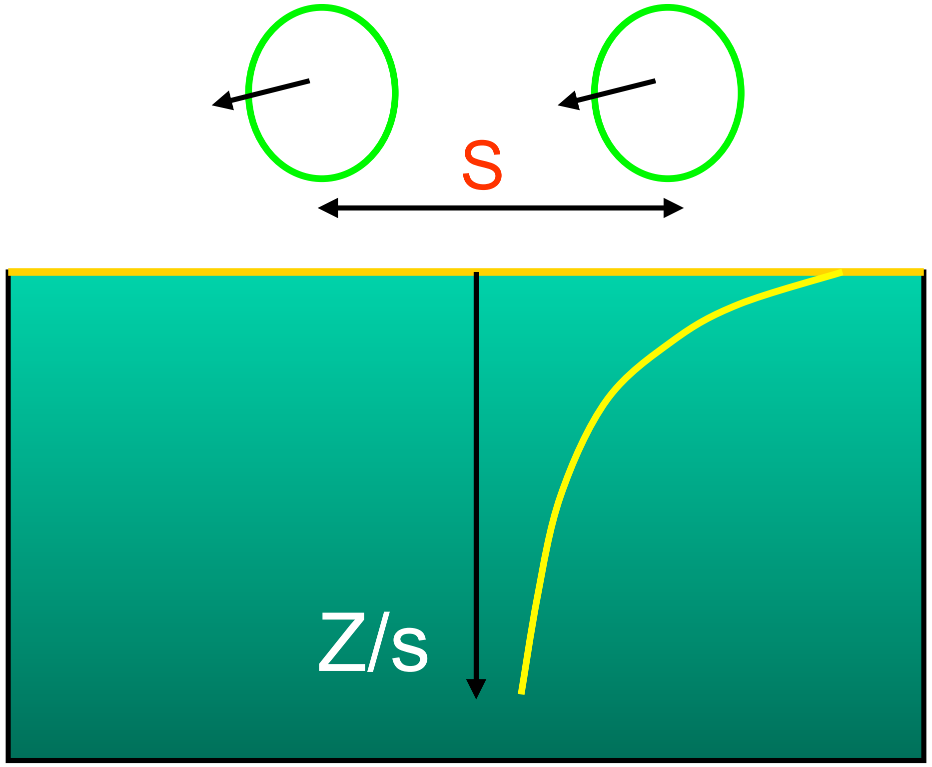
s: Rx-Tx distance

Stability of FDEM methods in low induction number



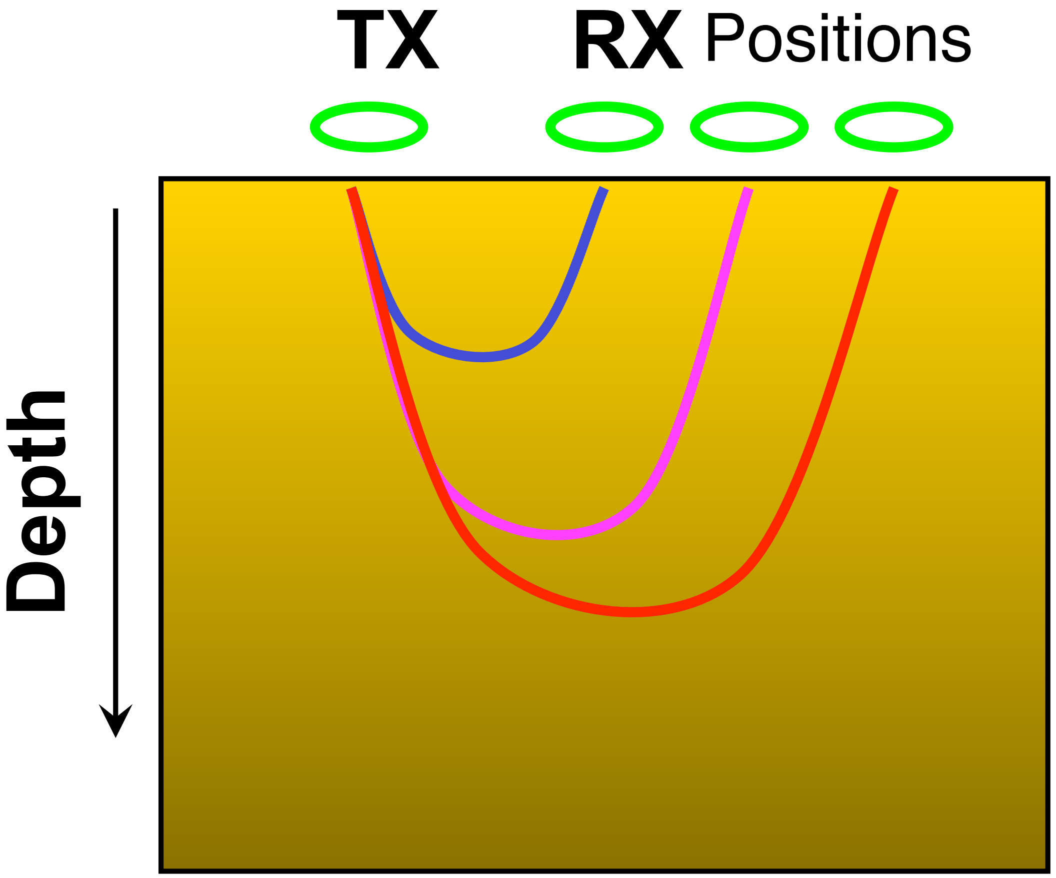
Horizontal coils
(and vertical magnetic dipole)

Vertical Coils
(and horizontal magnetic dipole)



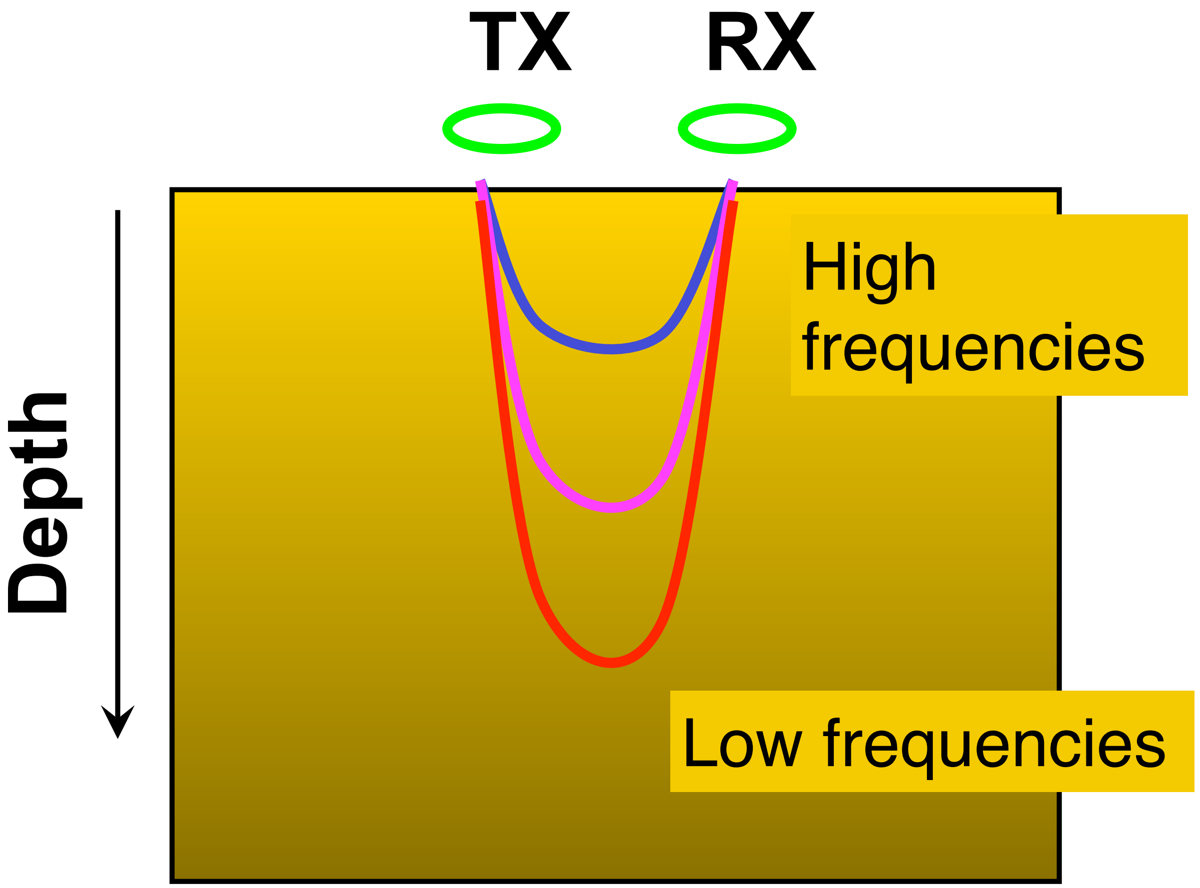
Geometric soundings

Fixed frequency and several coils



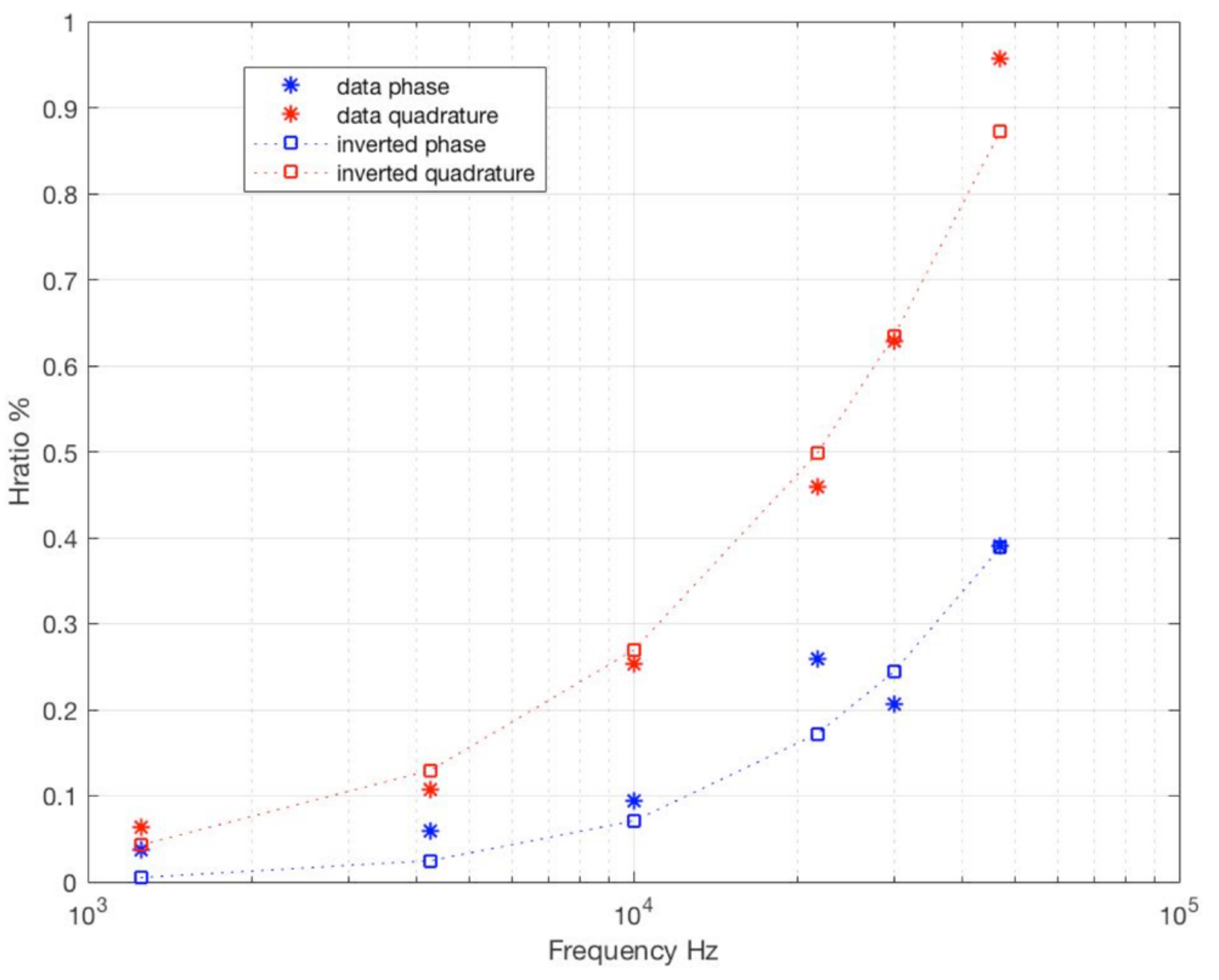
Frequency soundings

Fixed coils, several frequencies

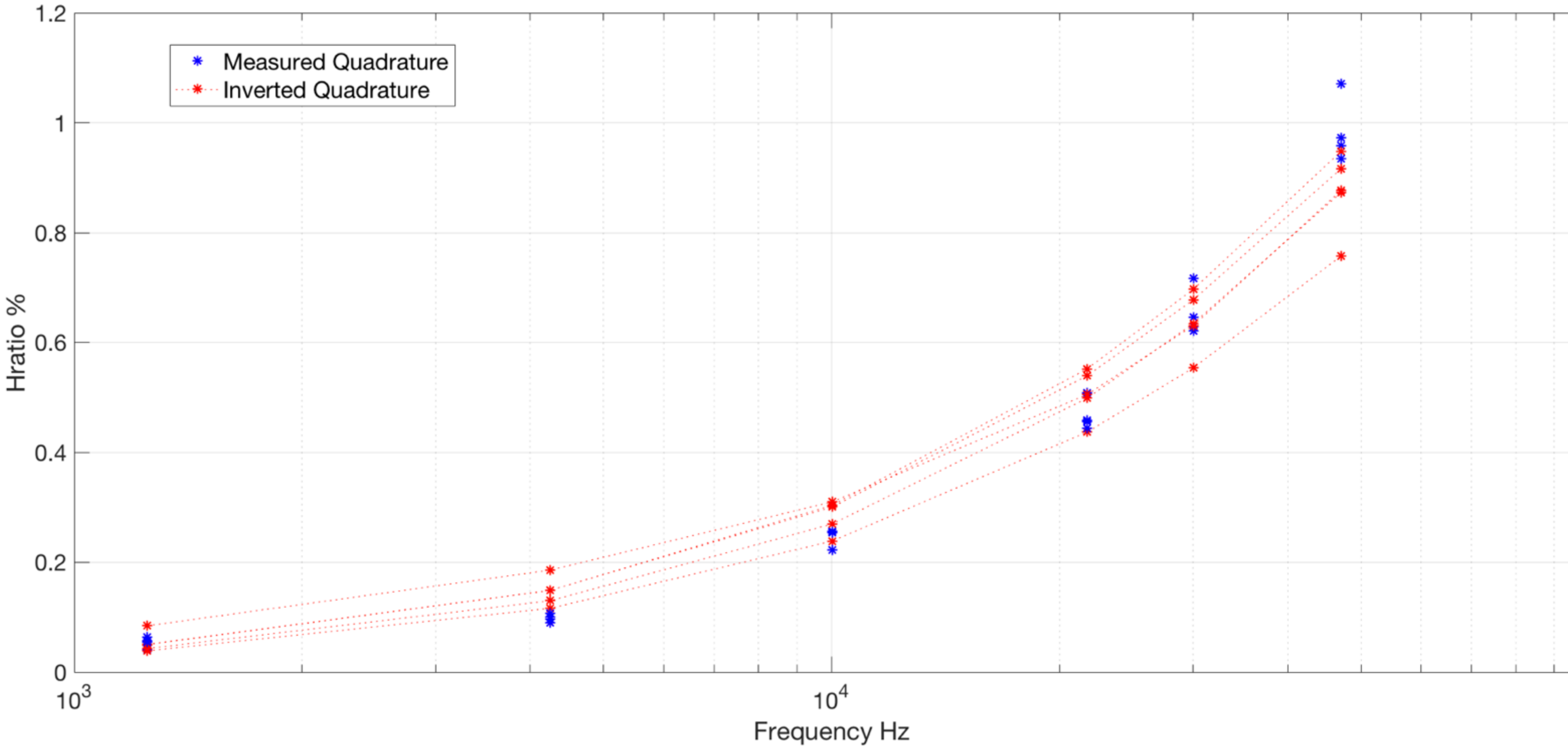


inversion of FDEM

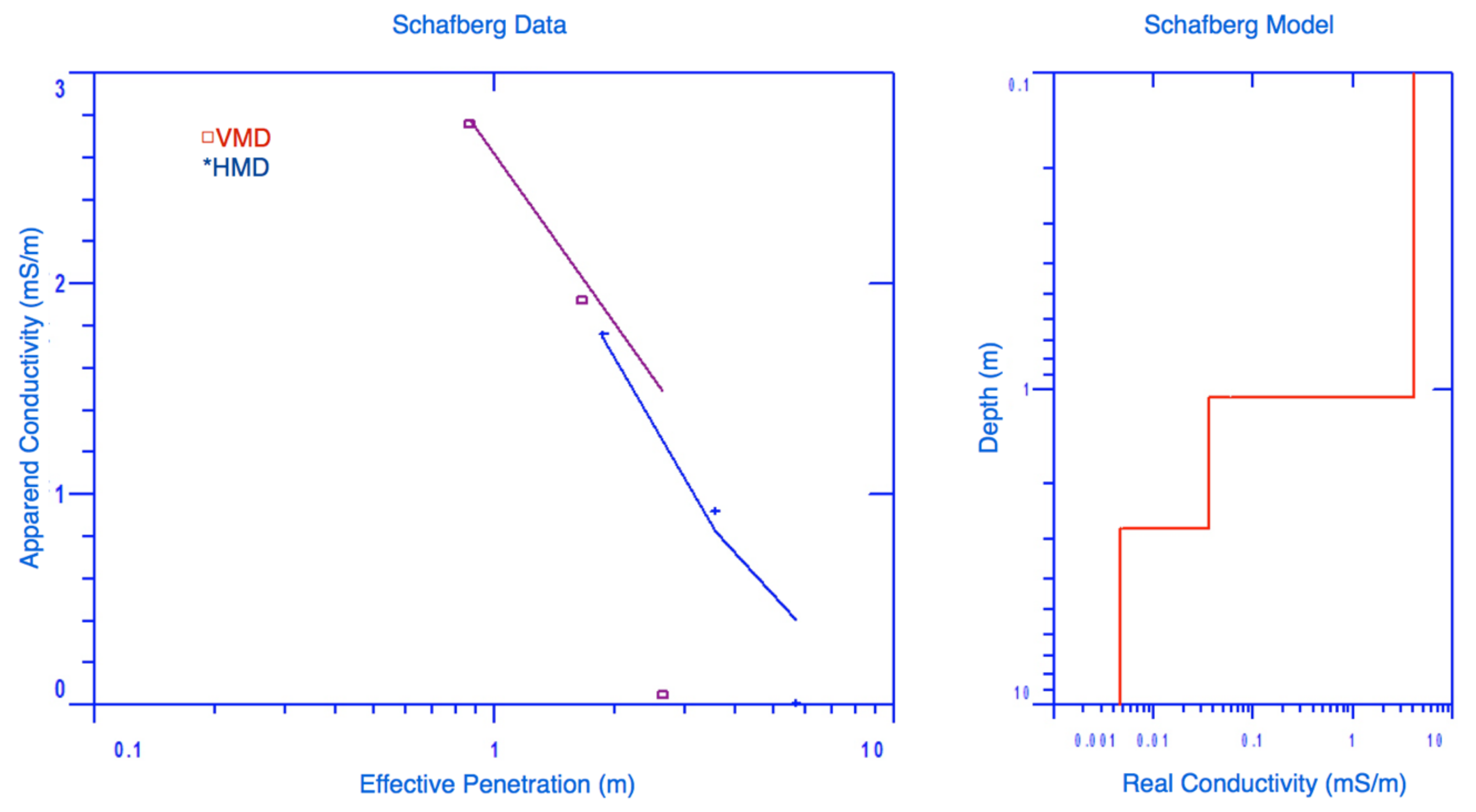
Inversion FDEM (Interpex, emagpy, etc)



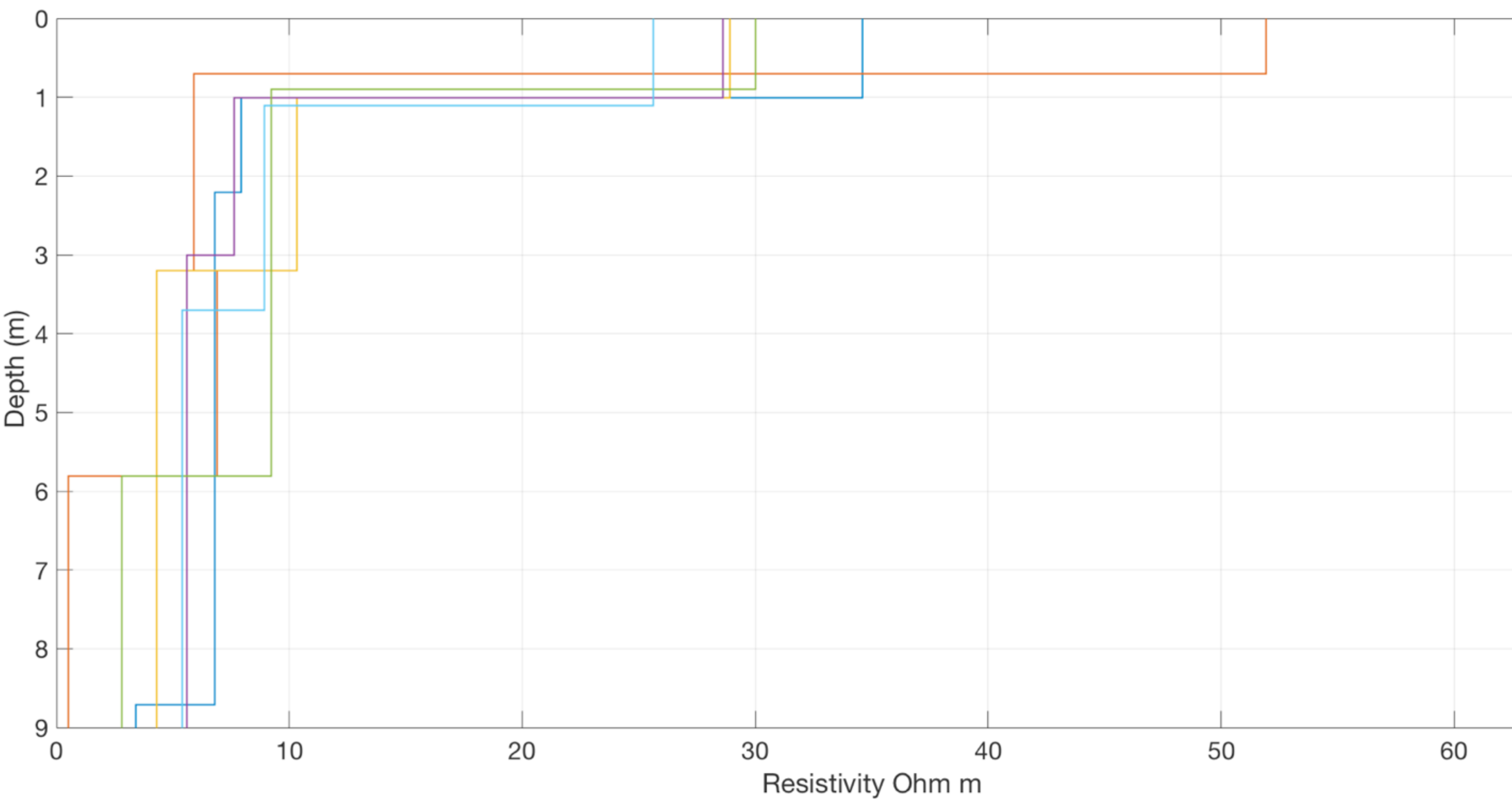
Inversion Interpex FDEM



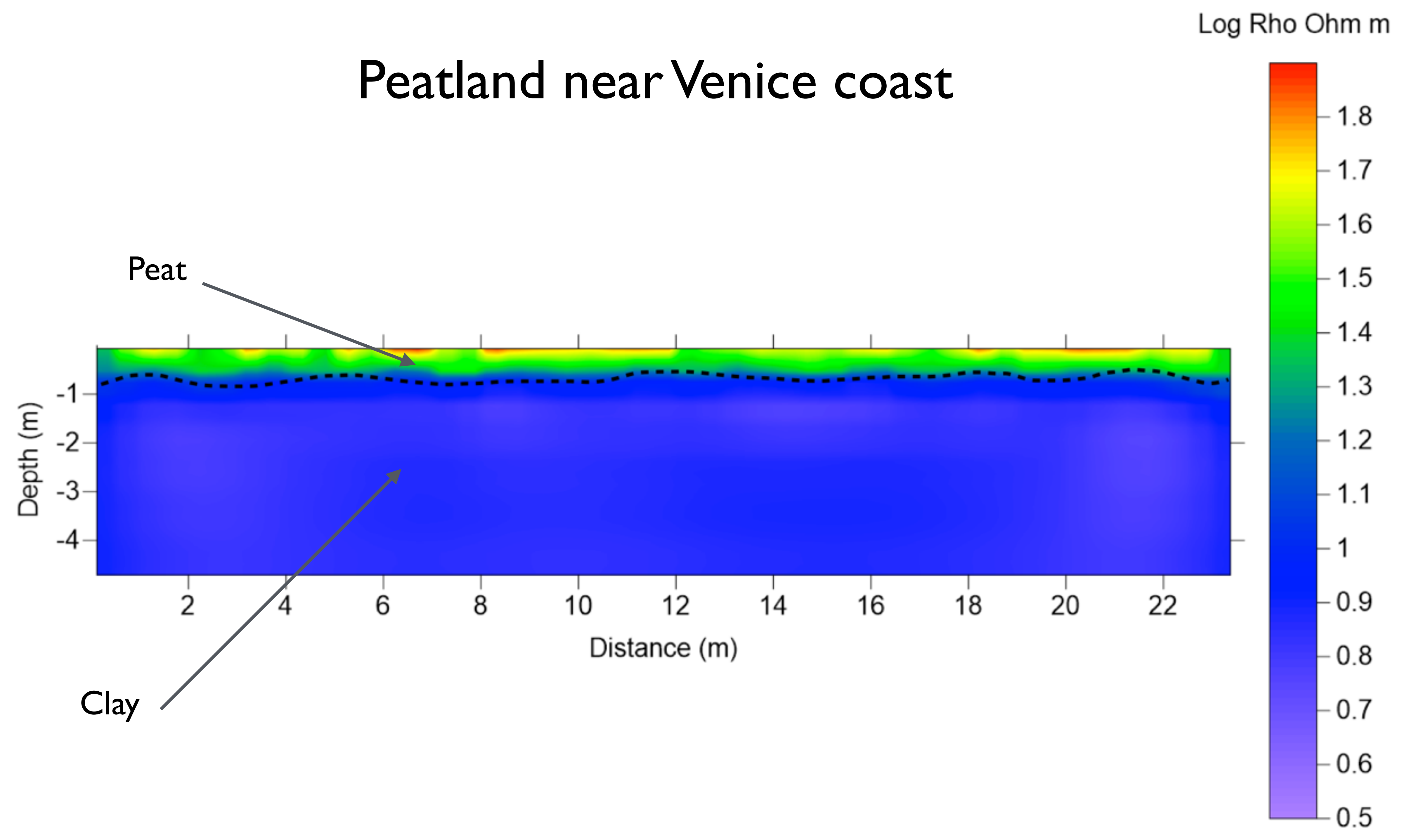
Inversion Interpex FDEM



Inversion Interpex FDEM 1D Results



Inversion Interpex interpolation Results
PSEUDO-2D



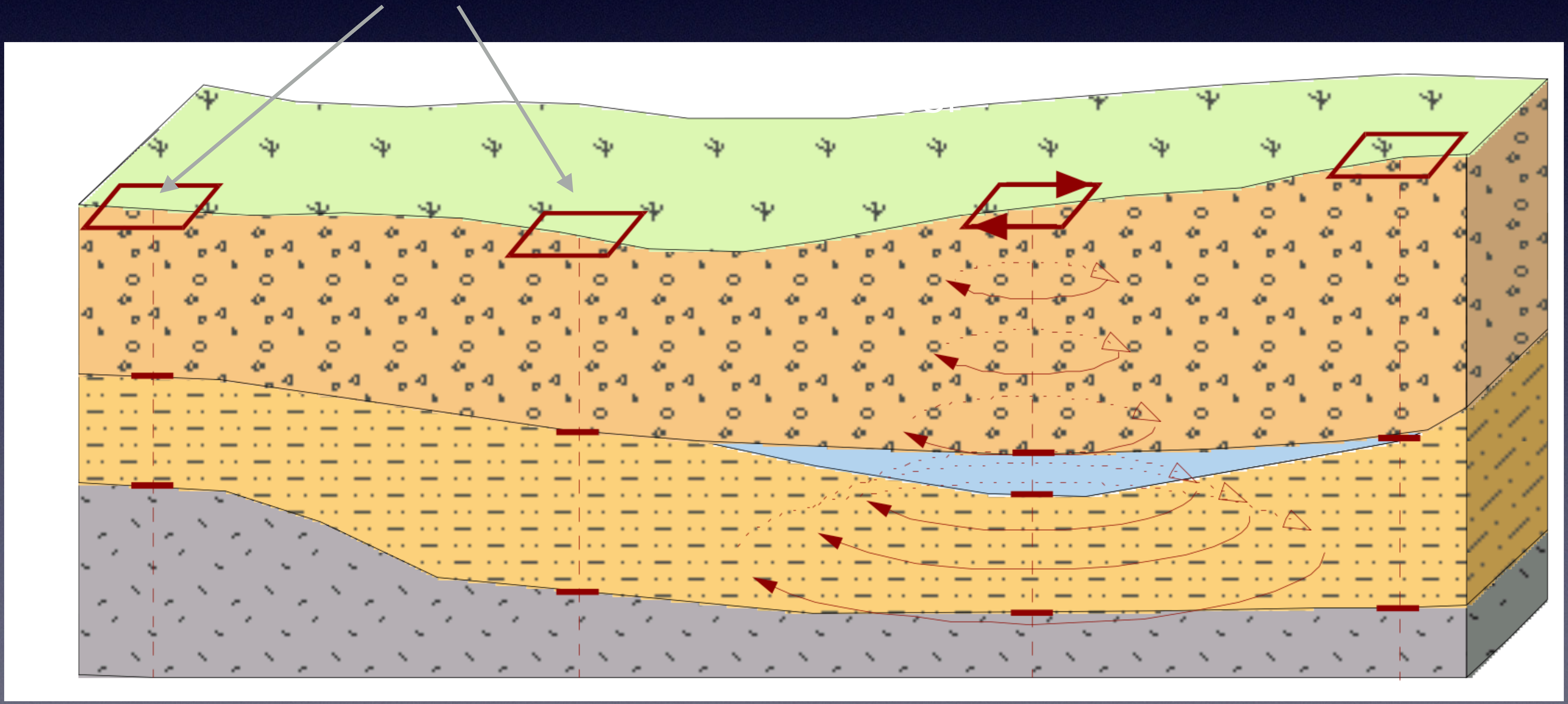
Peatland near Venice coast

Peat

Clay

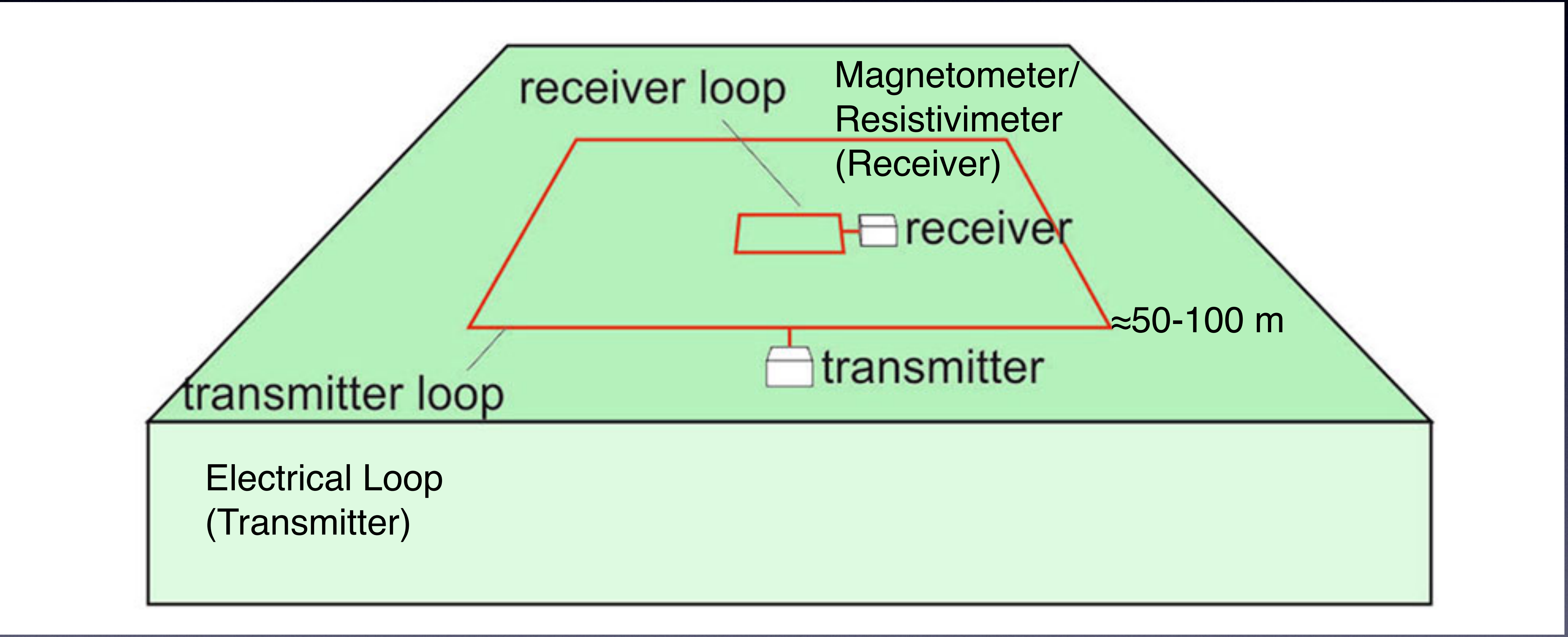
TIME DOMAIN
ELECTRO-MAGNETOMETER
TDEM

TDEM LOOP



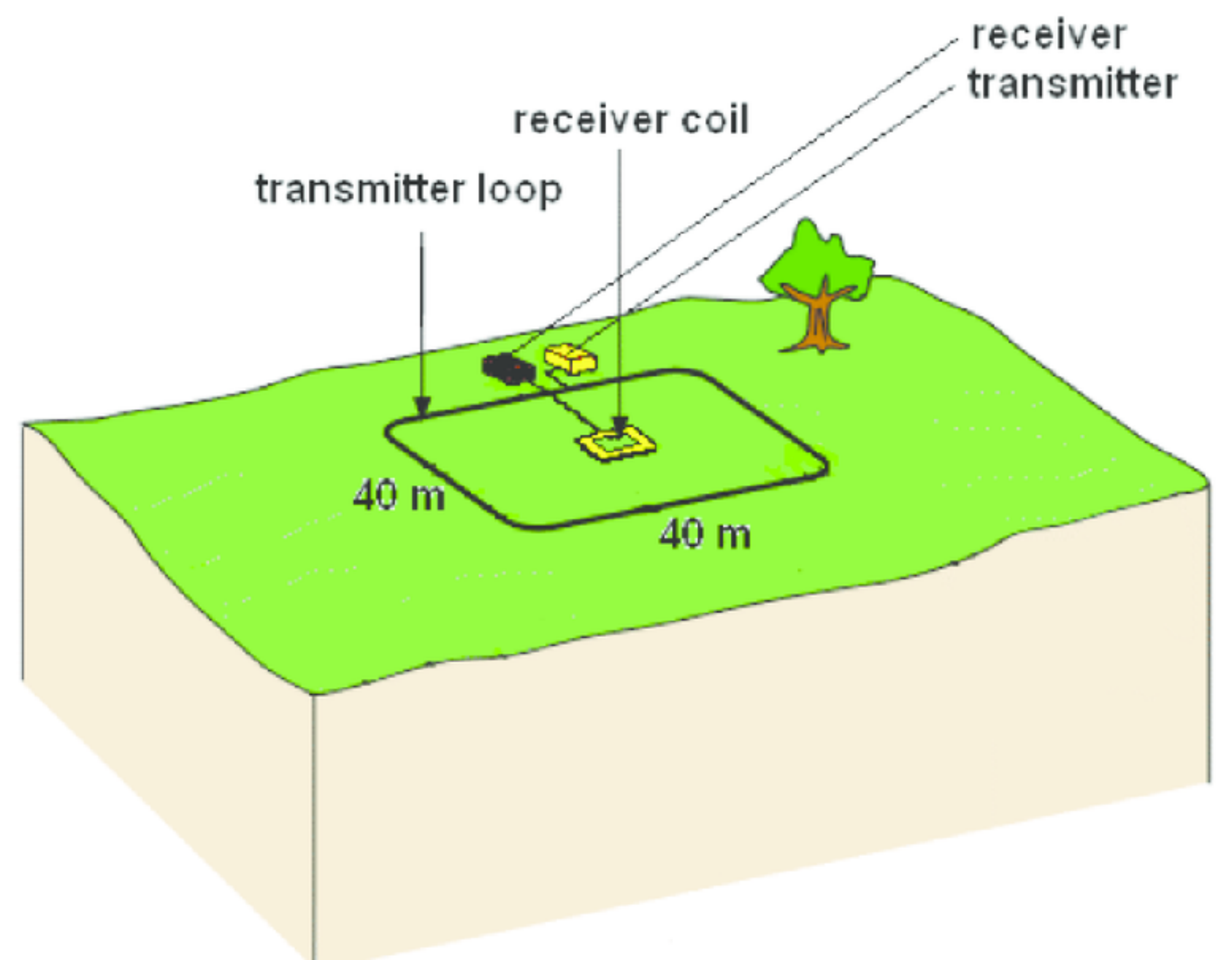
AIM: to retrieve ELECTRICAL properties of Deep targets

TIME DOMAIN
ELECTRO-MAGNETOMETER
TDEM



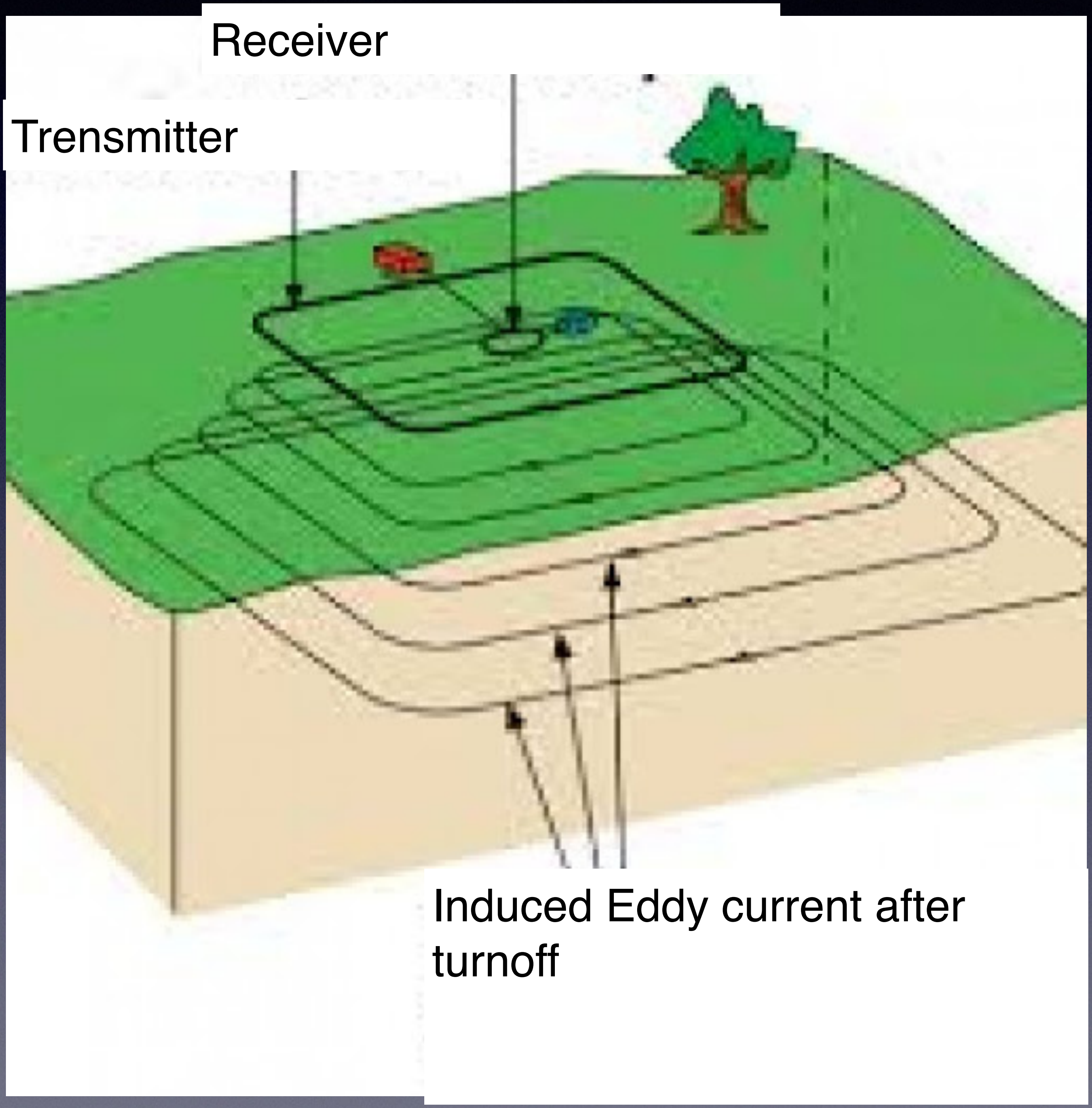
TIME DOMAIN ELECTRO-MAGNETOMETER

TDEM

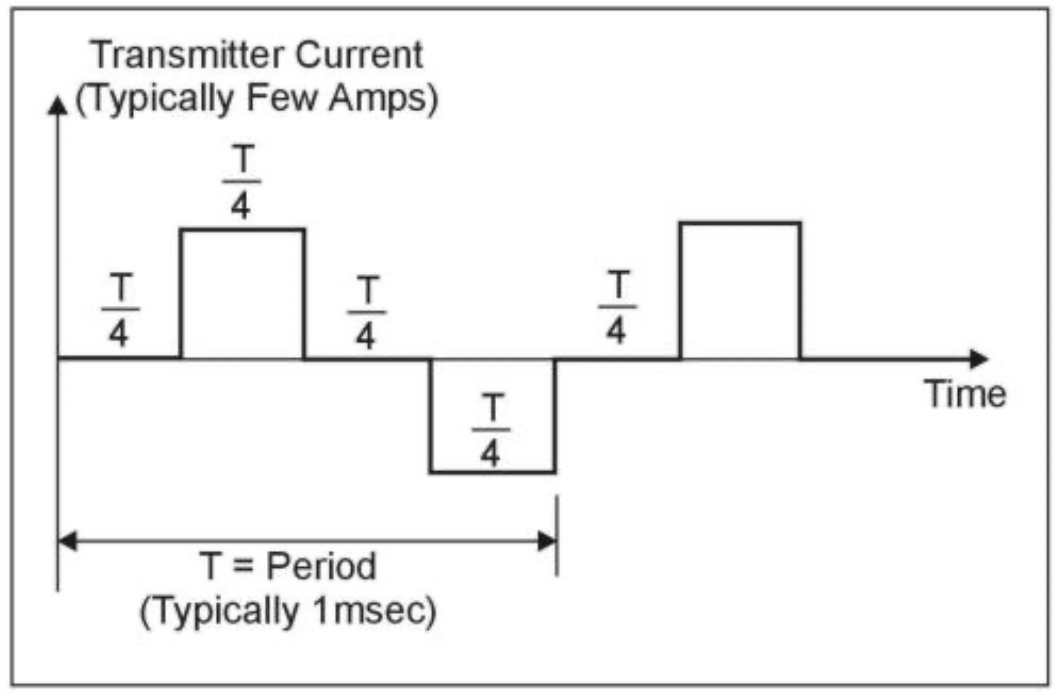


TIME DOMAIN ELECTRO-MAGNETOMETER

TDEM

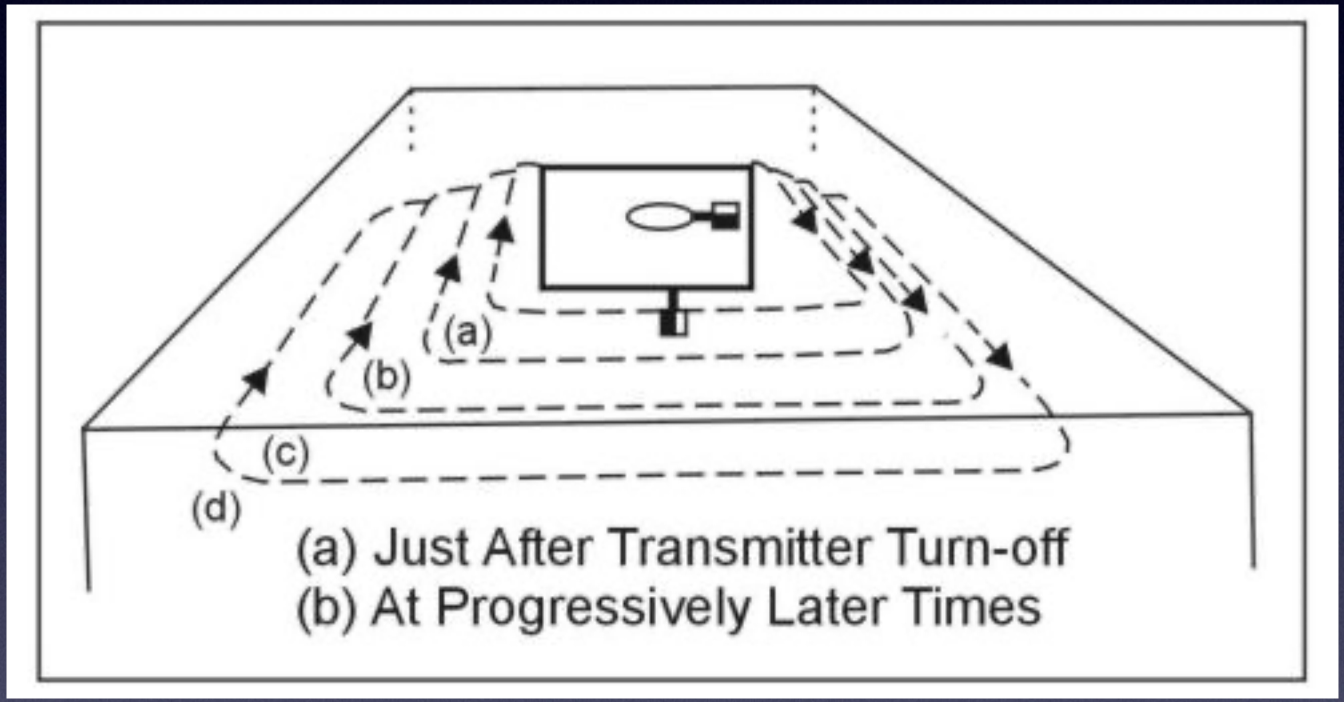


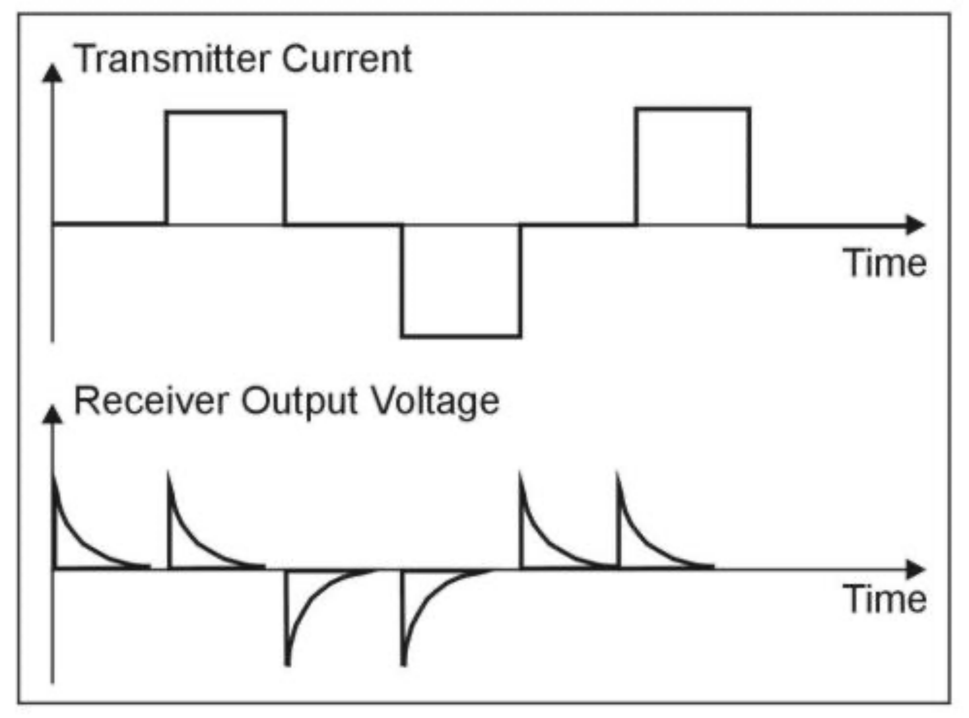
1. DC current flows in the transmitter
2. Current is turned off
3. Electro-Magnetic field propagates in the subsoil (Faraday's law)
4. EM fields generate Eddy current in the conductive body in the subsoil
5. Eddy current generates secondary EM field recorded at the Receiver (as a voltage)



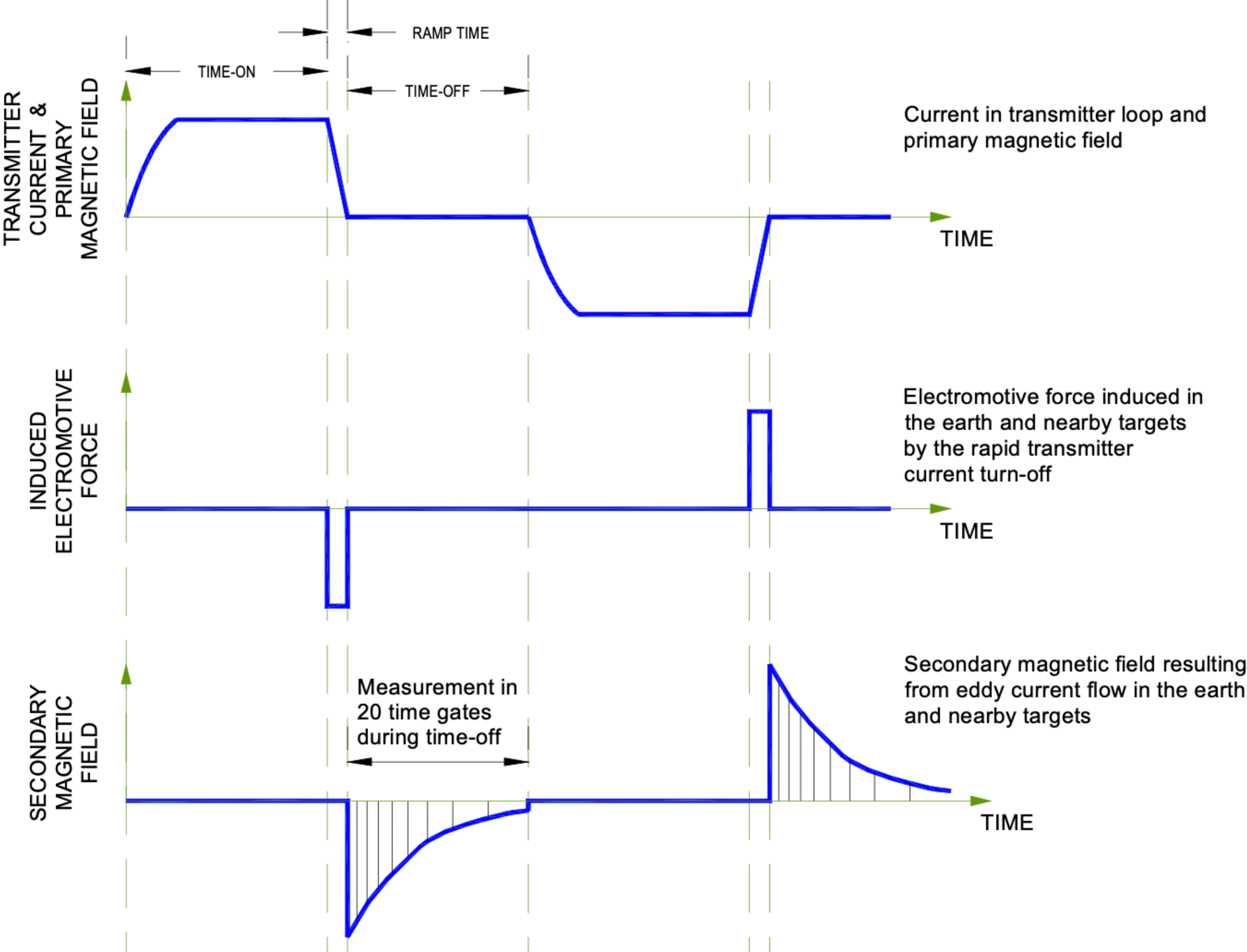
Current injected in the transmitter Loop

Induced Eddy current in The ground





Measure at the receiver the secondary EM field



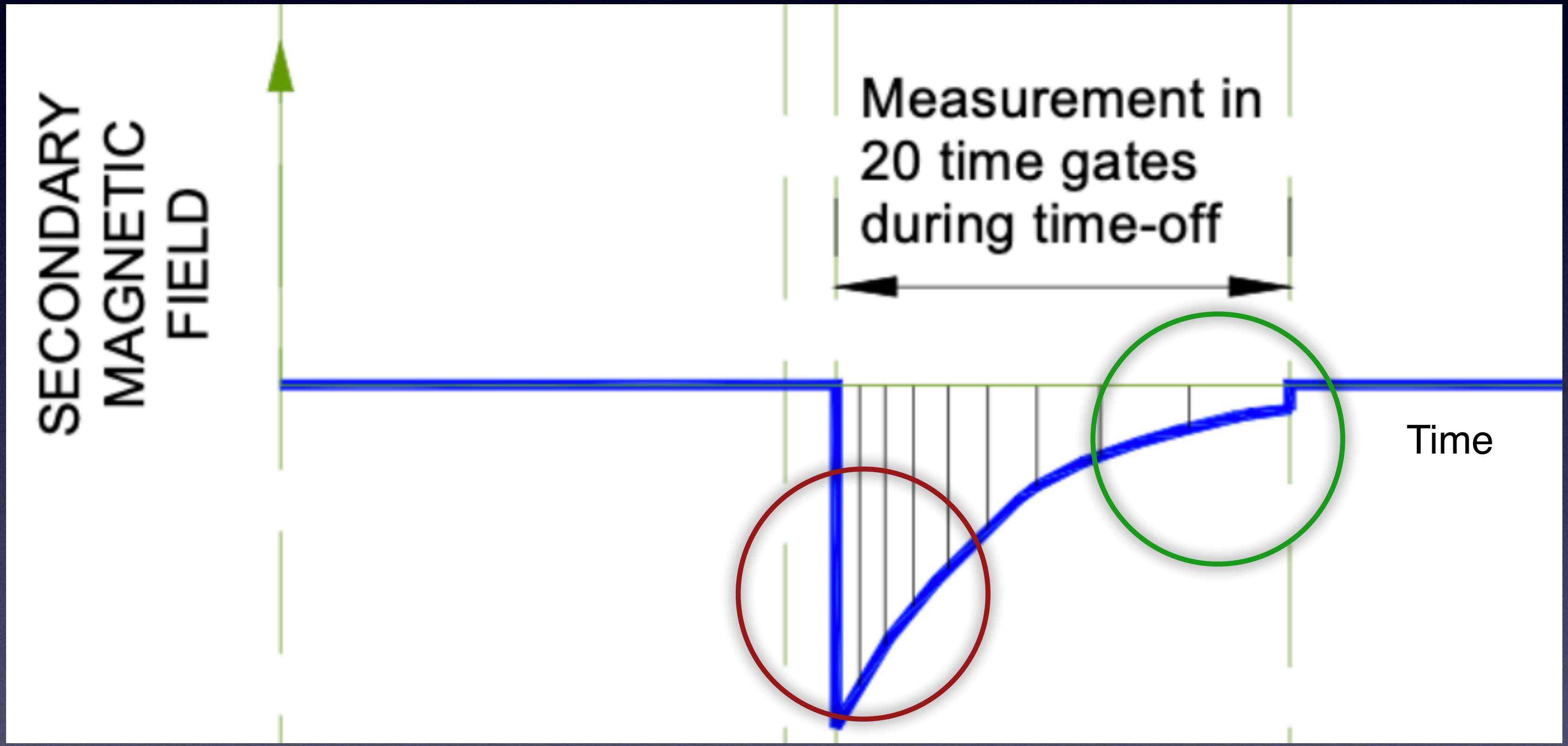
Current in transmitter loop and primary magnetic field

Electromotive force induced in the earth and nearby targets by the rapid transmitter current turn-off

Measurement in 20 time gates during time-off

Secondary magnetic field resulting from eddy current flow in the earth and nearby targets

TIME DOMAIN
ELECTRO-MAGNETOMETER
TDEM



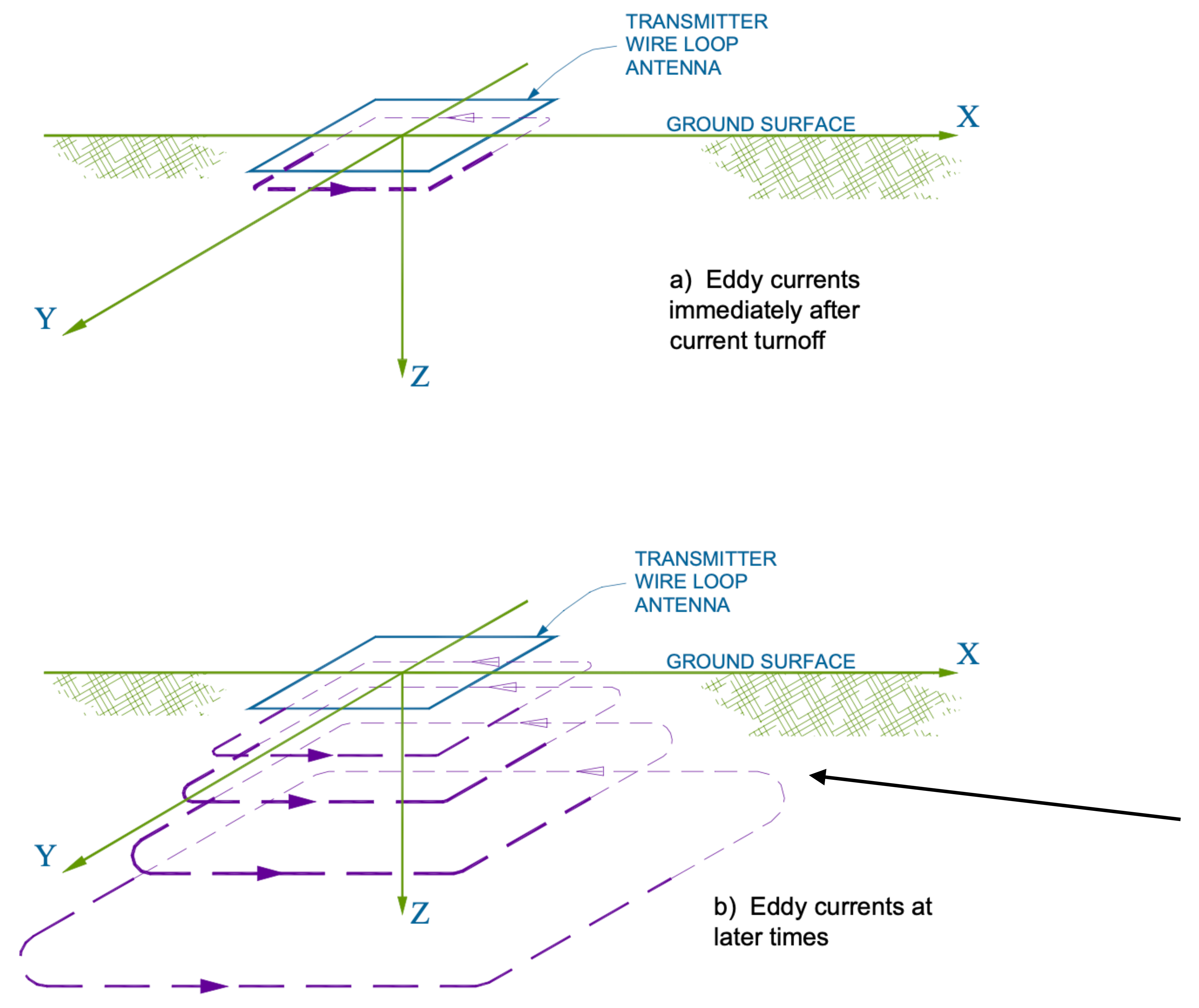
We measure the secondary EM effect (output voltage) at several times, (‘time gate’ usually every 10 ms).

Early time = shallow depth

Longer time= deeper depth

TIME DOMAIN ELECTRO-MAGNETOMETER TDEM

Different timing (period), different depths of penetration



Measurements are taken at several times.
Just after the turn off of the current in the transmitter loop and after some times (usually 10 ms)

Longer time, deeper depth

Output voltage

$$e(t) = \frac{k_1 M \sigma_A^{3/2}}{t^{5/2}},$$

From the receiver

Output voltage

where

$e(t)$= output voltage from a single-turn receiver coil of area 1 m2

k_1 = a constant

M = product of Tx current x area (*a*-m2)

σ = terrain conductivity (siemens/m = S/m = 1/Ωm)

t = time (s)

we can retrieve the

Apparent Resistivity

of the soil

Apparent Resistivity

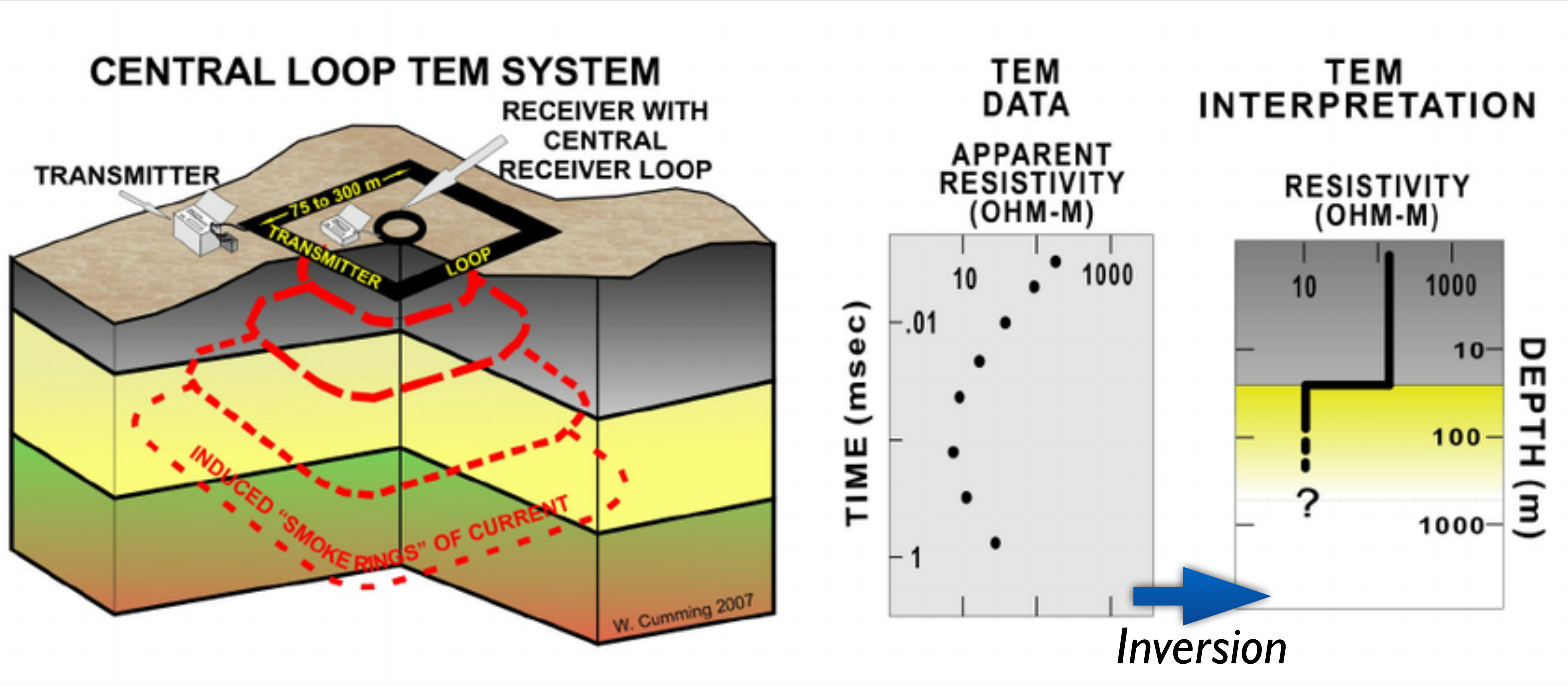
$$\rho_a(t) = \frac{k_2 M^{2/3}}{e(t)^{2/3}\, t^{5/3}}.$$

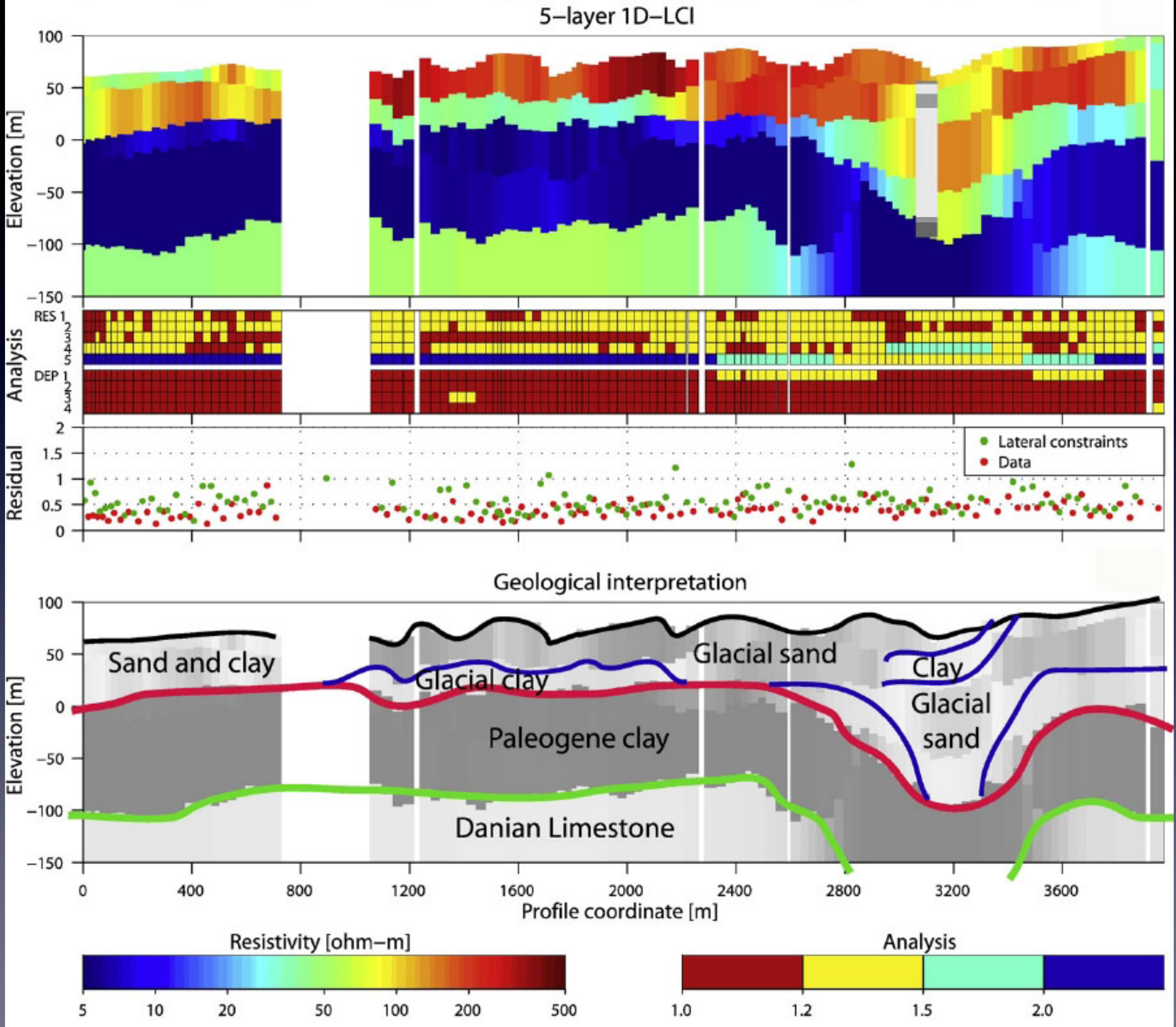
For different time of measurements (different depths) we can retrieve different apparent resistivity

TIME DOMAIN ELECTRO-MAGNETOMETER

TDEM

From the apparent resistivity with an INVERSION we can retrieve 1D model of real resistivity





Using
Several
1D models

We get
Pseudo
2D section

Geophysics for Natural Risks and Resources

Introduction to GEOPHYSICAL PROSPECTING for ENGINEERING

Kees Weemstra

Jacopo Boaga

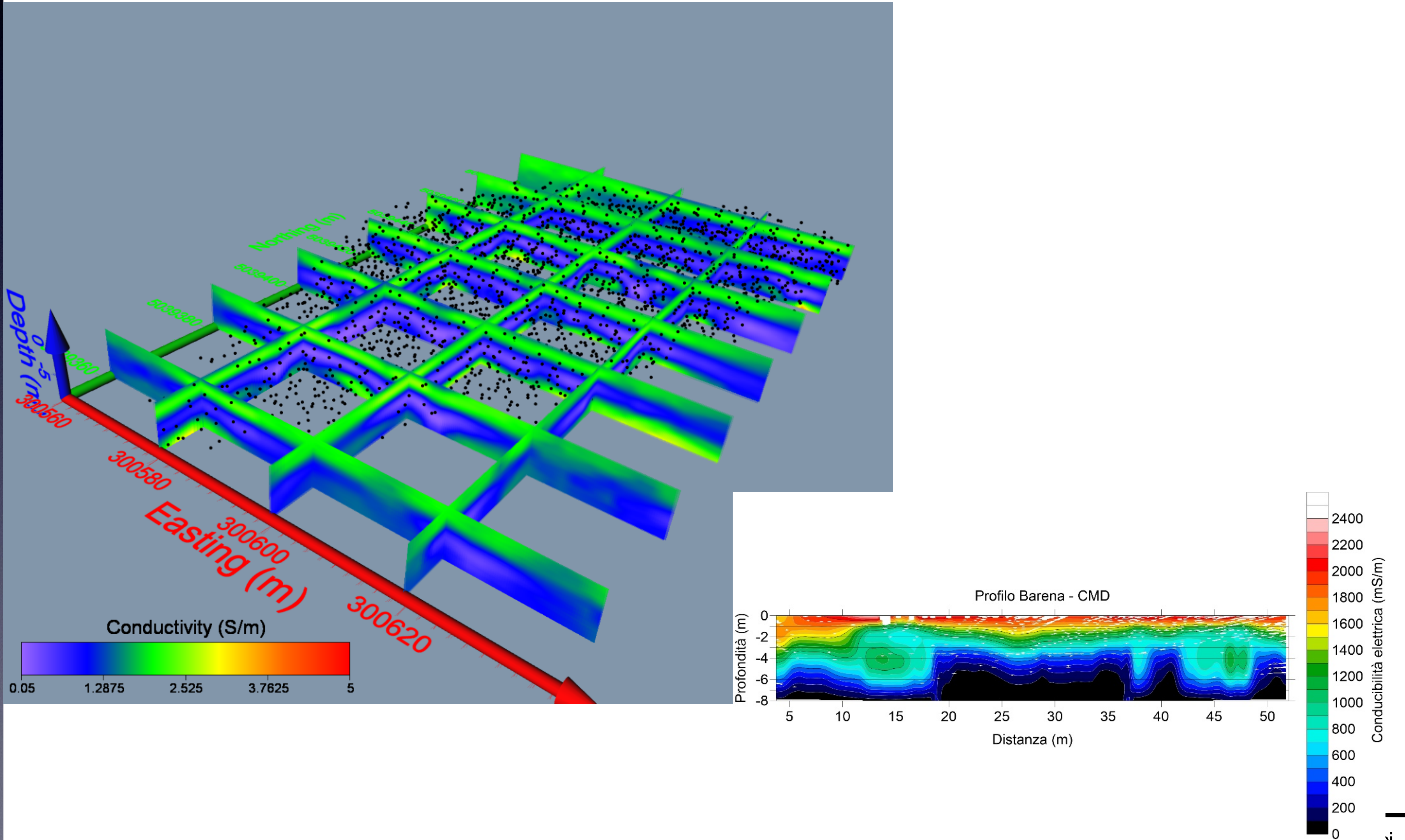
Dipartimento di Geoscienze
- Università di Padova -
jacopo.boaga@unipd.it

EM METHODS
FDEM

Environmental and Engineering Applications

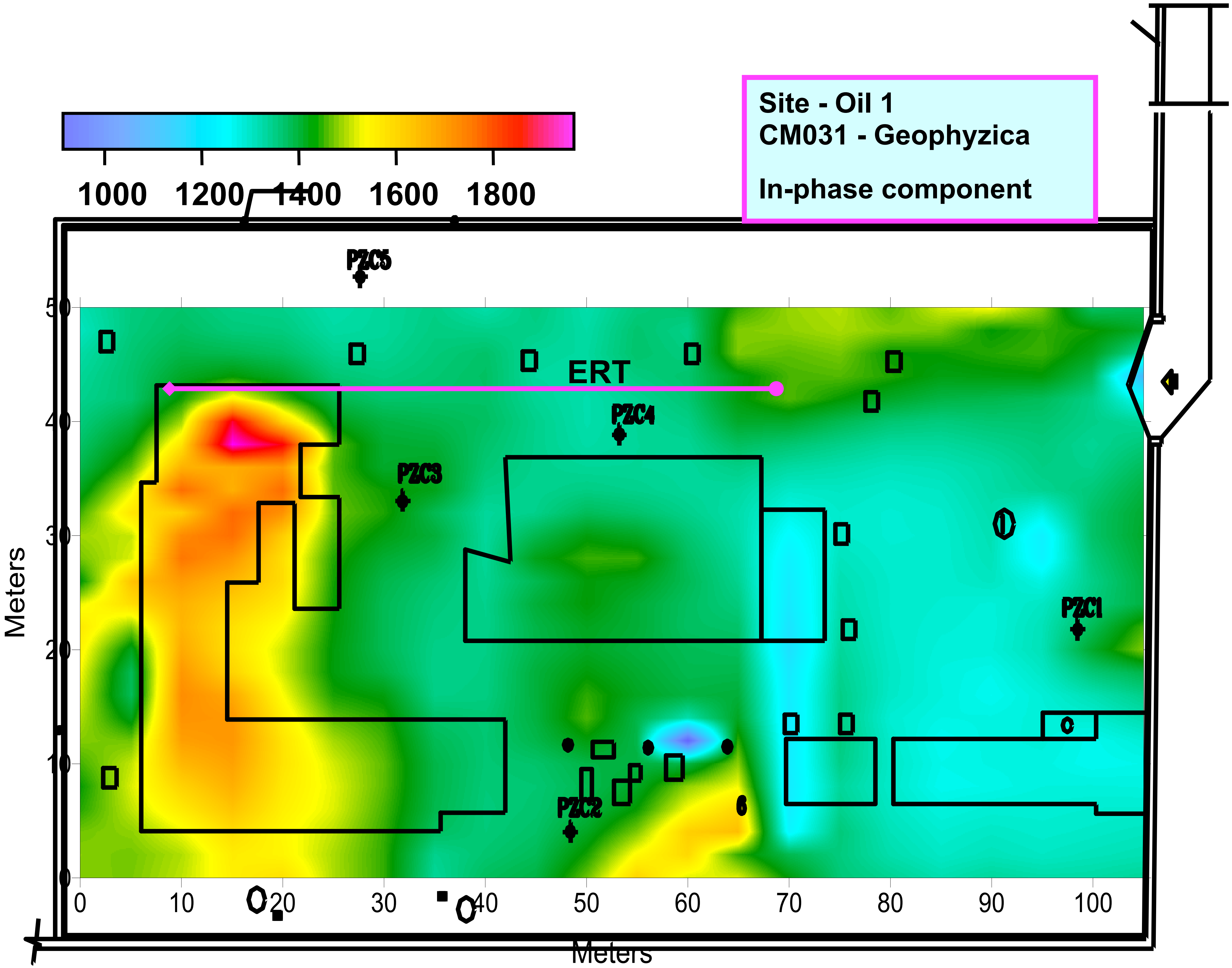
FDEM

FDEM INVERSION IN DEPTH



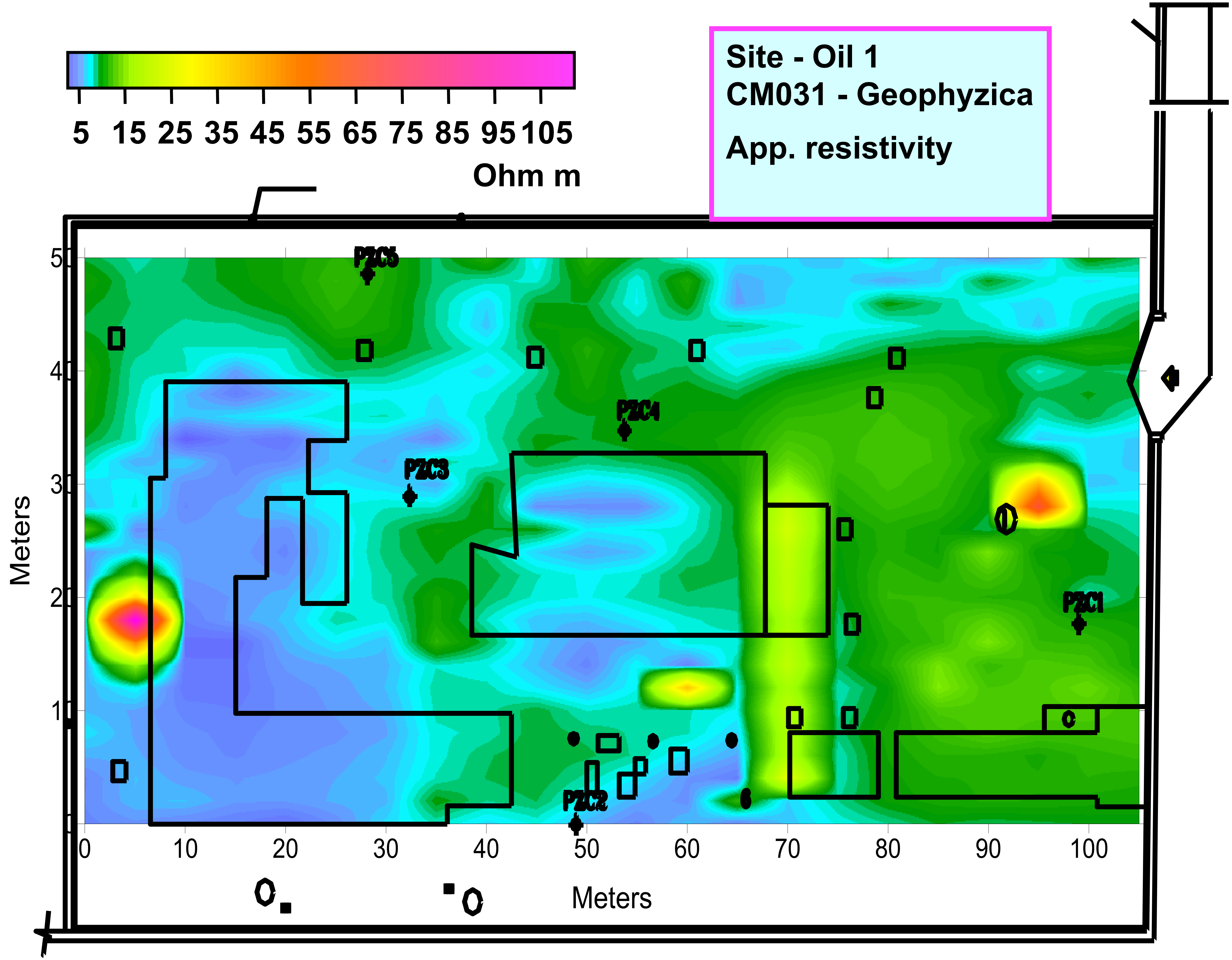
Site - Oil 1
CM031 - Geophyzica

In-phase component

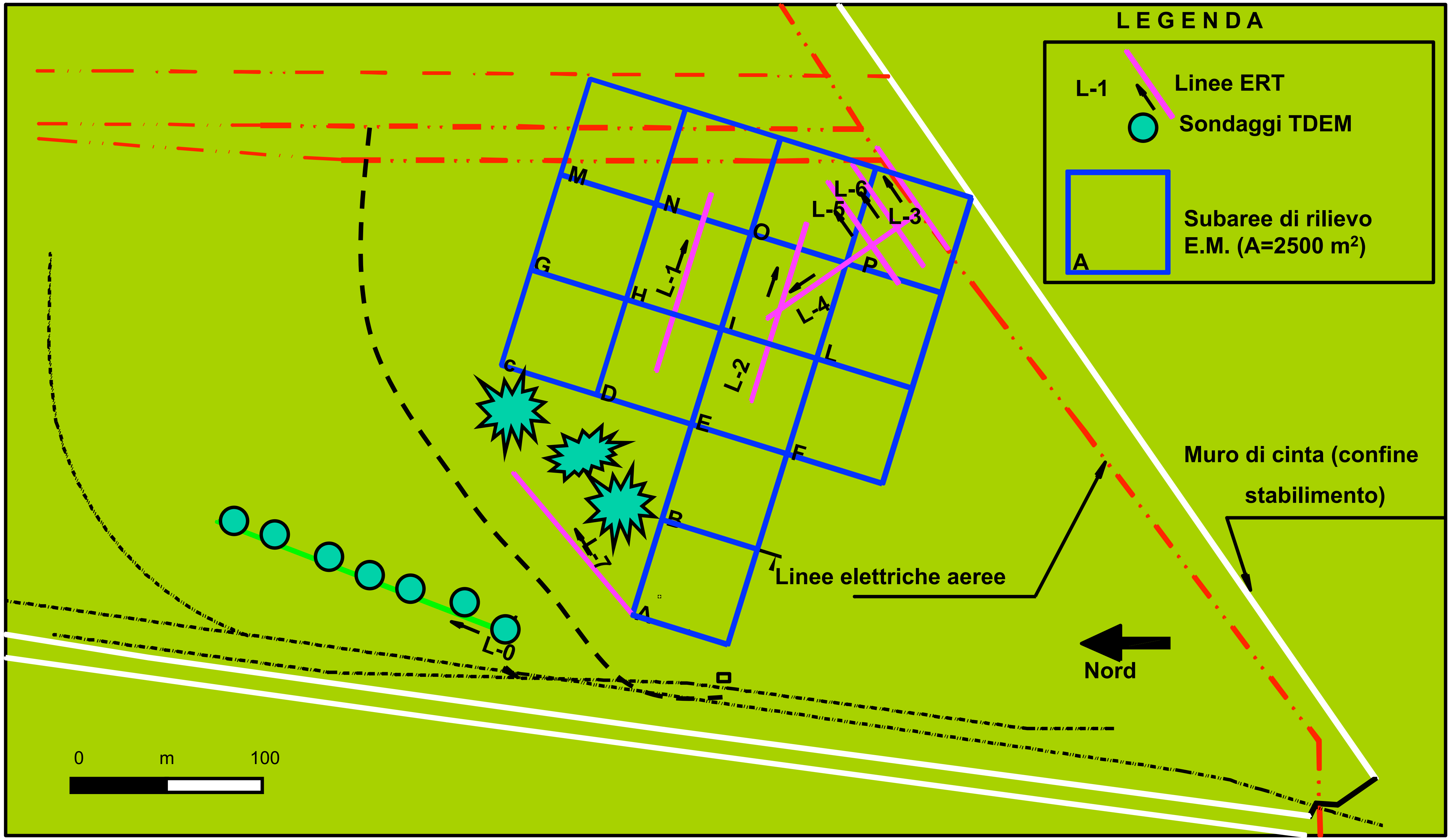


Site - Oil 1
CM031 - Geophyzica

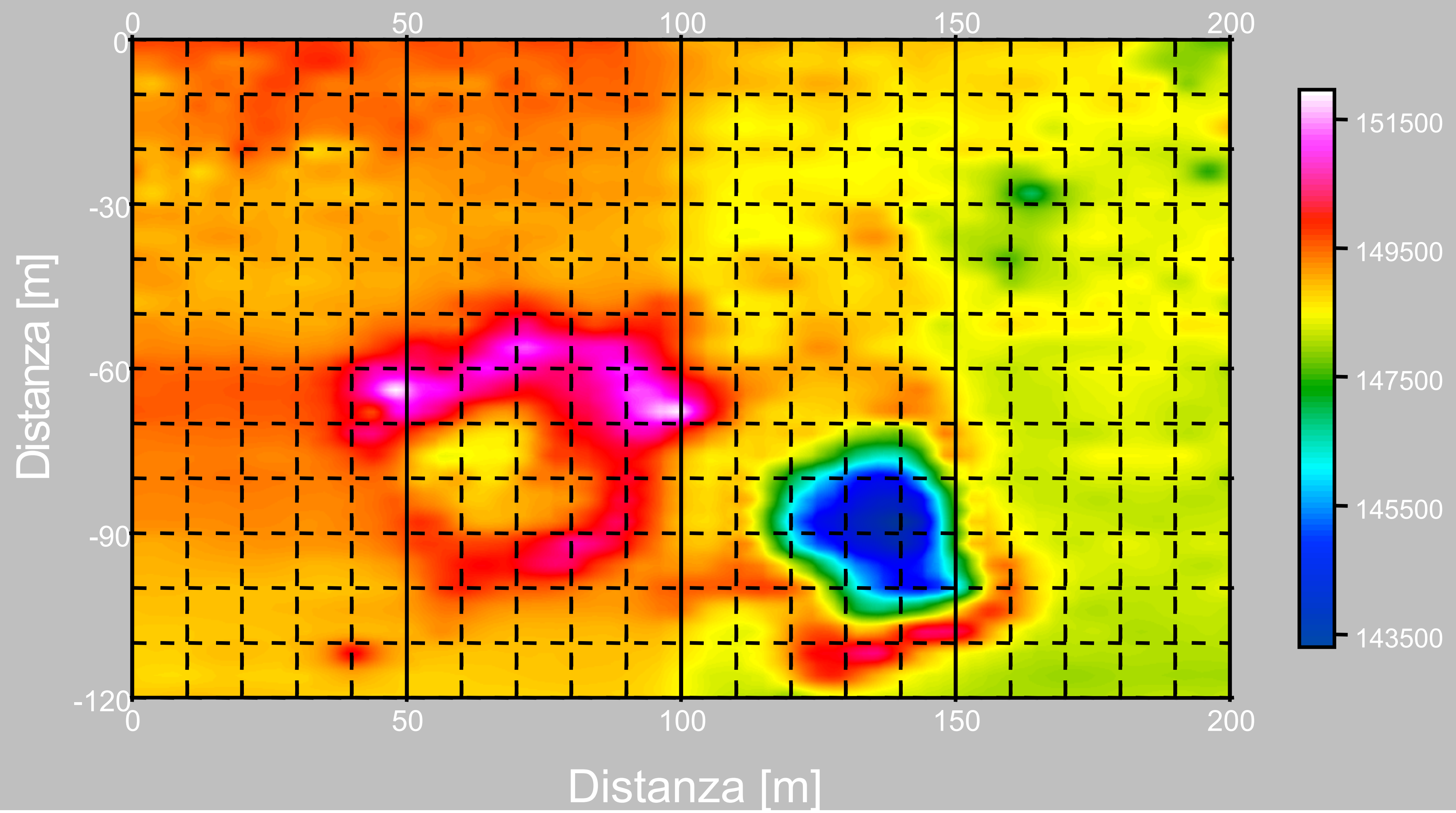
App. resistivity



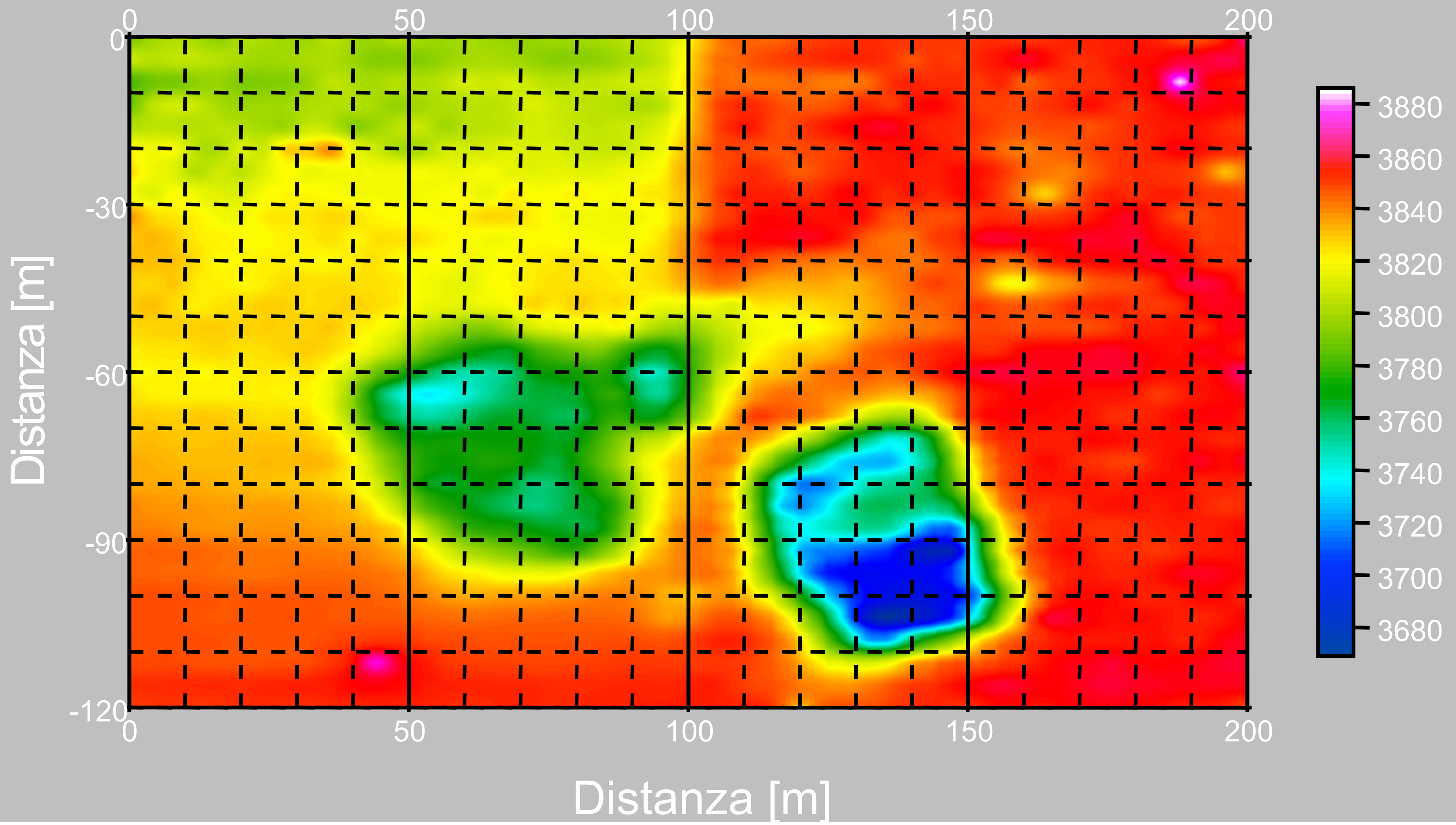
EXAMPLE OF DOUBLE USE OF FDEM AND ERT



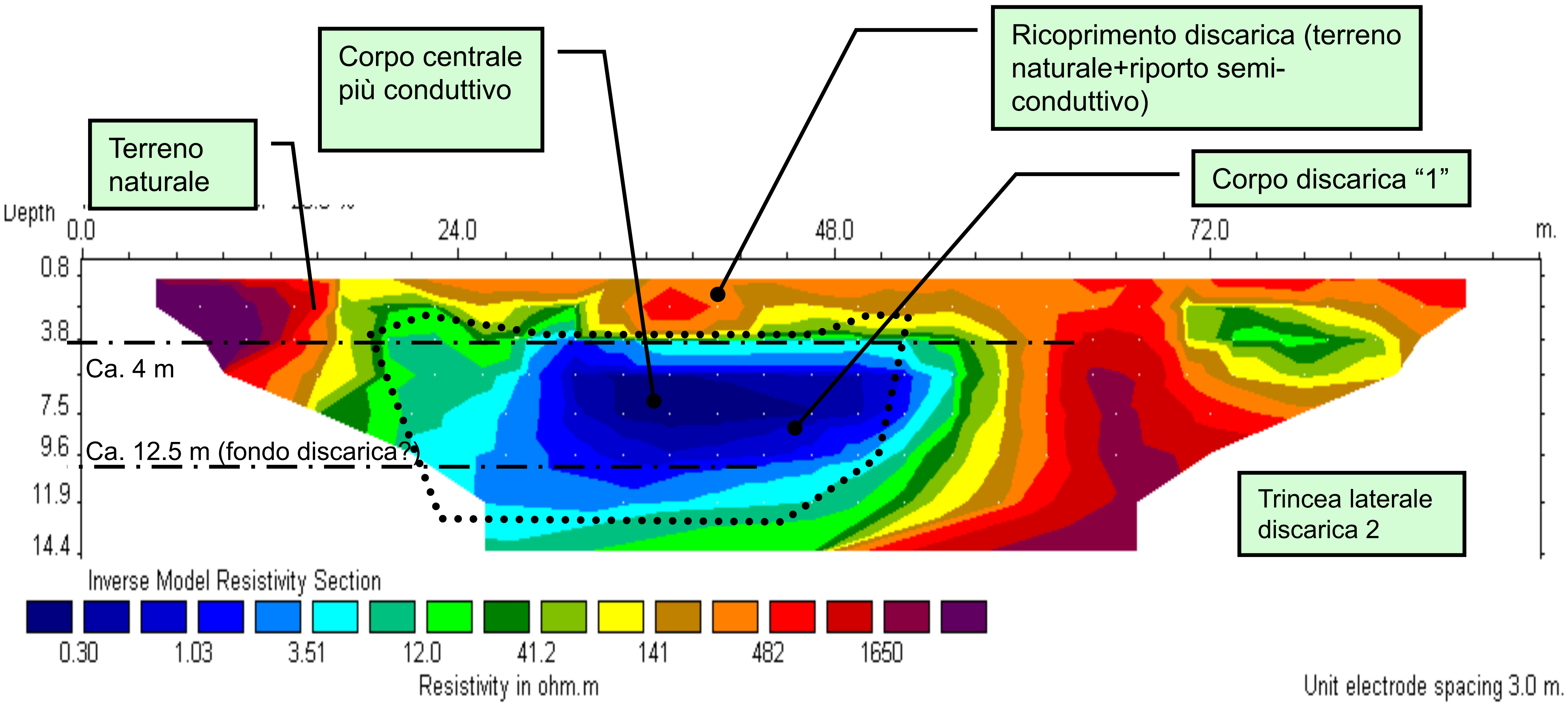
FDEM In Phase signal MAP



FDEM quadrature signal MAP



ERT along line 2



Terreno naturale

Corpo centrale più conduttivo

Ricoprimento discarica (terreno naturale+riporto semi-conduttivo)

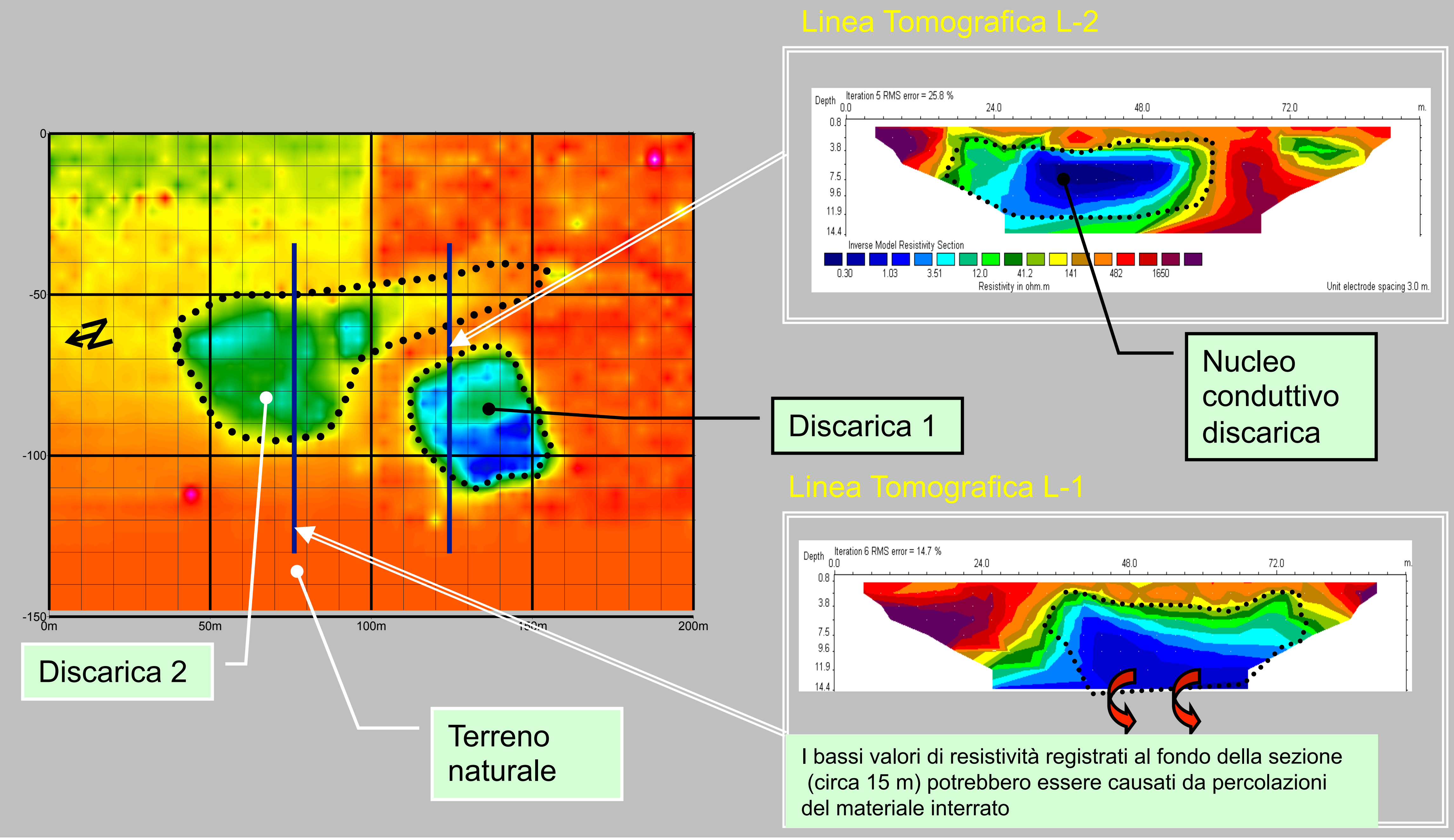
Corpo discarica “1”

Ca. 4 m

Ca. 12.5 m (fondo discarica?)

Trincea laterale discarica 2

Comparison of FDEM map and ERT line



Linea Tomografica L-2

Nucleo conduttivo discarica

Discarica 1

Linea Tomografica L-1

Discarica 2

Terreno naturale

I bassi valori di resistività registrati al fondo della sezione (circa 15 m) potrebbero essere causati da percolazioni del materiale interrato

FDEM for Agriculture

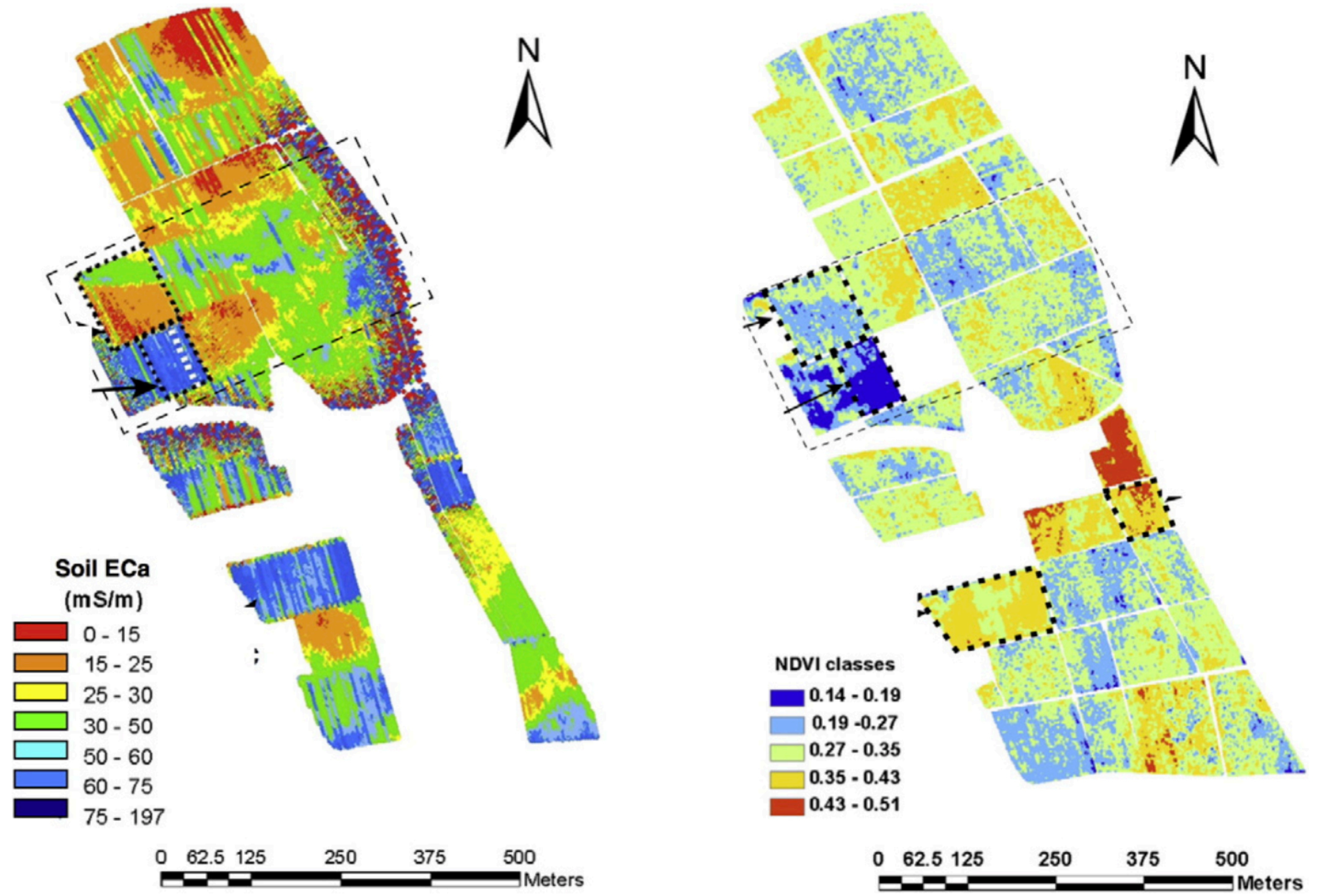
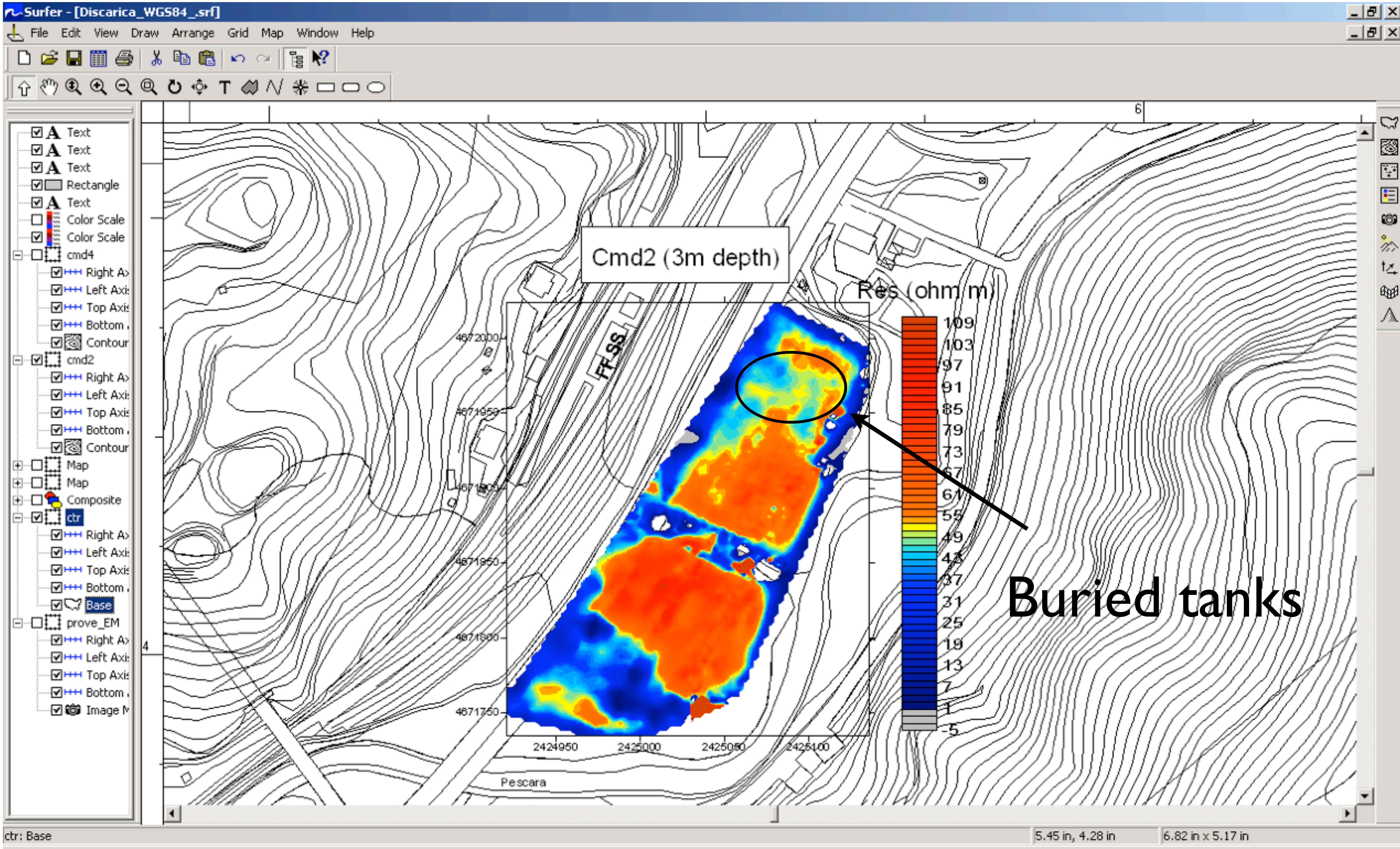


Fig. 5. FDEM apparent conductivity map (left) and NDVI vegetation index derived classes (right) in a France vineyard (from André et al., 2012, mod.).

FDEM conductivity and NDVI index

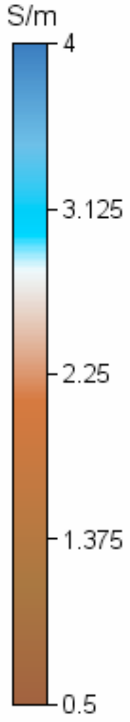
FDEM Buried Landfill



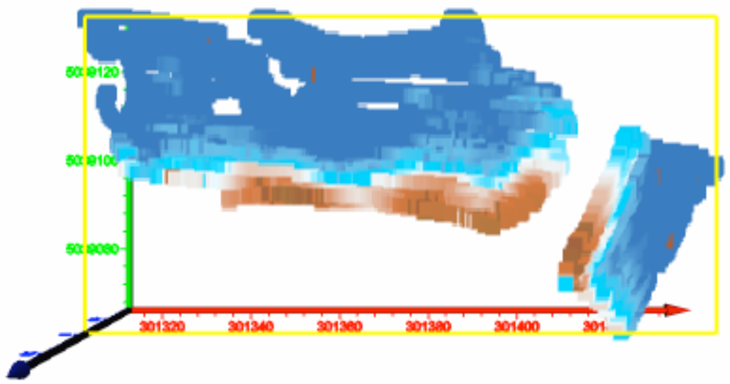
Buried tanks

Resistivity FDEM map

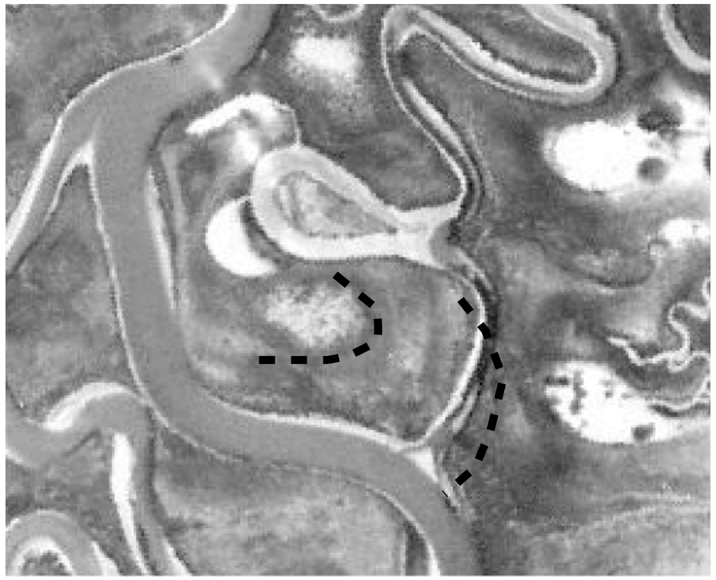
Em per riconoscere litologie



slide @ 0 m

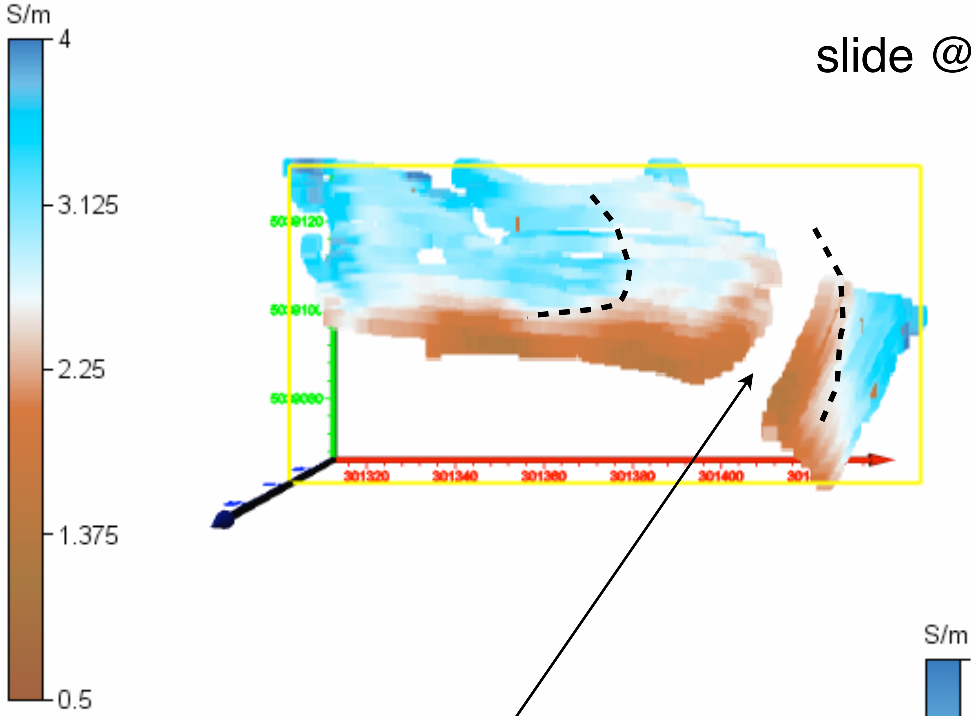


1950

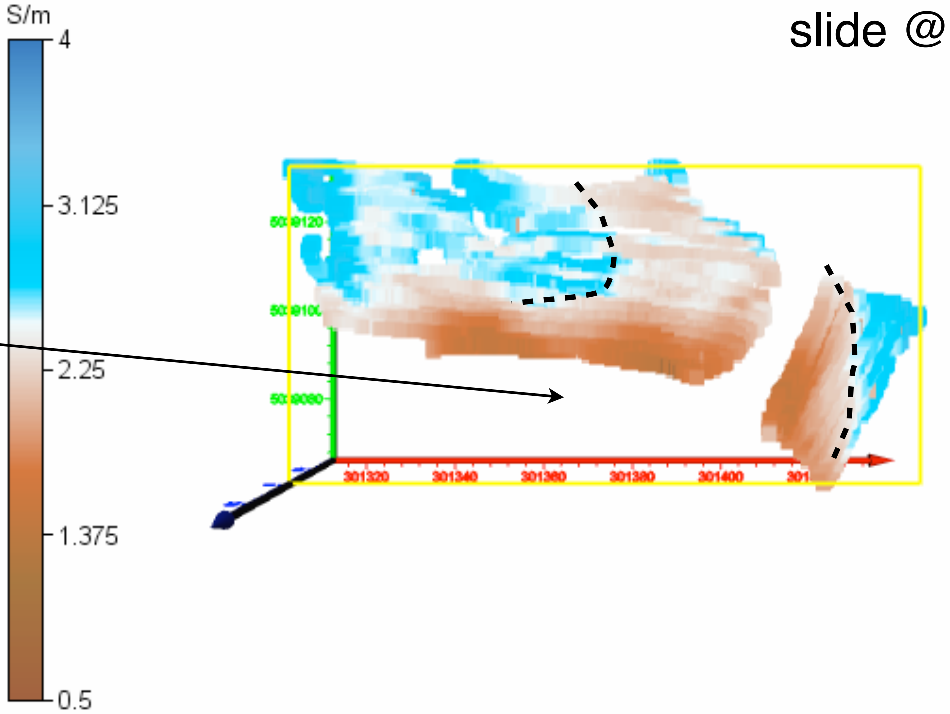


2014

slide @ -0.36 m



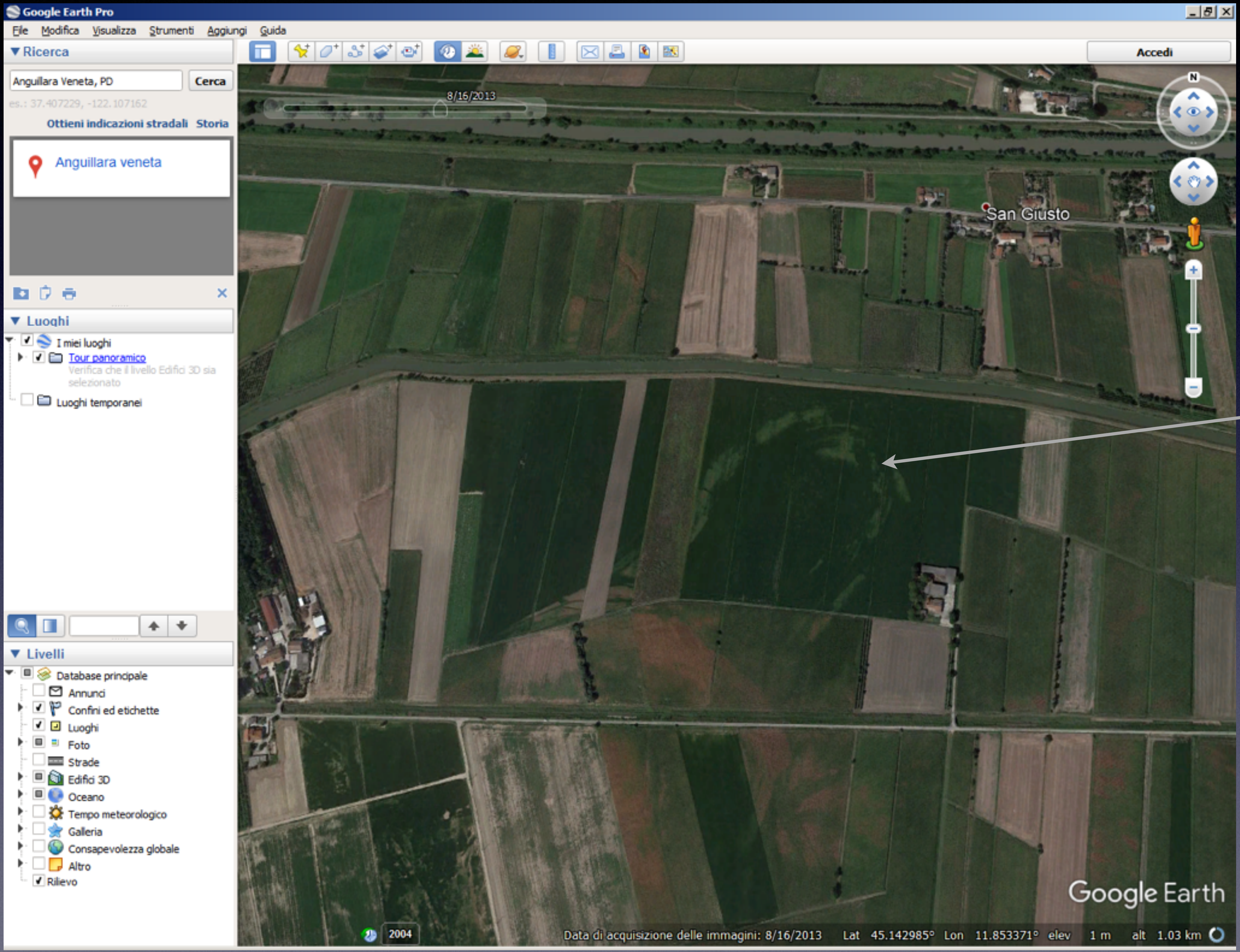
slide @ -0.55 m



Paleo Meandro
più sabbioso ?

Sedimentological project

FDEM for paleo channel



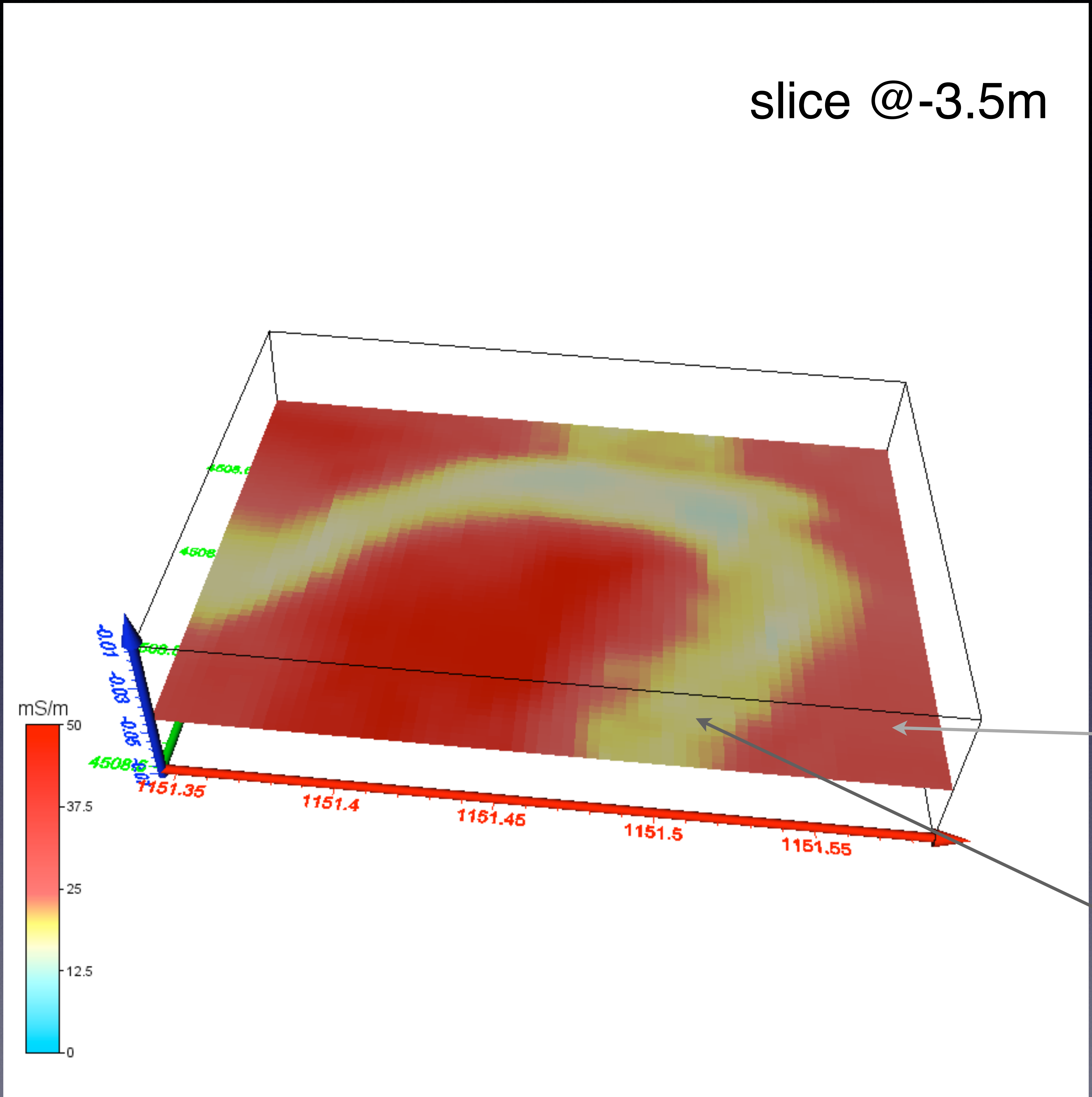
Anguillara Veneta, PD

es.: 37.407229, -122.107162

Data di acquisizione delle immagini: 8/16/2013 Lat 45.142985° Lon 11.853371° elev 1 m alt 1.03 km

Paleo Channel

Metodi Elettro-magnetici

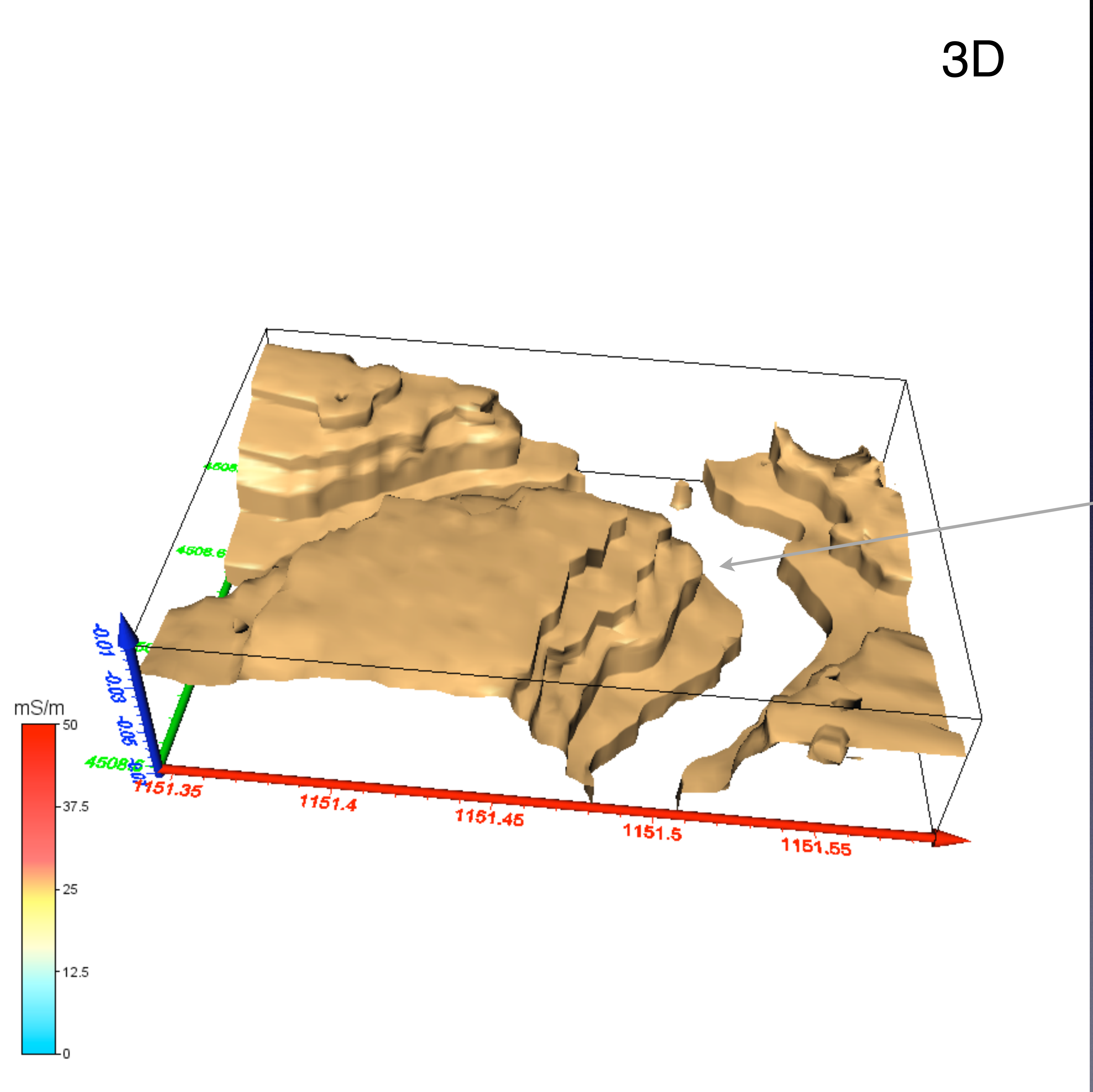


Paleo Channel

Fine sediments (red, conductive)

Coarse sediments (Yellow, resistive)

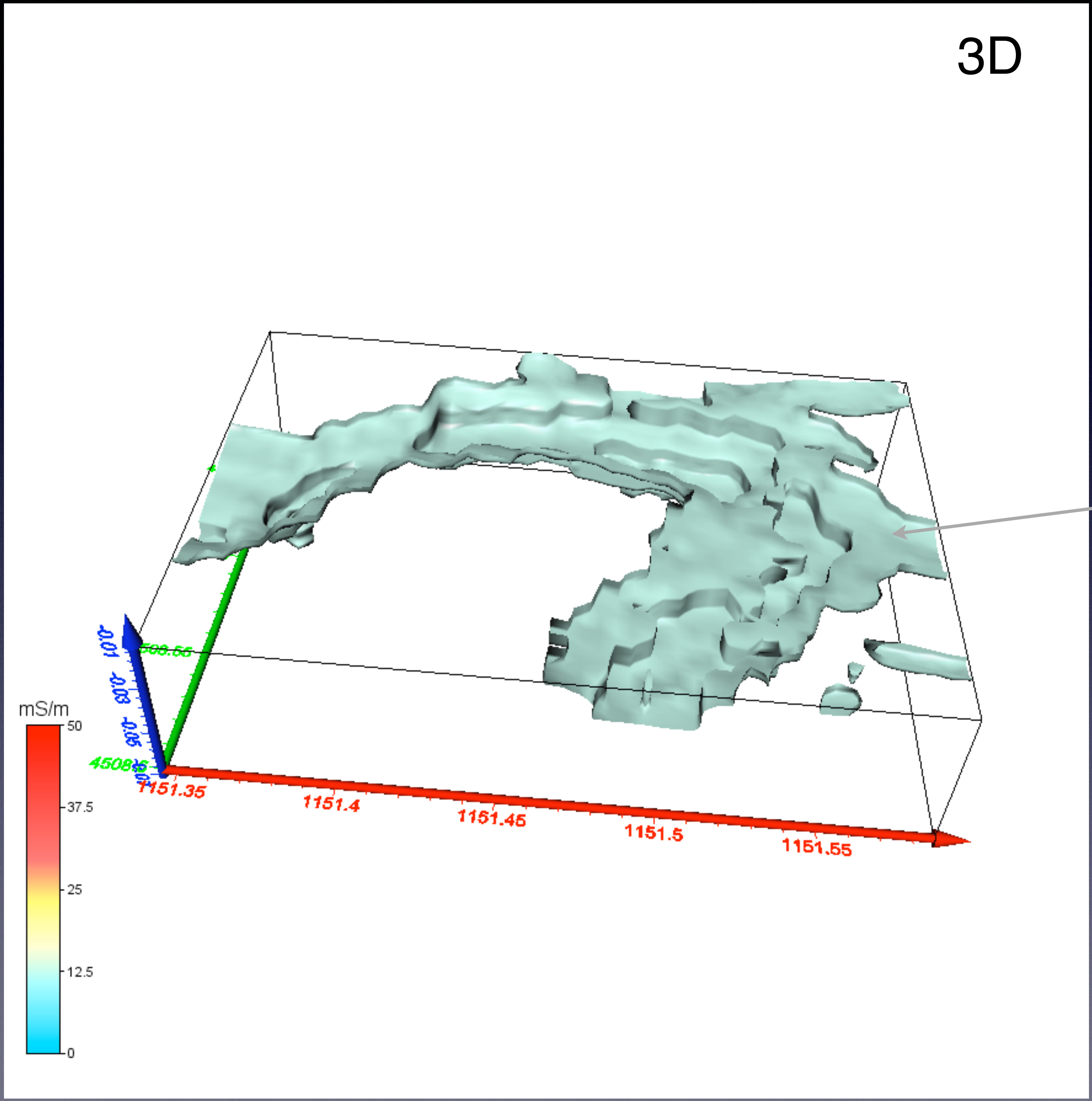
Metodi Elettro-magnetici



Paleo Channel

Fine material Isosurface

Metodi Elettro-magnetici



Paleo Channel

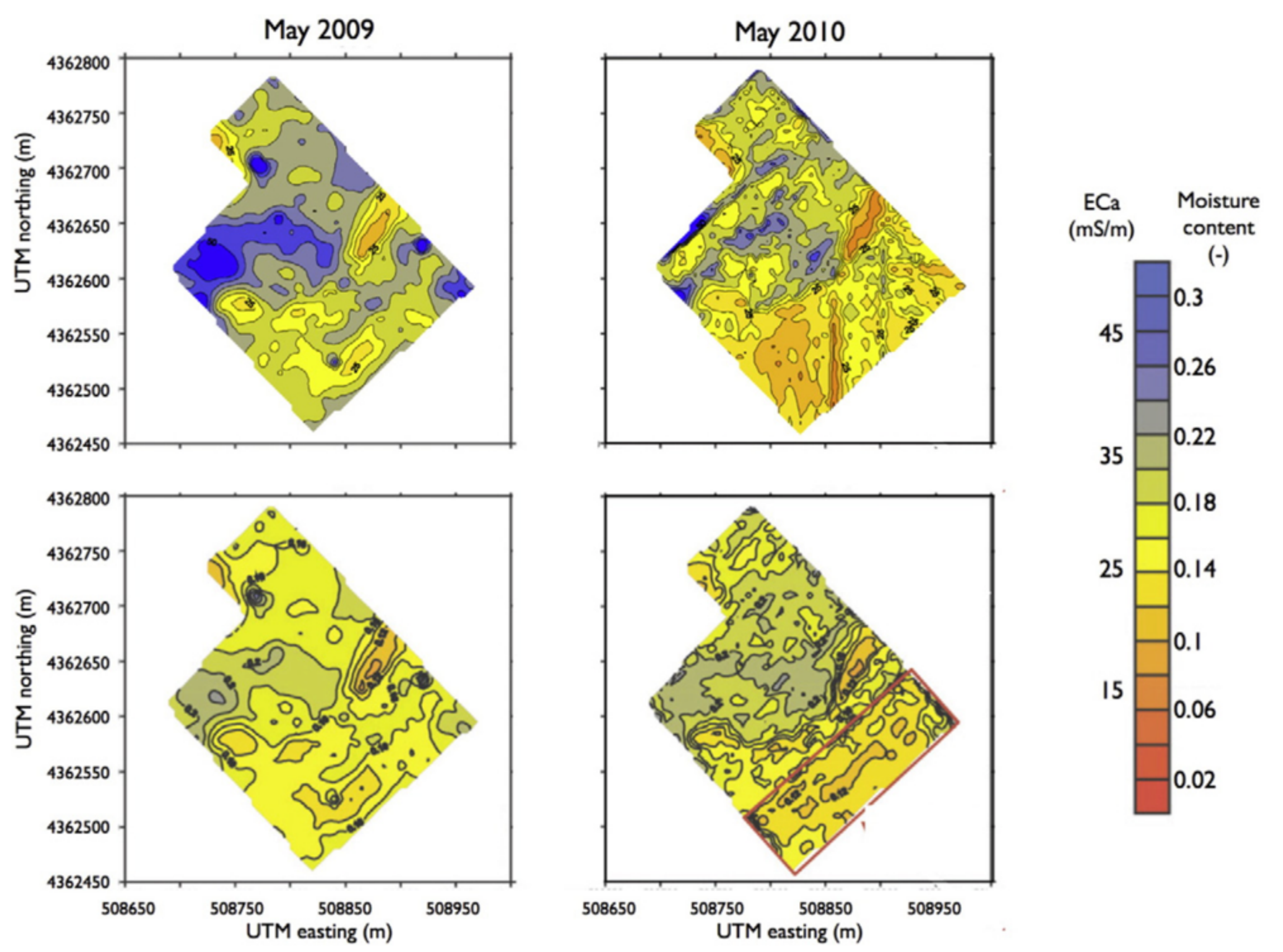
Coarse material Isosurface

FDEM in time-lapse

FDEM for Agricultural use of soil

Archie's law

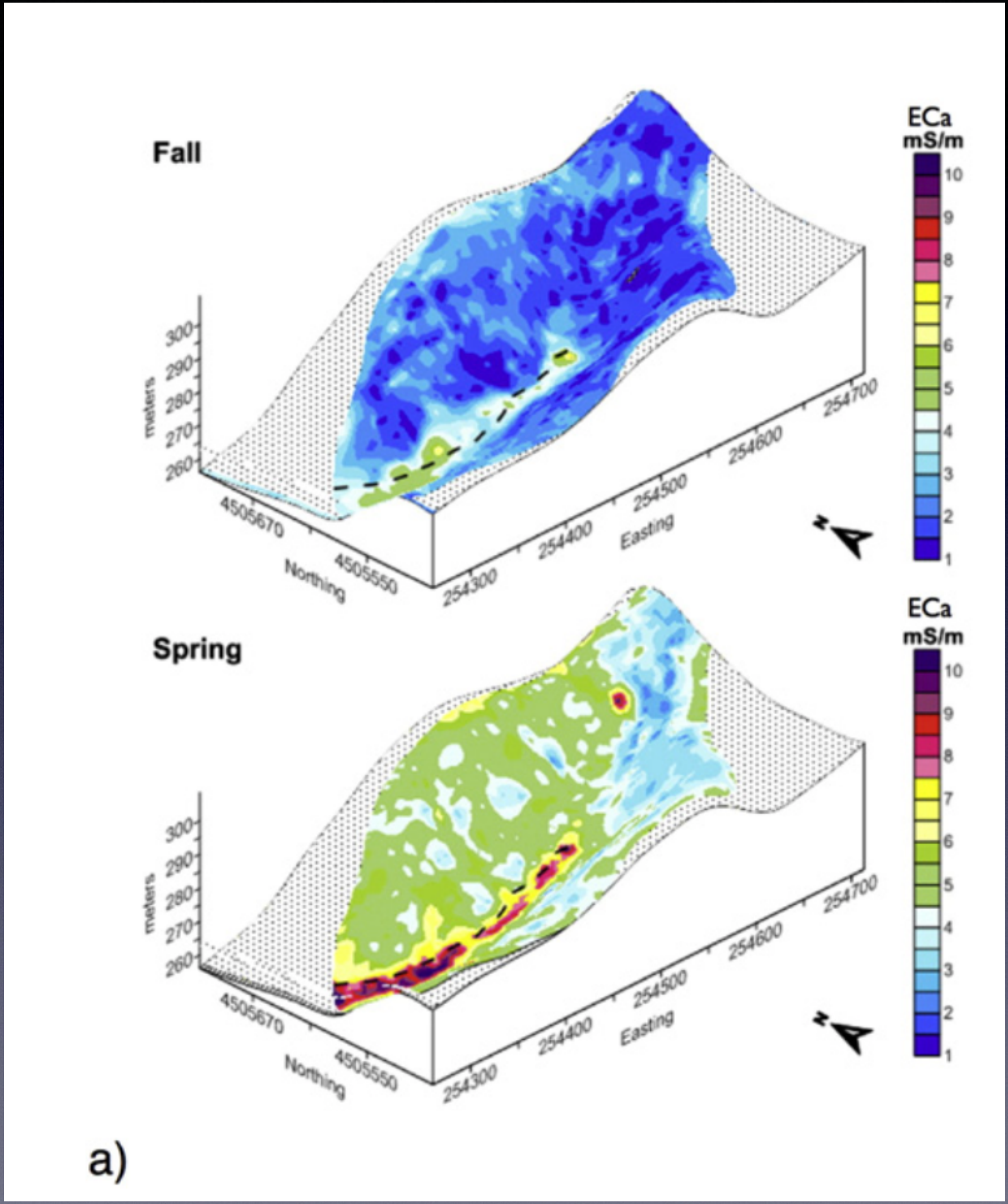
$$\sigma = a \; \sigma_w \, S_w^{\,n} \, \phi^{m}$$



Moisture content map

geologia = cost saturazione S = *variabile*

Metodi Elettro-magnetici

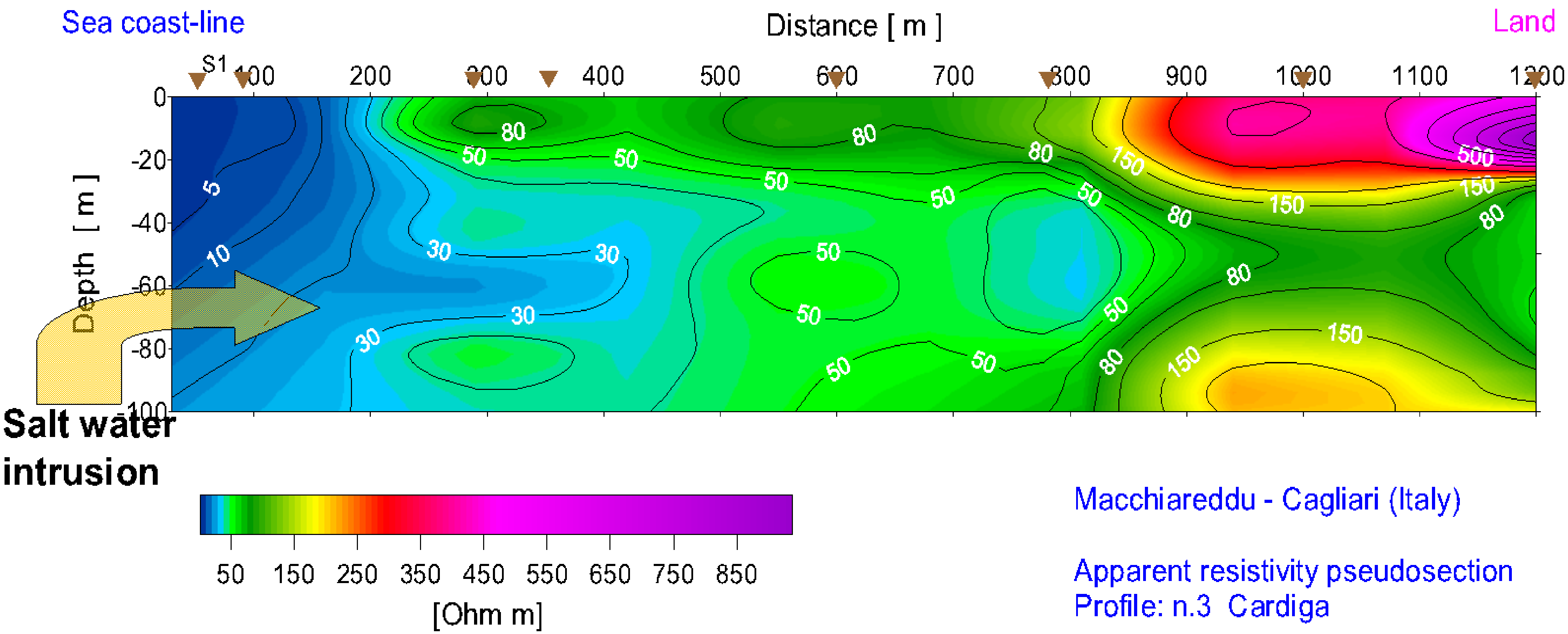


FDEM for hillslope hydrology

seasonal changes of conductivity (water content)

Time domain electro-magnetometer

Time domain for saline intrusion studies



Salt water intrusion

Macchiareddu - Cagliari (Italy)

Apparent resistivity pseudosection
Profile: n.3 Cardiga

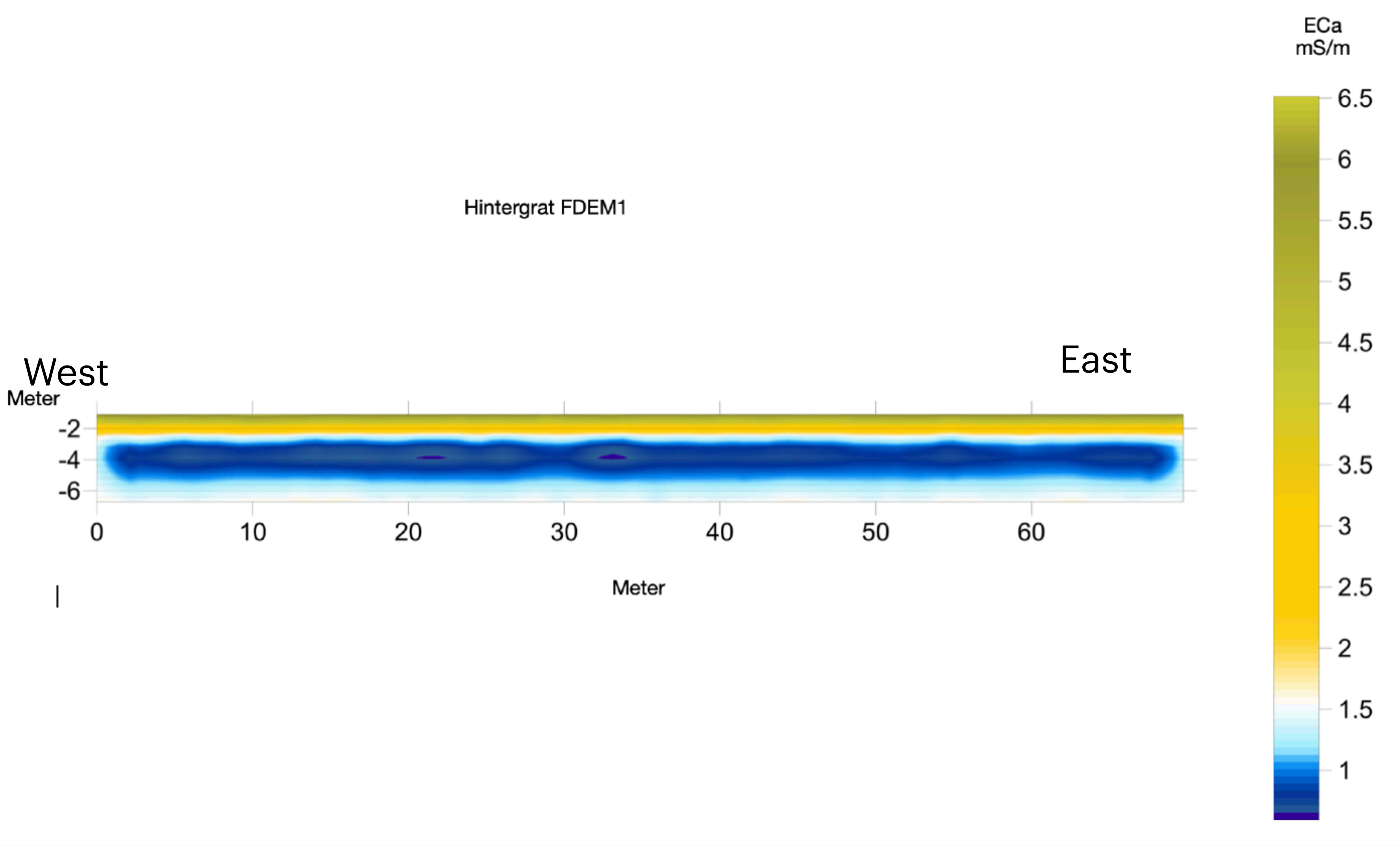
Permafrost Geophysical Measurements 2020

2) Hintergrat Rock Glacier - Solda (Ortles)

EM1

Active layer ≈ 3-4 m

In agreement with ert

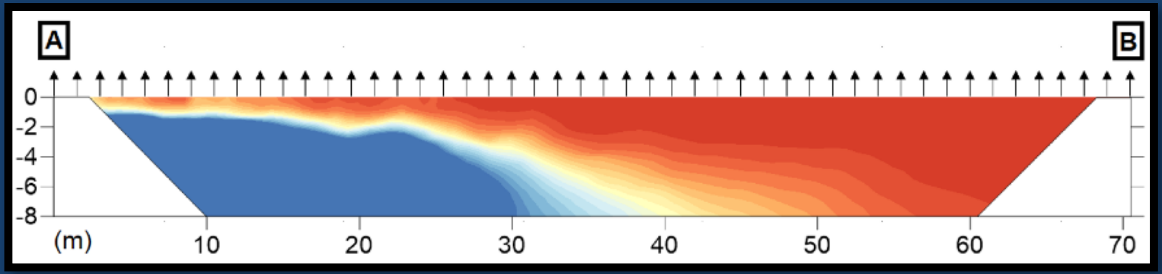


DIPARTIMENTO DI GEOSCIENZE

UNIVERSITÀ DEGLI STUDI DI PADOVA

CASE STUDY: MURFREIT ROCK GLACIER

ERT SURFEY



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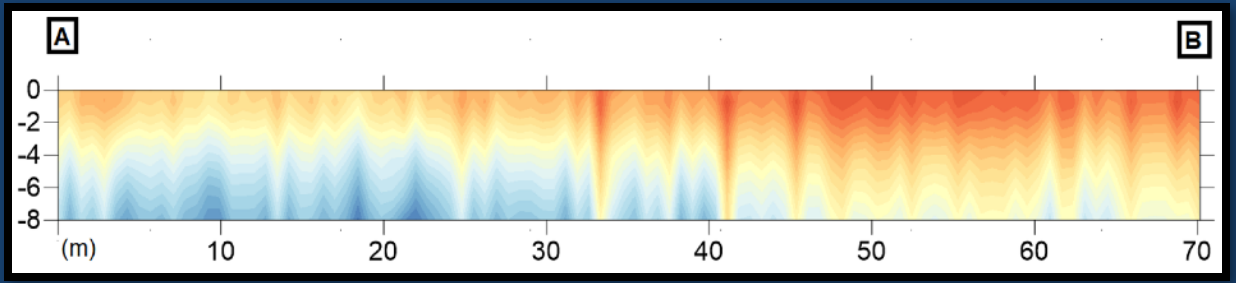
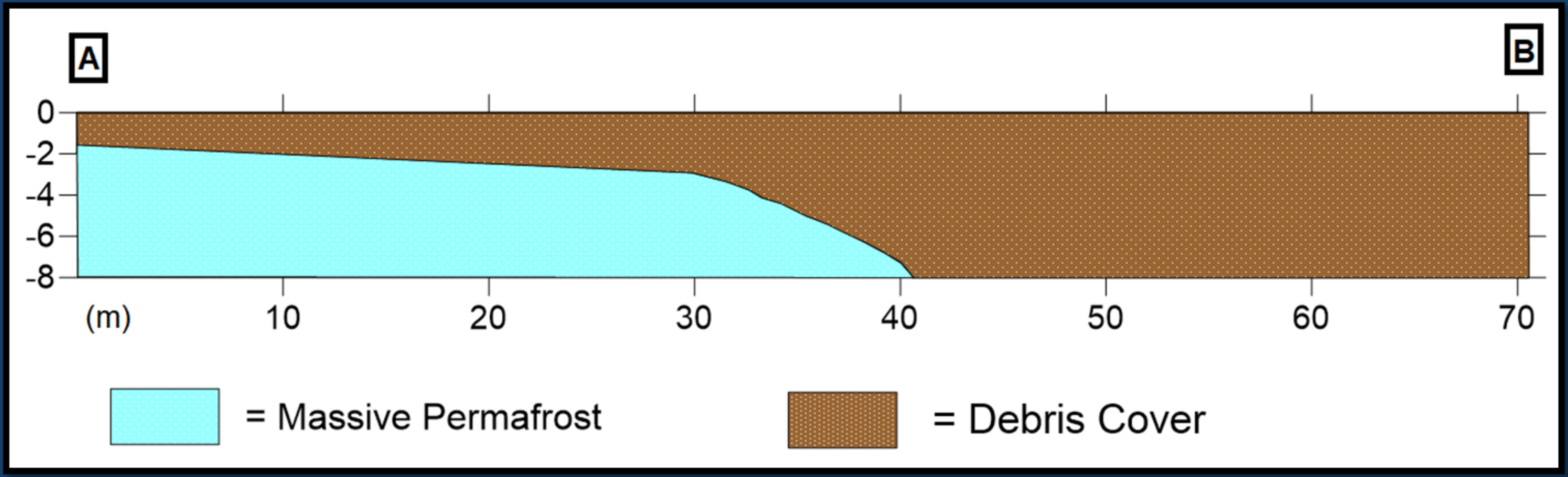
FDEM SURFEY





EM Logistic

Method	N. Probe	Dimensions	Depth
FDEM	2 + GPS	1m /3m	0.5m-7m (Fixed coils)

COST: - FDEM 15-20k

EM methods

Equipments

EM methods

FDEM probes

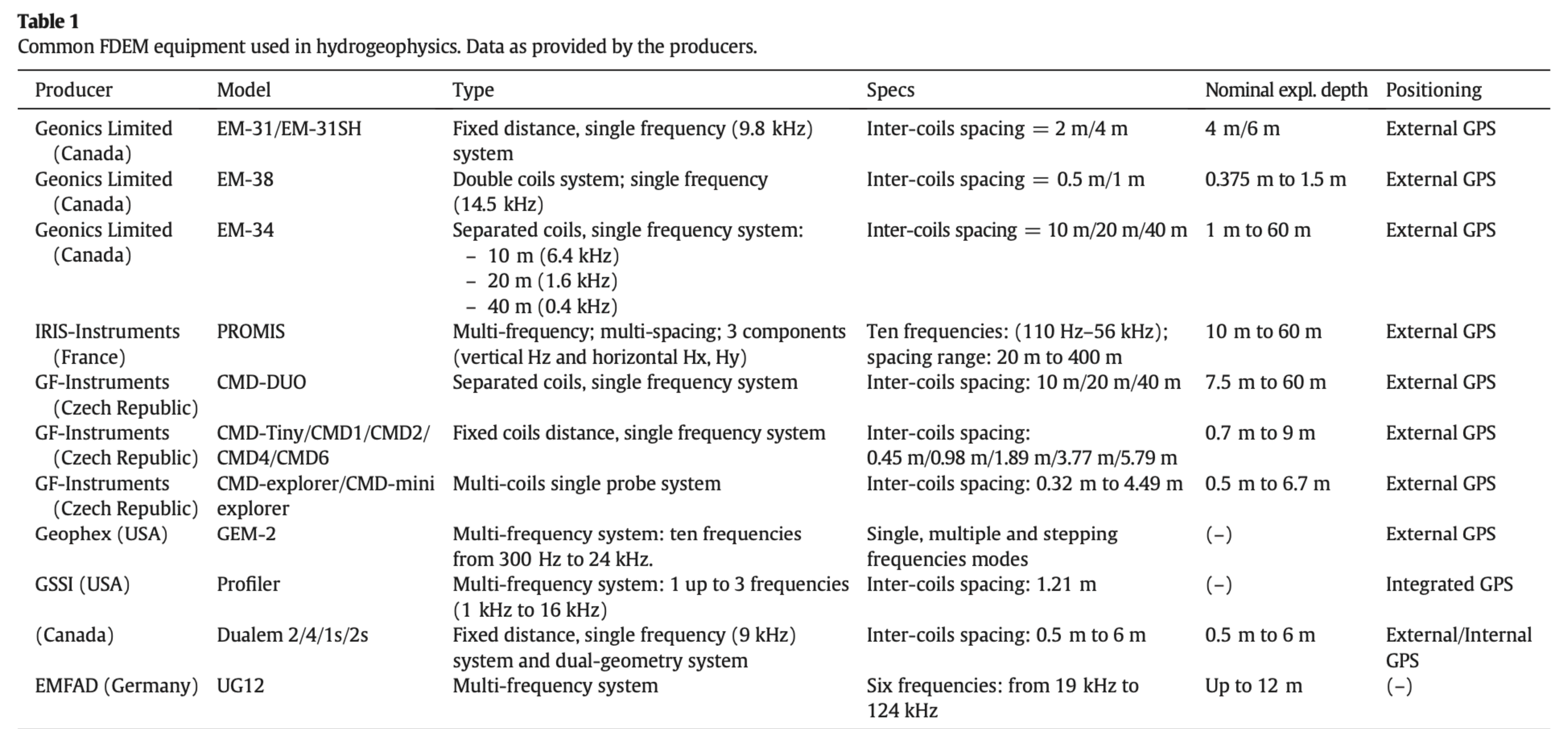


Table 1
Common FDEM equipment used in hydrogeophysics. Data as provided by the producers.

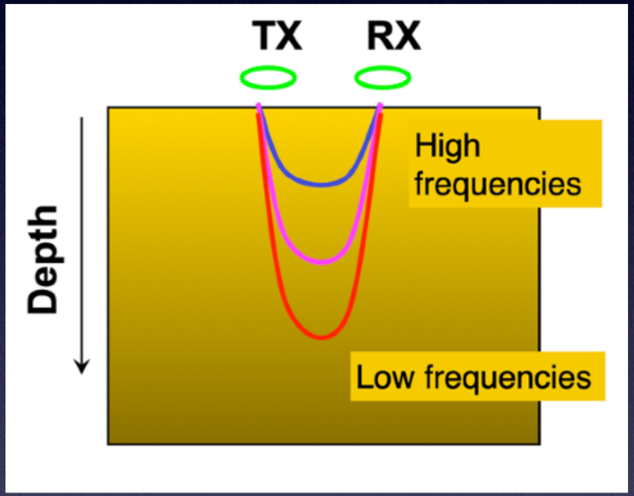
Producer	Model	Type	Specs	Nominal expl. depth	Positioning
Geonics Limited (Canada)	EM-31/EM-31SH	Fixed distance, single frequency (9.8 kHz) system	Inter-coils spacing = 2 m/4 m	4 m/6 m	External GPS
Geonics Limited (Canada)	EM-38	Double coils system; single frequency (14.5 kHz)	Inter-coils spacing = 0.5 m/1 m	0.375 m to 1.5 m	External GPS
Geonics Limited (Canada)	EM-34	Separated coils, single frequency system: – 10 m (6.4 kHz) – 20 m (1.6 kHz) – 40 m (0.4 kHz)	Inter-coils spacing = 10 m/20 m/40 m	1 m to 60 m	External GPS
IRIS-Instruments (France)	PROMIS	Multi-frequency; multi-spacing; 3 components (vertical Hz and horizontal Hx, Hy)	Ten frequencies: (110 Hz–56 kHz); spacing range: 20 m to 400 m	10 m to 60 m	External GPS
GF-Instruments (Czech Republic)	CMD-DUO	Separated coils, single frequency system	Inter-coils spacing: 10 m/20 m/40 m	7.5 m to 60 m	External GPS
GF-Instruments (Czech Republic)	CMD-Tiny/CMD1/CMD2/CMD4/CMD6	Fixed coils distance, single frequency system	Inter-coils spacing: 0.45 m/0.98 m/1.89 m/3.77 m/5.79 m	0.7 m to 9 m	External GPS
GF-Instruments (Czech Republic)	CMD-explorer/CMD-mini explorer	Multi-coils single probe system	Inter-coils spacing: 0.32 m to 4.49 m	0.5 m to 6.7 m	External GPS
Geophex (USA)	GEM-2	Multi-frequency system: ten frequencies from 300 Hz to 24 kHz.	Single, multiple and stepping frequencies modes	(–)	External GPS
GSSI (USA)	Profiler	Multi-frequency system: 1 up to 3 frequencies (1 kHz to 16 kHz)	Inter-coils spacing: 1.21 m	(–)	Integrated GPS
(Canada)	Dualem 2/4/1s/2s	Fixed distance, single frequency (9 kHz) system and dual-geometry system	Inter-coils spacing: 0.5 m to 6 m	0.5 m to 6 m	External/Internal GPS
EMFAD (Germany)	UG12	Multi-frequency system	Six frequencies: from 19 kHz to 124 kHz	Up to 12 m	(–)

EM methods

GEM-2
Multifrequency system

Producer: Geophex (Usa)

Frequency: 100Hz- 100 KHz



-Up to 7 frequencies simultaneous acquisition
- coil separation 1.6 m
- Weight: 5 kg
- External GPS
- Connected via bluetooth with the controller

Figure 1. GEM-2, a multi-frequency EM sensor, in operation.

EM methods

GEM-2
Multifrequency system

Pro: light, small, up to 7 different depths

Cons: response instabilities, drift

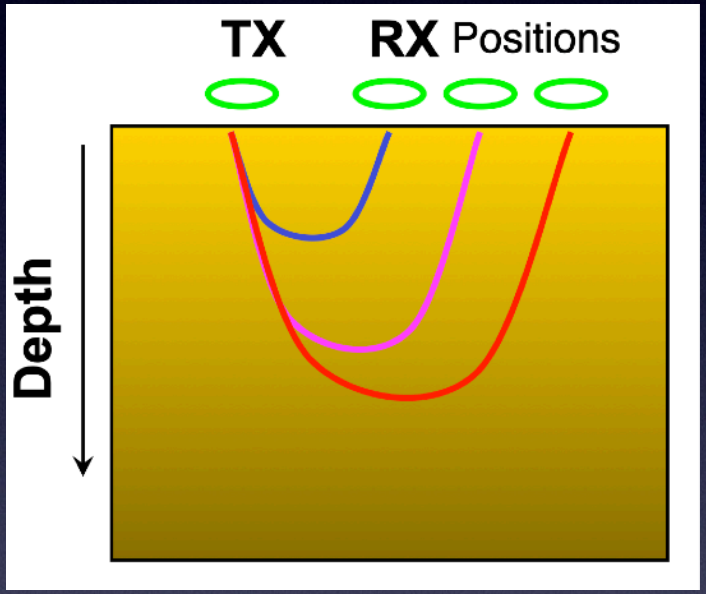
EM methods

GEONICS
EM 38

Producer: Geonics (Canada)

Multi-coils instrument

- Several coils distance with different frequencies



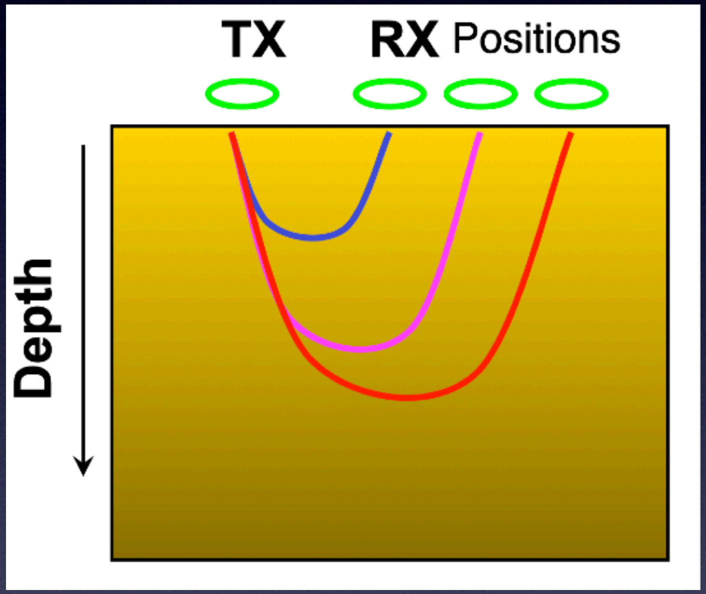
- Very diffused (especially in soil sciences and archeology)

EM methods

GF
Explorer

Producer: GF (Czech Republic)

Multi-coils instrument

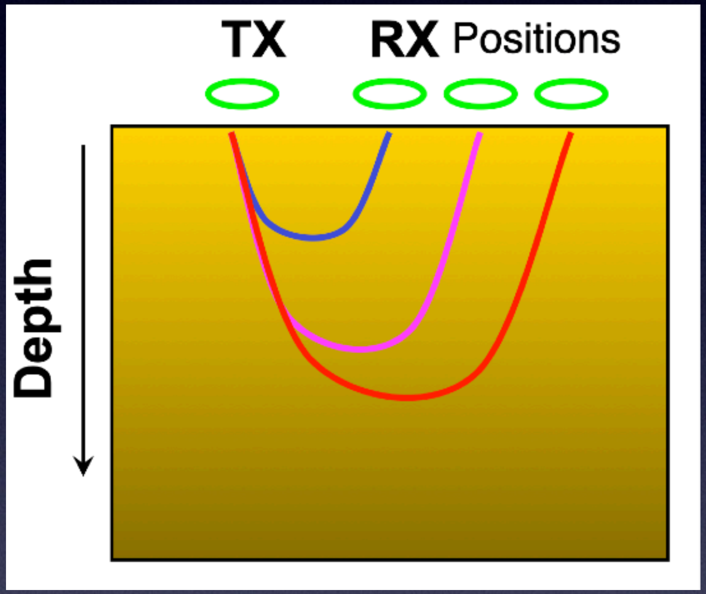


From 1.5 m to separated coils

10 kHz or 20 KHz
Fixed frequency

EM methods

GF
Explorer



Producer: GF (Czech Republic)

Mini explorer
(Up to 2 m depth investigation)

20 Khz
Length: 1.5 m
Weight: 3 kg

3 coils spacing (3 different depths of penetration)

EM methods

GF
Explorer

Producer: GF (Czech Republic)

Explorer
(Up to 7 m depth investigation)

10 Khz
Length: 6 m
Weight: 8 kg

3 coils spacing (3 different depths of penetration)

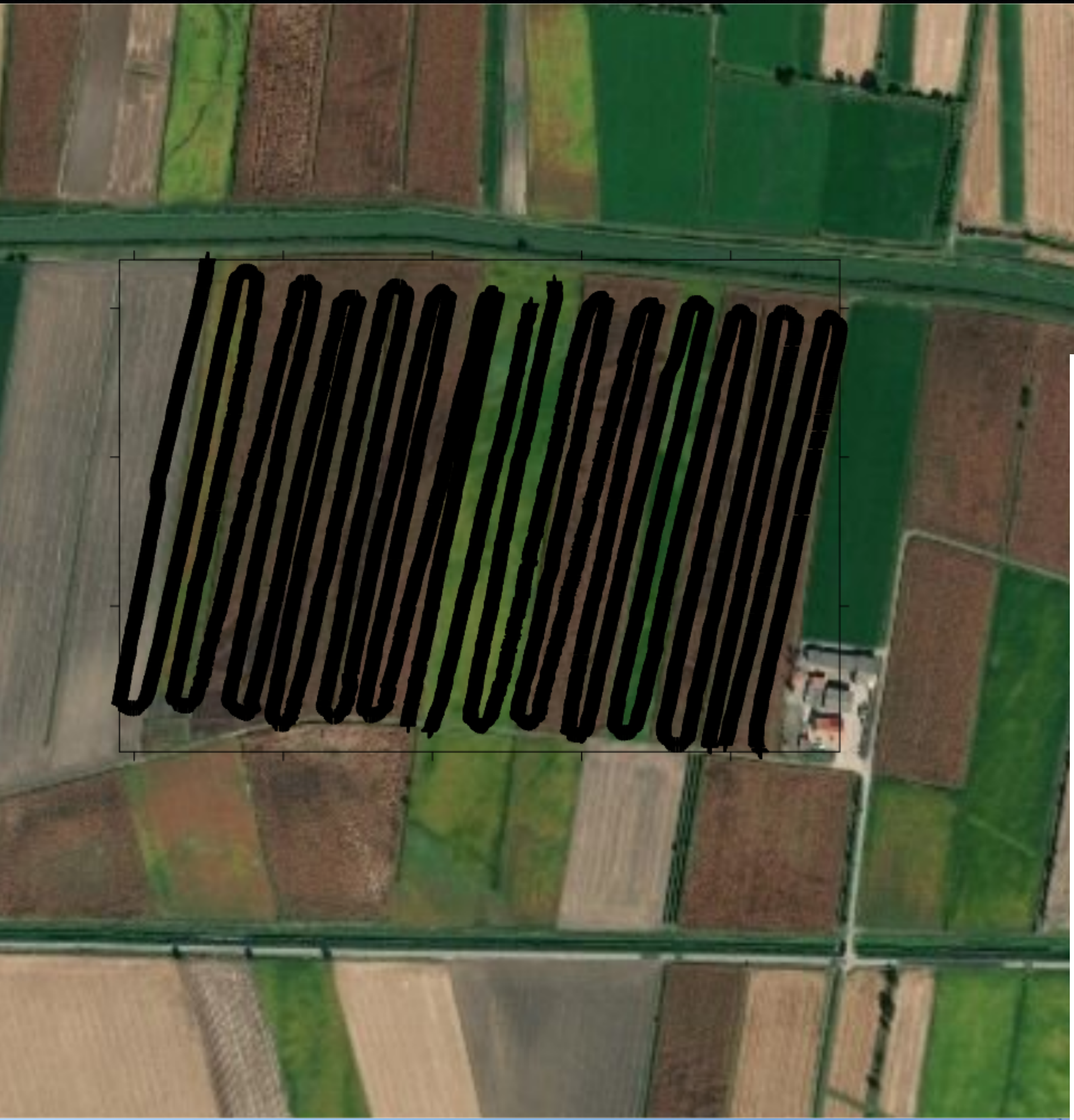
EM methods

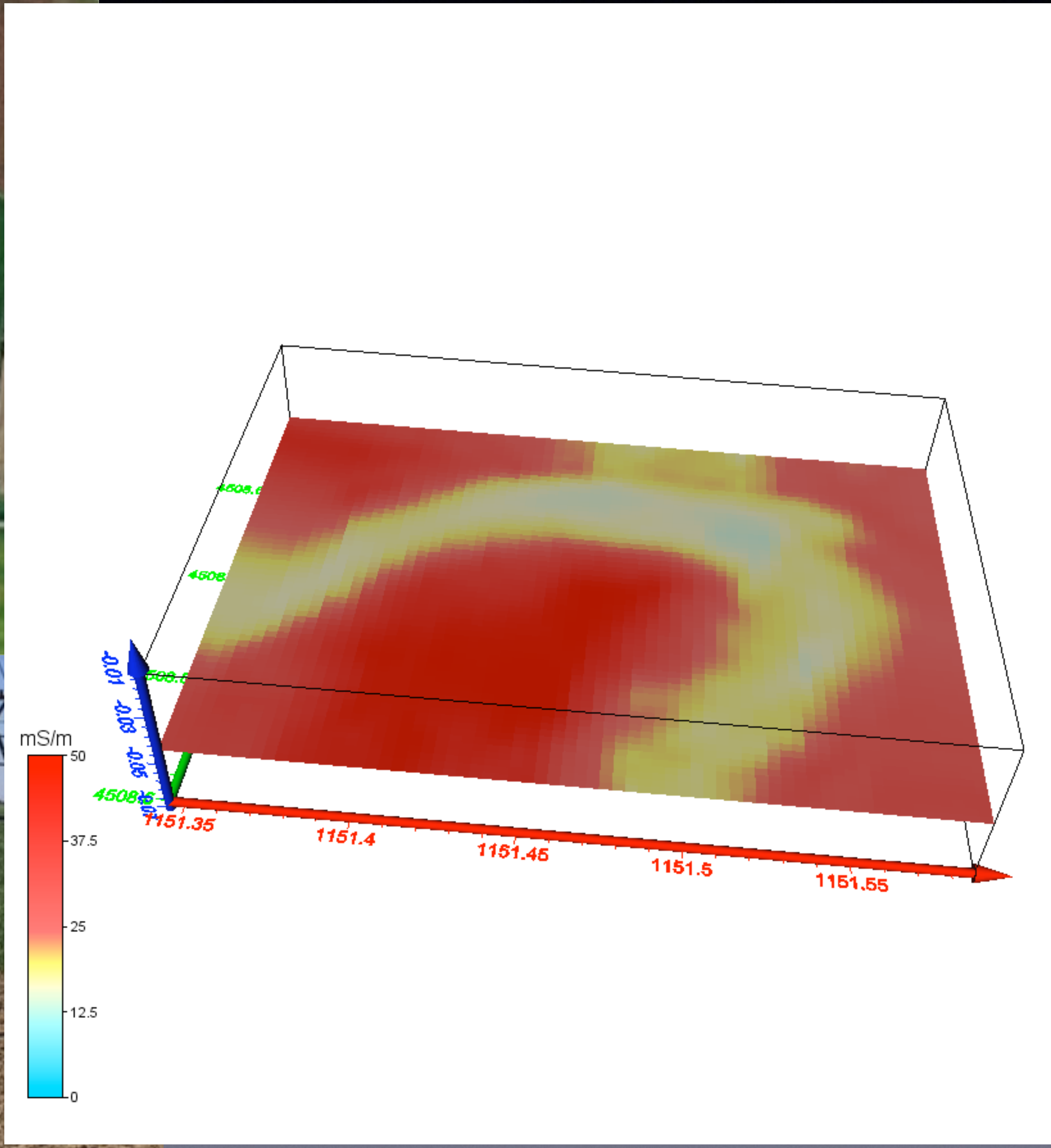
GF
Explorer
Multi-coils system

Pro: several antennas with 1 consolle,
Very reliable and stable in response, cheap

Cons: weight and dimension (heavy to transport, no drone flight)
External GPS need

(Can be drag by tractor with a sledge)




mS/m
50
37.5
25
12.5
0
1151.35
1151.4
1151.45
1151.5
1151.55

EM methods
GF
Explorer
Multi-coils system

CMD -DUO

Receiver and transmitter separated,
Up to 60 m depth

(Hard and slow logistic)

GEORADAR

High Frequency EM methods

GPR

GROUND PENETRATING RADAR

Electro-magnetic methods

Electric and Magnetic waves in EM fields in conductors

$$\nabla^2 E = \mu\sigma \frac{\partial E}{\partial t} + \mu\varepsilon \frac{\partial^2 E}{\partial t^2}$$

if $\sigma \gg \omega\varepsilon$

if $\sigma \ll \omega\varepsilon,$

I cannot modify the electric properties of the soil
(σ, ε)
but I can change the frequency (ω)
in the generation of the EM field...

Electro-magnetic methods

Electric and Magnetic waves in EM fields in conductors

$$\nabla^2 E = \cancel{\mu\sigma\frac{\partial E}{\partial t}} + \mu\varepsilon\frac{\partial^2 E}{\partial t^2}$$

if $\sigma \ll \omega\varepsilon$, *DIELECTRIC CASE*

$$\mu\sigma\frac{\partial E}{\partial t} \Longrightarrow 0$$

Electro-magnetic methods

Electric and Magnetic waves in EM fields in conductors

HIGH FREQUENCY EM METHOD *(e.g. M Hz)*

if $\sigma \ll \omega\varepsilon$,

$$\nabla^2 E = \mu\varepsilon \frac{\partial^2 E}{\partial t^2}$$

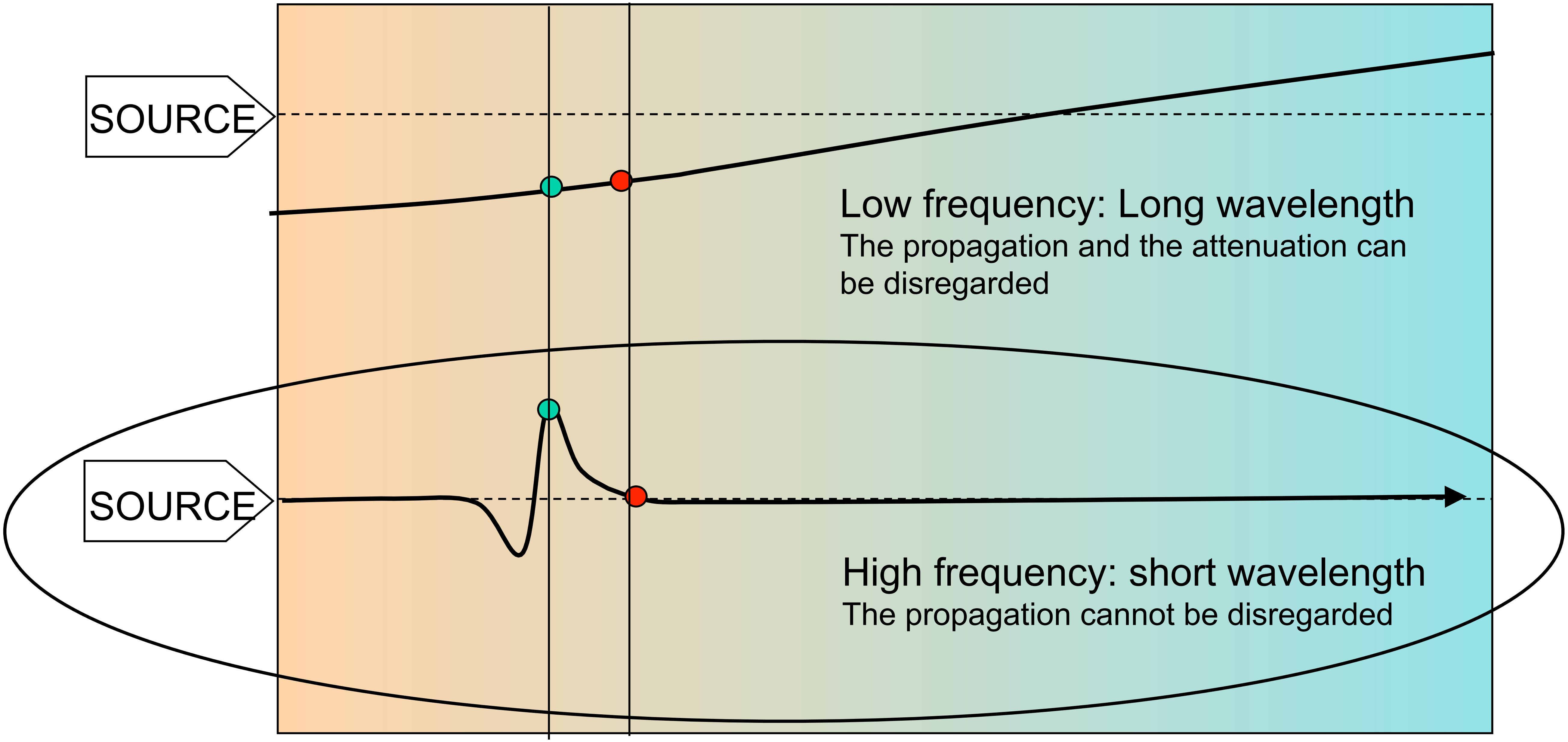
DISPLACEMENT CURRENTS

I CAN STUDY THE PROPAGATION OF EM WAVES

EM METHODS

Propagation of an electromagnetic wave

A primary field is generated and the sent into the ground, the response is measured



Low frequency: Long wavelength

The propagation and the attenuation can be disregarded

High frequency: short wavelength

The propagation cannot be disregarded

RADAR

propagation in a resistive medium

In resistive media (low electric conductivity σ, order of 100 S/m) the propagation is controlled by the dielectric properties

Low-loss media (loss tangent $\sigma/\varepsilon\omega$ <<1)

Dielectric permittivity

$$\boxed{\nabla^2 E = \mu\cancel{\sigma\frac{\partial E}{\partial t}} + \mu\varepsilon\frac{\partial^2 E}{\partial t^2}}$$

High frequency, low conductivity

$$\left(\nabla^2 E = \mu\varepsilon\frac{\partial^2 E}{\partial t^2} \right)$$

Velocity of EM wave $= \dfrac{c}{\sqrt{\mu_r \varepsilon_r}}$

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \approx 3 \cdot 10^8$$

Light velocity

Dielectric constant and magnetic Permeability in the vacuum

$$\mu_r \cong 1 \qquad v = \frac{c}{\sqrt{\varepsilon_r}}$$

GeoRadar velocity

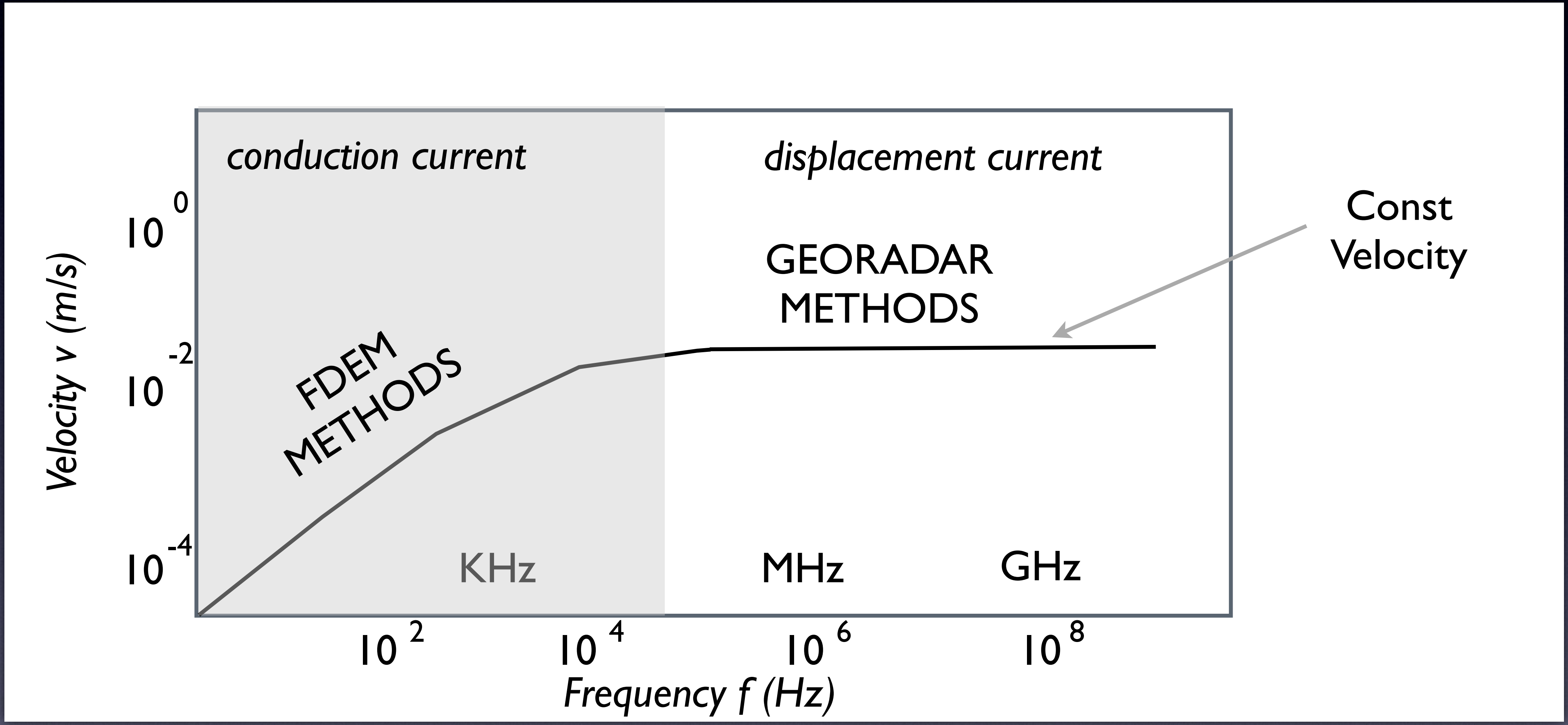
The relative permittivity ε_r (called also dielectric constant) is hence the most important parameter

ε_r = 3-10

ε_r = 81 water

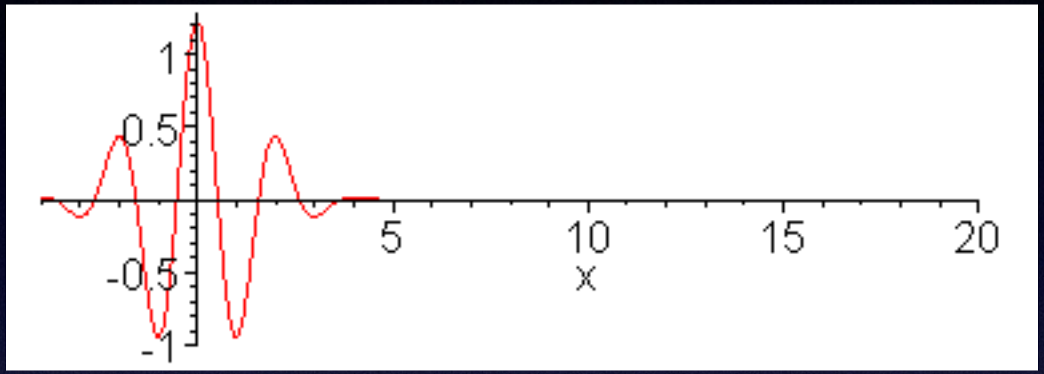
GEORADAR

High frequency velocity of EM wave is constant!!

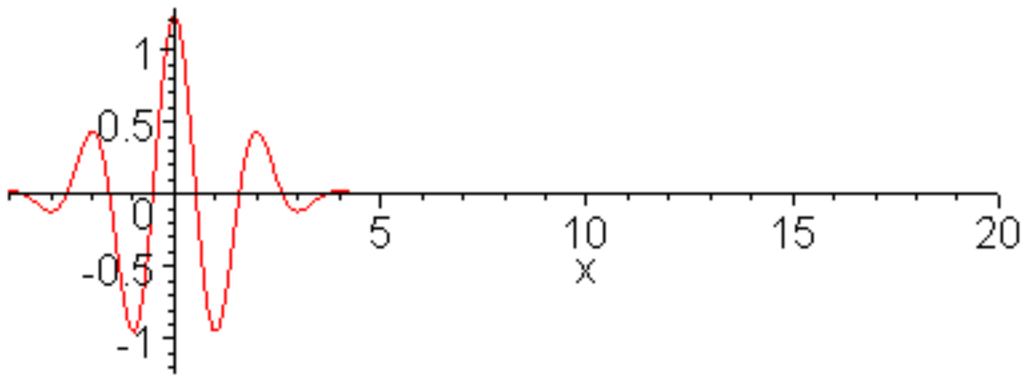


We can study the waveform as transmitting wave
And study the reflection of the reflected wave

https://www.youtube.com/watch?v=tlM9vq-bepA
Wave_group.gif
Wave_disp.gif

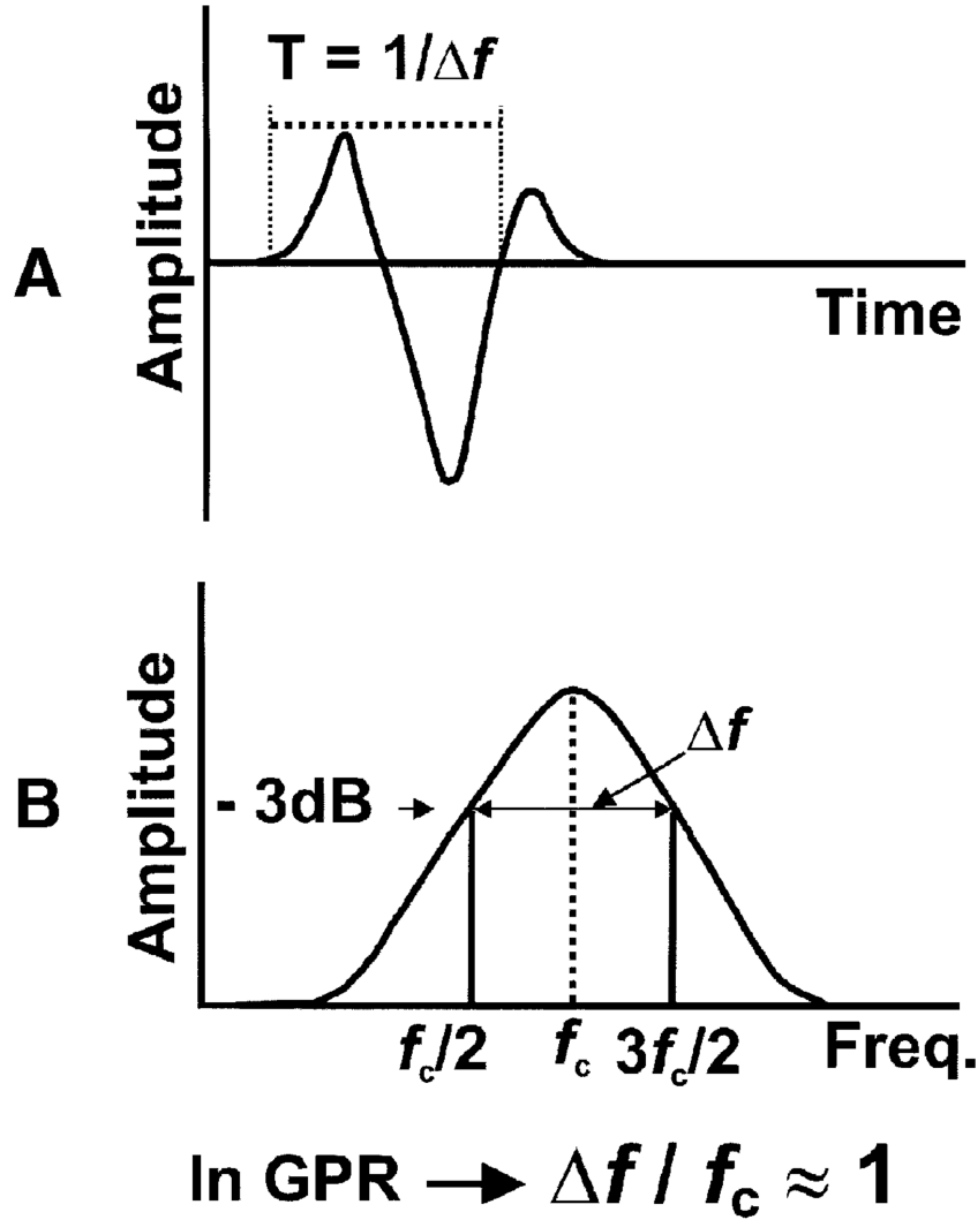


Onde di Volume (P e S)
non dispersive



Onde di Superficie
dispersive

Electro-magnetic methods



$>>$ frequency (f)
$<<$ period T

Bandwidth has same dimension of central Frequency

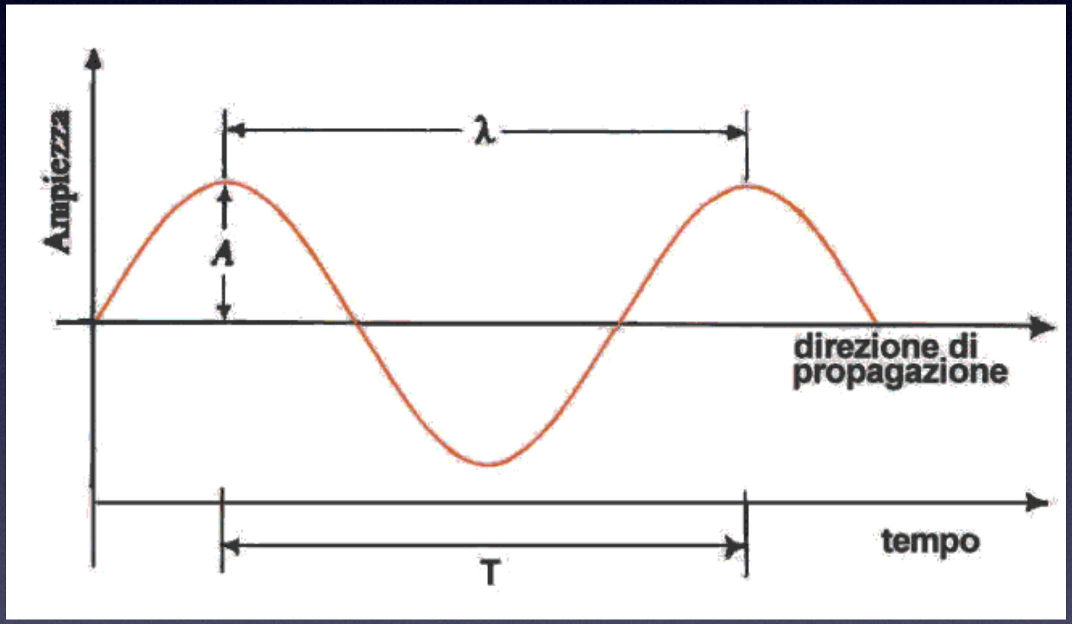
Eg.
Georadar antenna 100Mhz

Bandwidth Δf da 50 a 150 Mhz
Δf = 100 Mhz

Electro-magnetic methods

GEORADAR

>> frequency (f) << wavelength λ



Light Velocity

$$v = \frac{c}{\sqrt{\varepsilon_r}}$$

radar wave Velocity

$$\lambda = \frac{v}{f}$$

Wavelength

EXAMPLE:

Velocity sand = 0.06 m ns^{-1}

Frequency of *GPR* = 100 Mhz

λ = 60 cm

Max Resolution

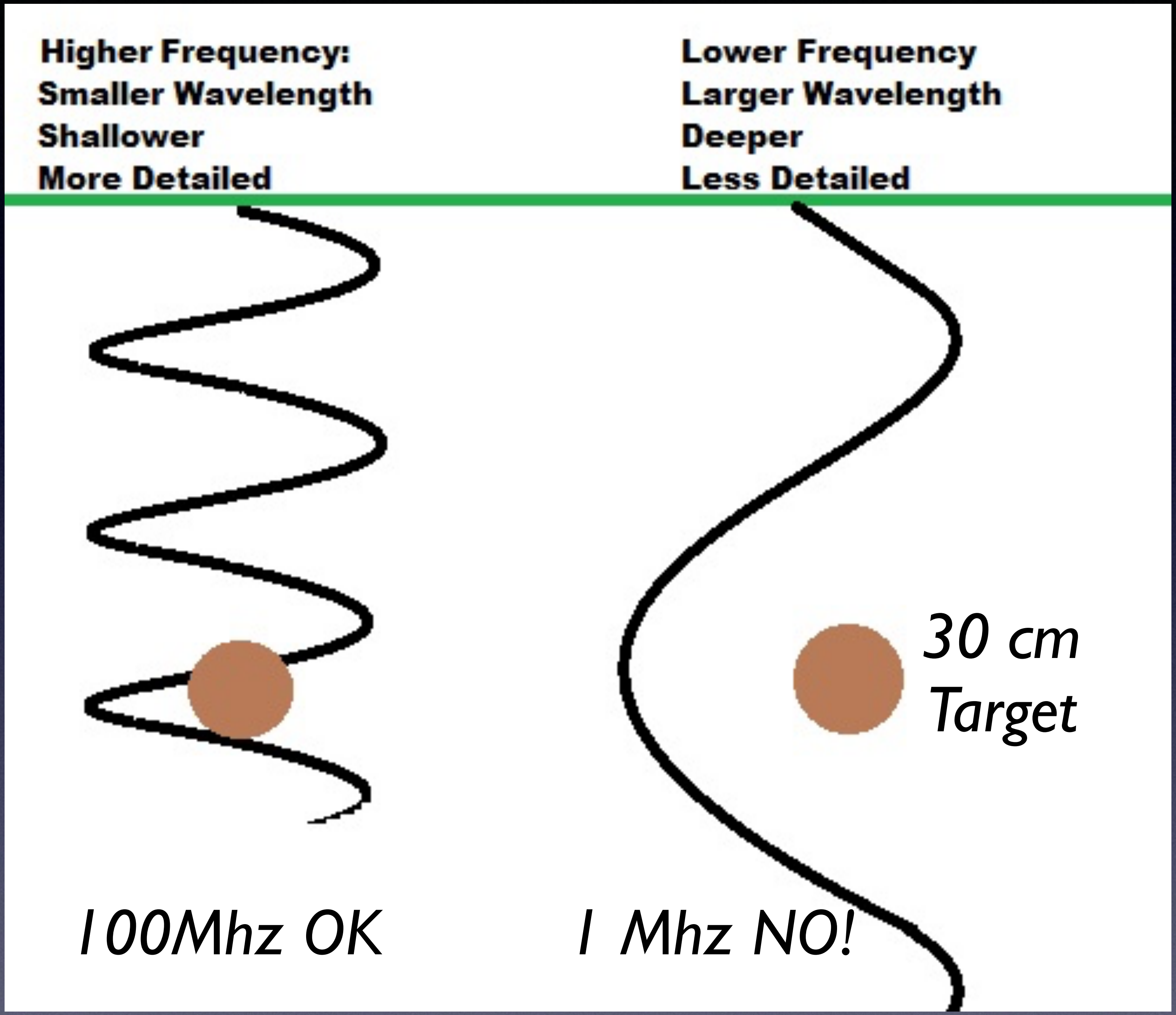
≈λ/4 = 15 cm

Excellent resolution!

Resolution is commonly considered as 1/4 of the wavelength

Electro-magnetic methods

GEORADAR



>> frequency (f)
<< wavelength (λ)

Excellent
Resolution

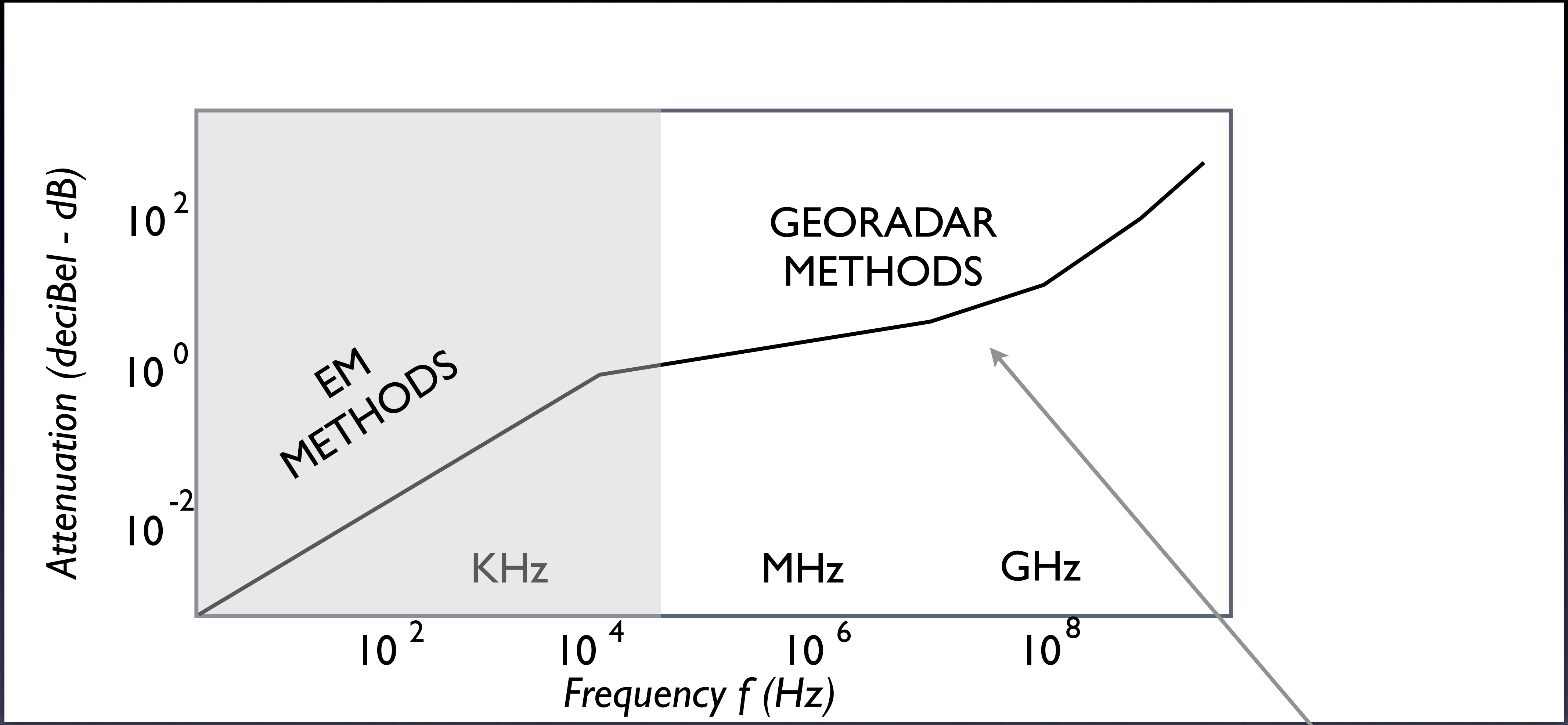
E.g. antenna da GHz
$\lambda \approx 1$ cm

Electro-magnetic methods

GEORADAR

Attenuation

>> frequency (f) >> Attenuation



Attenuation alfa

Frequency

Conductivity

$$\alpha = \omega\sqrt{\varepsilon\mu}\left\{\frac{1}{2}\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^{2}}-1\right]\right\}^{1/2},$$

Dielectric const.

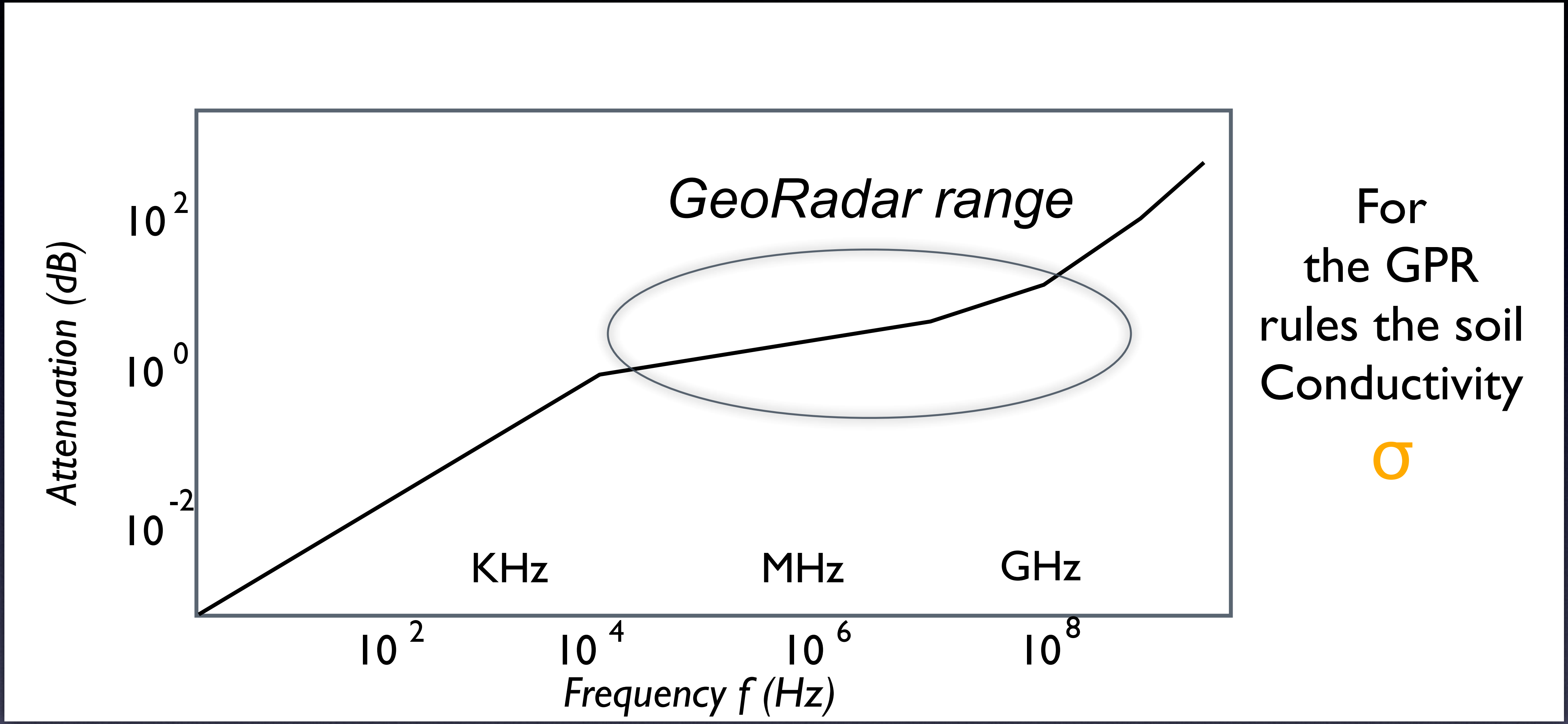
Magnetic Perm.

RADAR
HAVE POOR
PENETRATING
POWER !

Electro-magnetic methods

GEORADAR

>> conductivity (σ) >> Attenuation



For
the GPR
rules the soil
Conductivity
σ

const.

Conductivity

$$\lambda \approx 1690 \frac{\sigma}{\sqrt{\varepsilon_r}} \quad (dB/m)$$

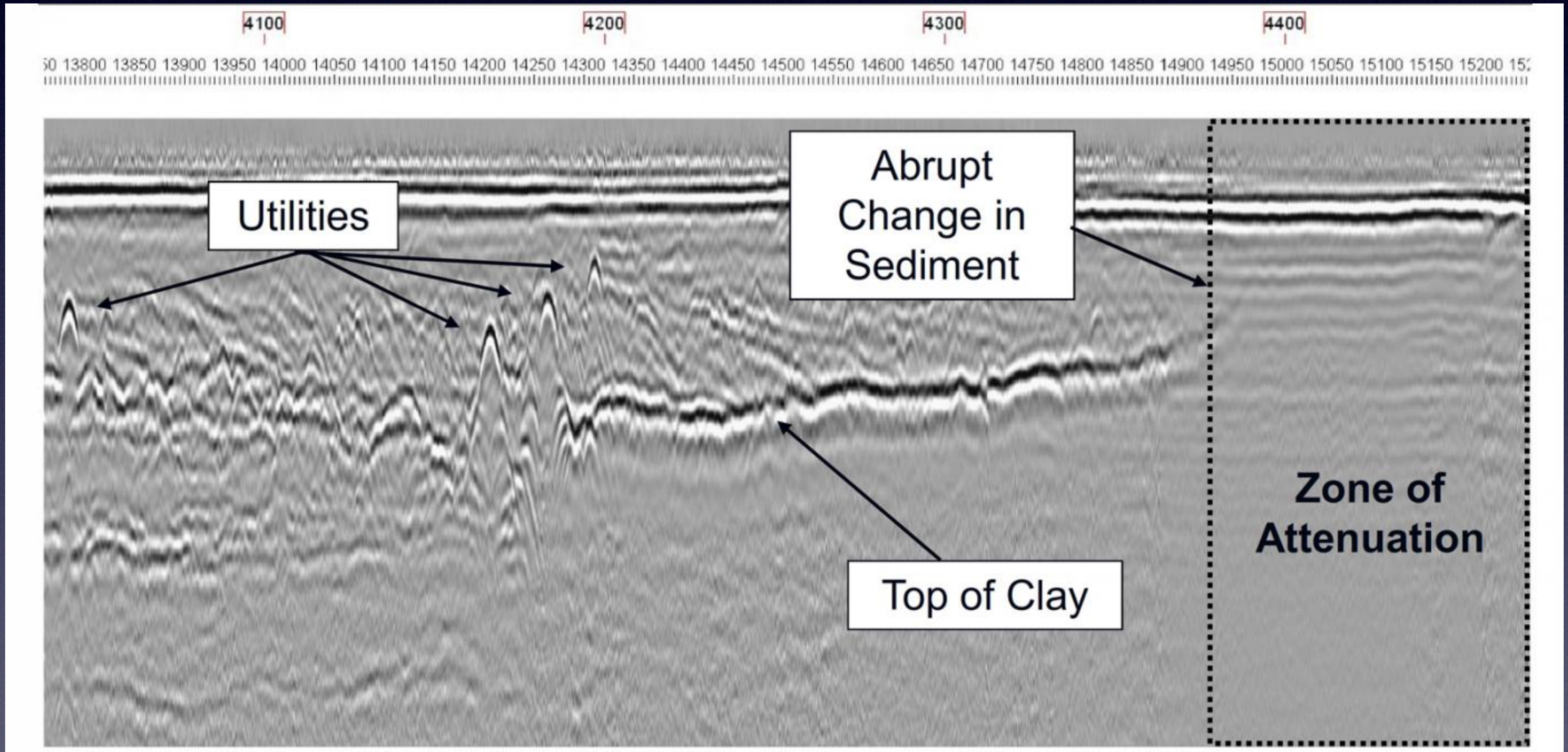
Attenuation alfa

Const diel.

Attenuation for a GPR
Is function of soil conductivity

GEORADAR

>> conductivity (σ) >> Attenuation



Geotechnical Evaluation (250 MHz Antenna; 55 mph at 4 inch intervals; 118 ns time window; approximately 15 feet in depth)

High conductivity
Terrains
(*clay, silt, ecc*)
Has limited
Penetration depth

>>> ATTENUATION <<< PENETRATION

Physical principles: penetration

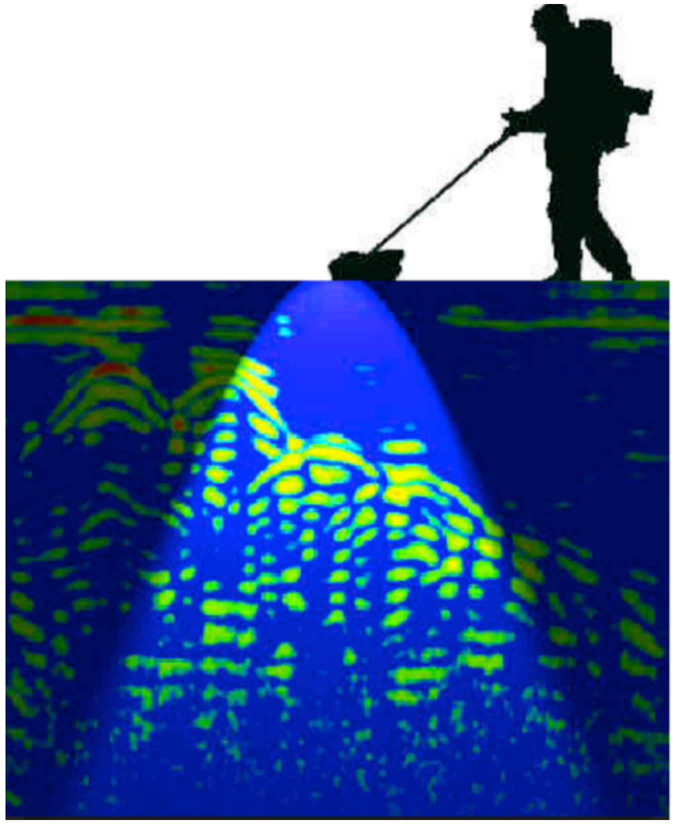
$$\nabla^2 E = \overset{\boxed{\text{energy loss}}}{\mu\sigma\frac{\partial E}{\partial t}} + \overset{\boxed{\text{wave propagation}}}{\mu\varepsilon\frac{\partial^2 E}{\partial t^2}}$$

The georadar penetration is rather limited. Under normal conditions, soil conductivity is controlled by the presence of ions in soil/ground water solution.

Typical attenuation values for 100-200 MHz frequency (α), resistivity (ρ) and relative permittivity (ε_r):

Material	Attenuation α (dB/m)	Resisitivity ρ (ohm/m)	Relative permittivity ε_r
Saturated shale	51.8	10	10
Argillaceous marl	14.5	40	8
Calcareous marl	5.8	100	8
Saturated sand	3	100	30
Limestone	2	400	4
Fresh water	1.8	100	81
Dry sand	0.82	1000	4
Pure water	0.2	1000	81
Ice	0.082	10000	4
Sound concrete or sound granite	0.06	10000	6.5

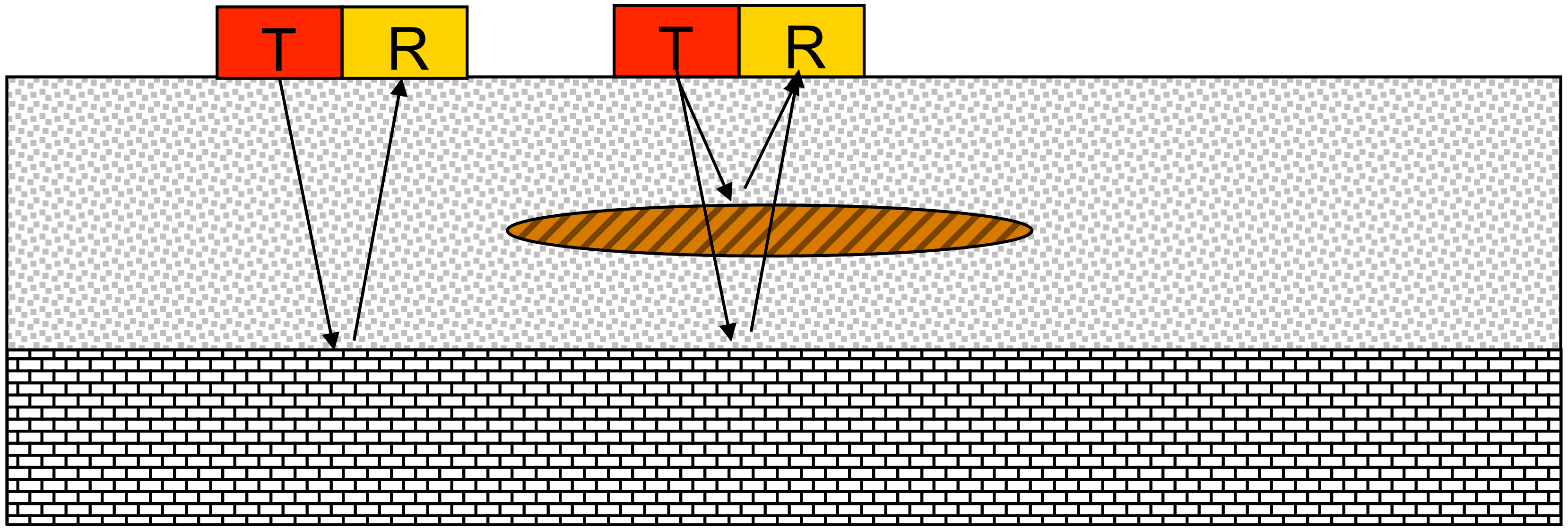
Georadar



G P R

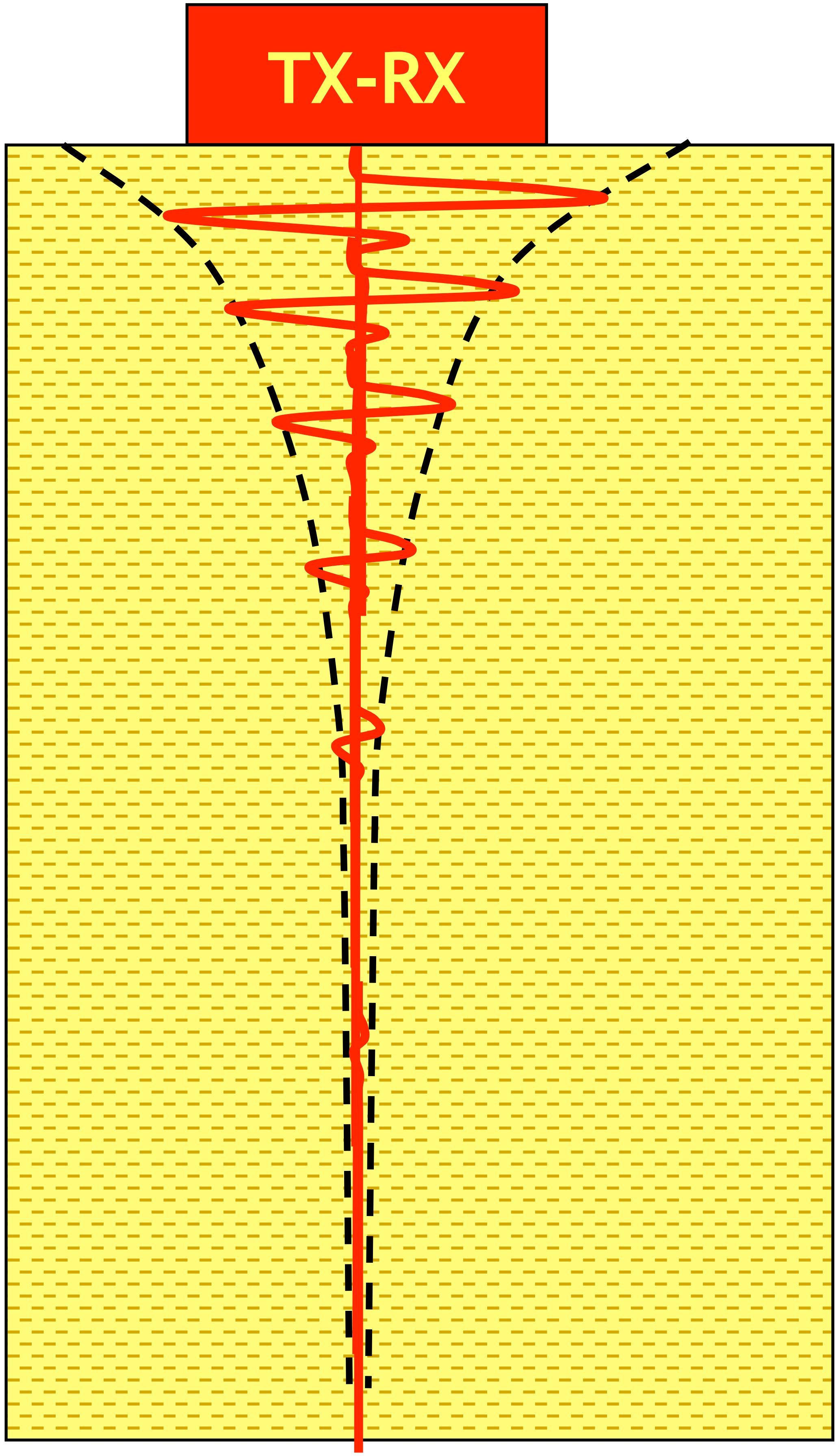
Ground Probing Radar (or Ground Penetrating Radar) is a high frequency EM technique (in the band 10-2500 MHz) based on the response of the subsoil to a short EM pulse.

A signal of short wavelength is radiated into the ground, is reflected, refracted, diffracted and hence detects the anomalous variations in the dielectric properties.



Anomalies can be soil horizons, the groundwater surface, soil/rock interface, man made objects (pipes, foundations, cables…)

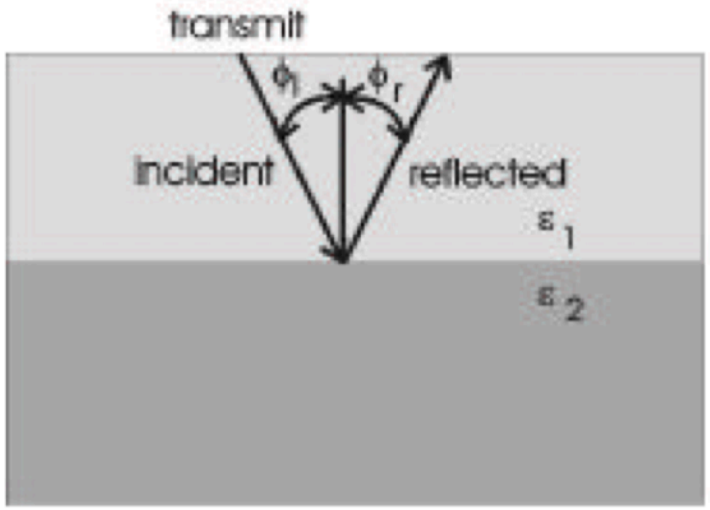
HIGH RESOLUTION, LOW PENETRATION DEPTH



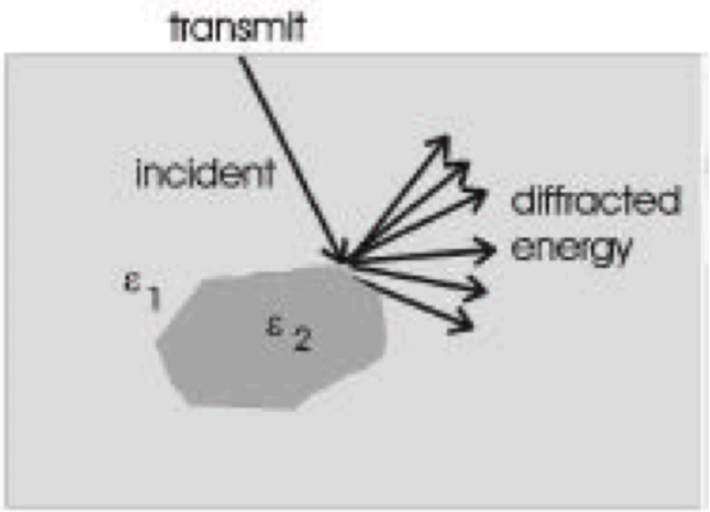
A signal is sent into the ground:

It propagates, is attenuated, and come back to the surface when variation of properties are encountered

- •Reflection
- •Diffraction



Reflection

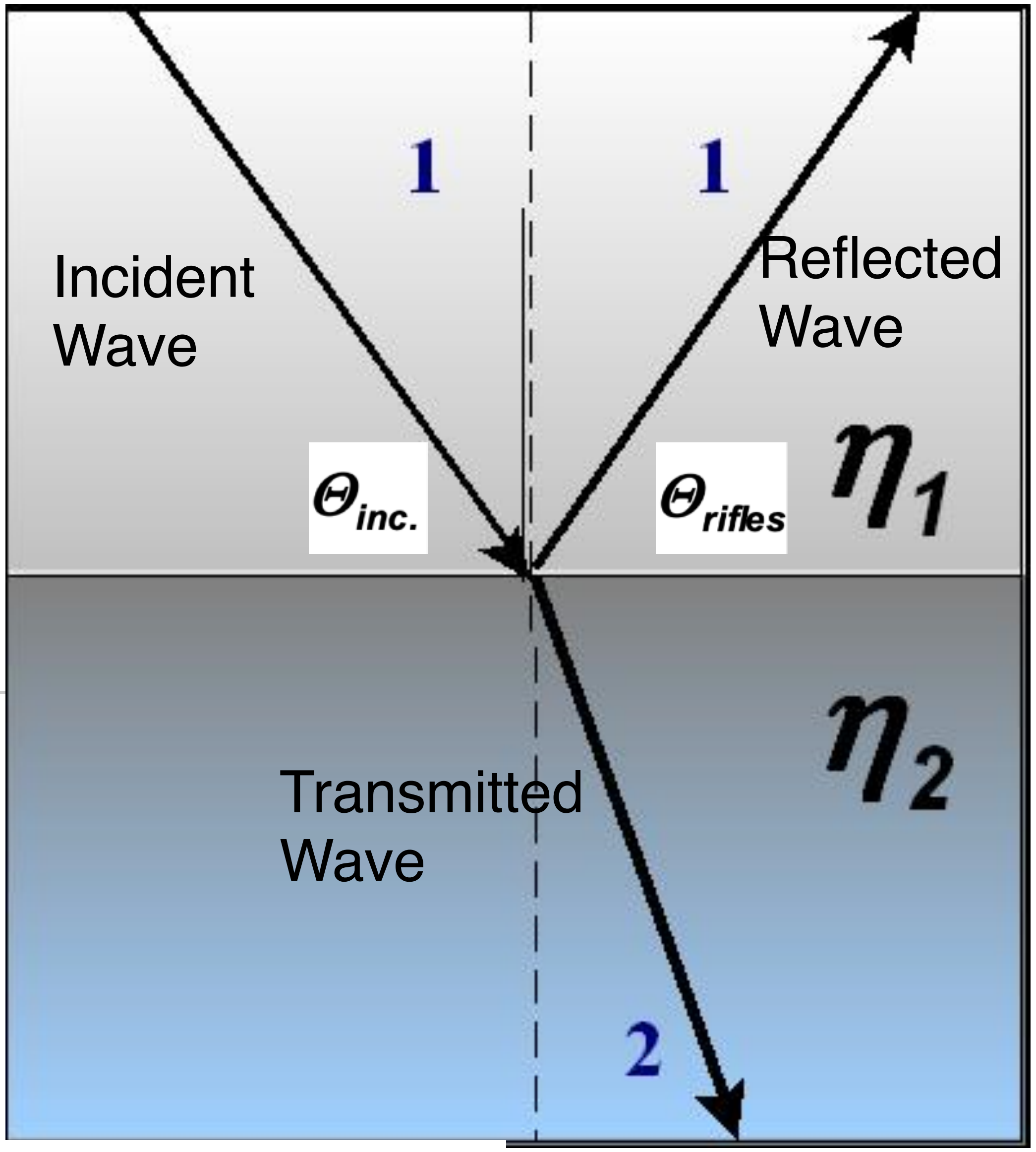


Diffraction

REFLECTION

Transmission and reflection coefficients at an interface

The anglo of incidence $\Theta_{inc.}$ is equal to the angle of reflection Θ_{rifles}



$$\Theta_{inc.} = \Theta_{rifles.}$$

$$\frac{\sin\Theta_{tras.}}{\sin\Theta_{inc.}} = \frac{v_2}{v_1} = \sqrt{\frac{\mu_1\varepsilon_1}{\mu_2\varepsilon_2}}$$

$$\Gamma = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1}$$

Coeff. of Reflection

$$\tau = \frac{2\cdot\eta_1}{\eta_2 + \eta_1}$$

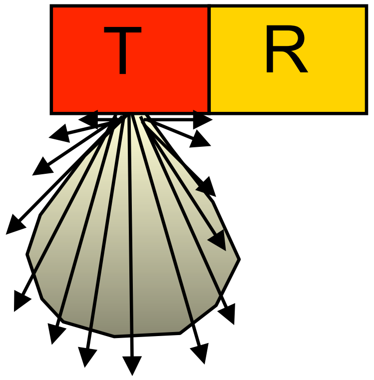
Coeff. of Transmission

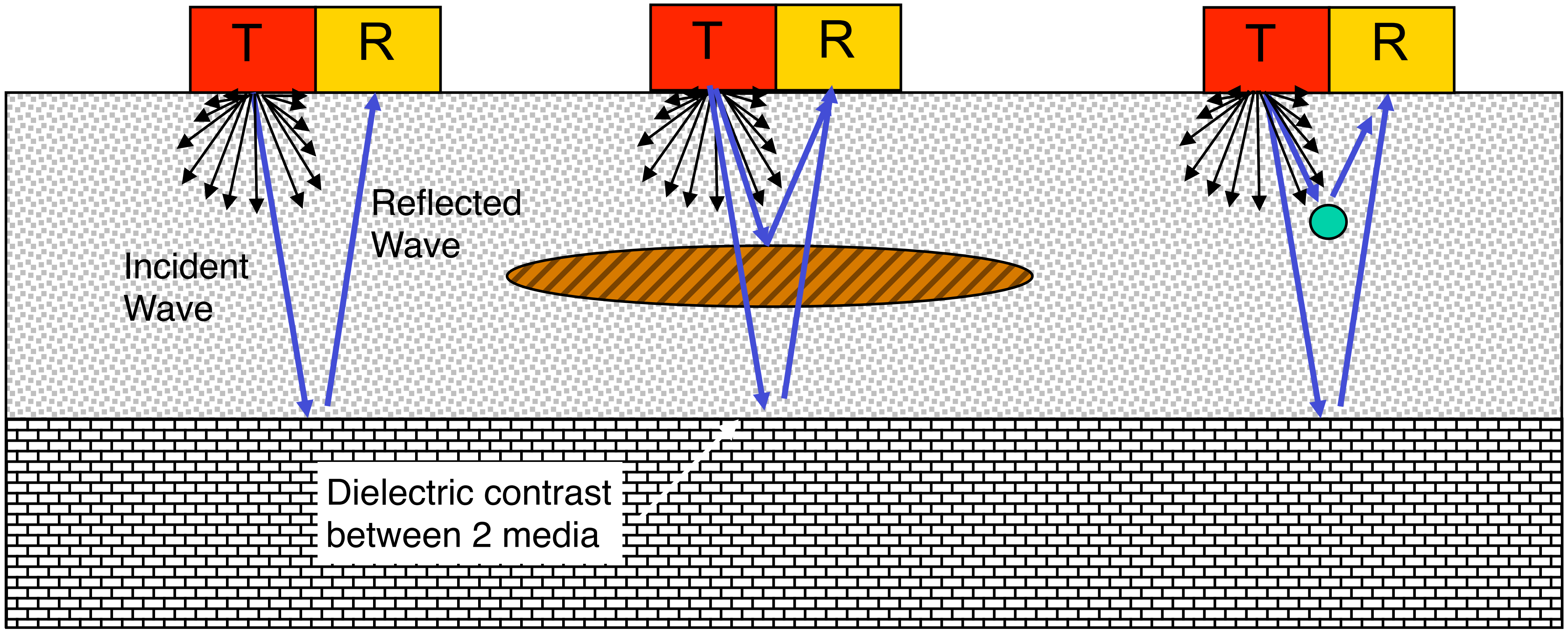
$$\eta = \left(\frac{\mu}{\varepsilon}\right)^{1/2}$$

Dielectric Impedance

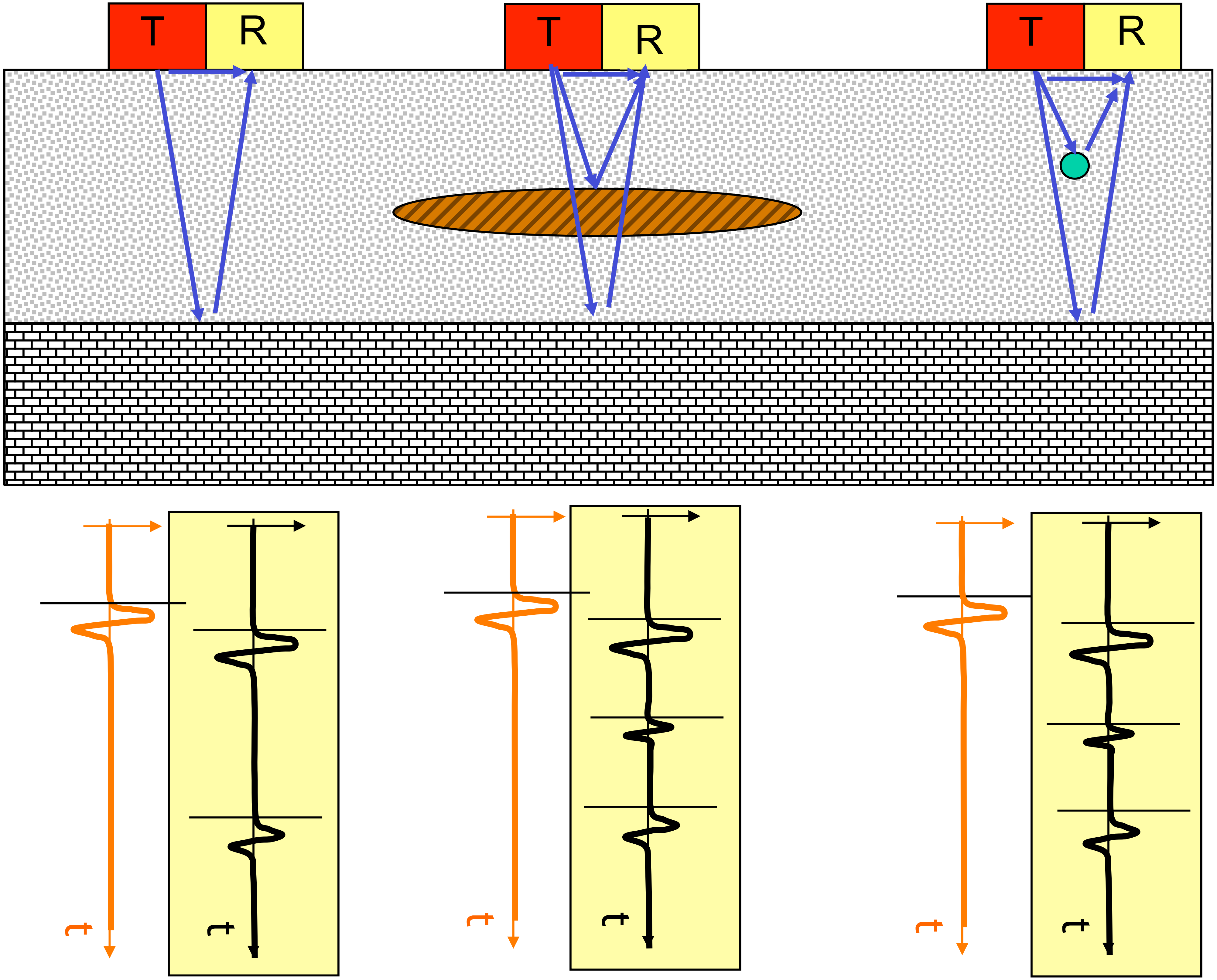
OPERATING GPR

detecting the presence of anomalies from the surface



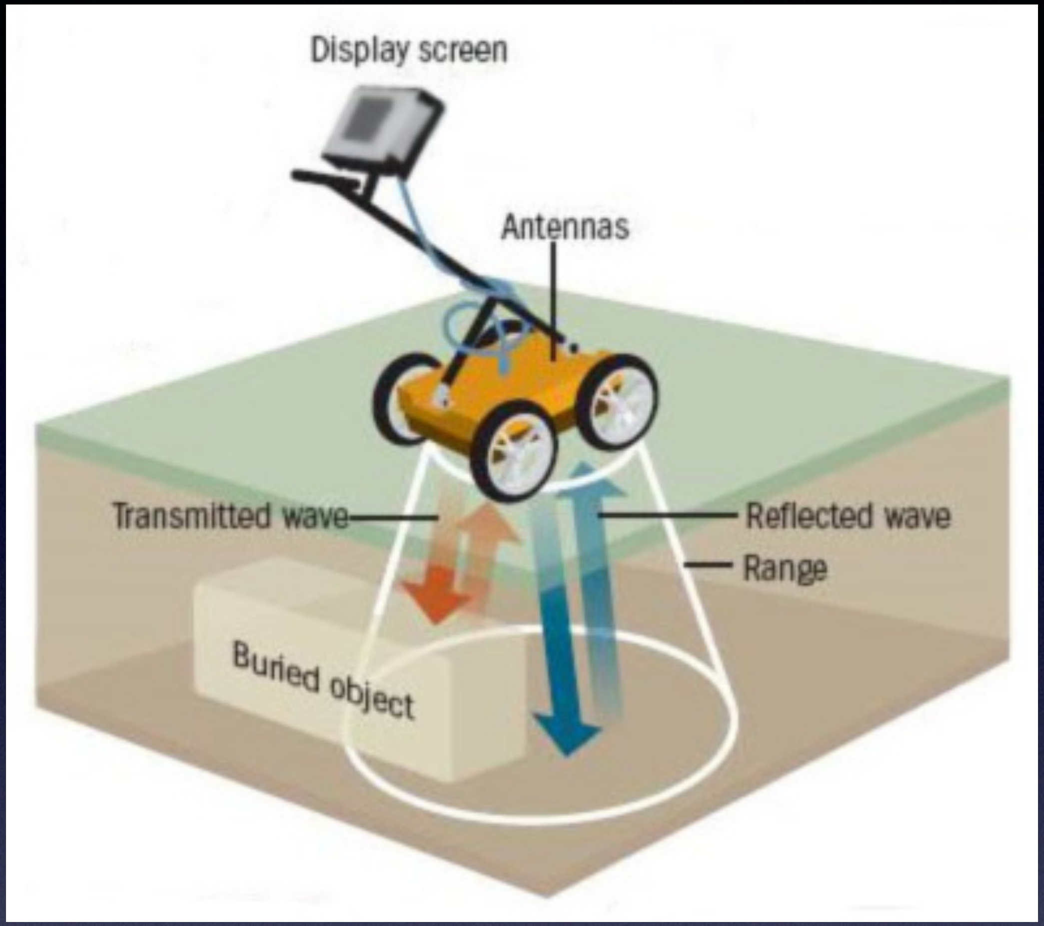


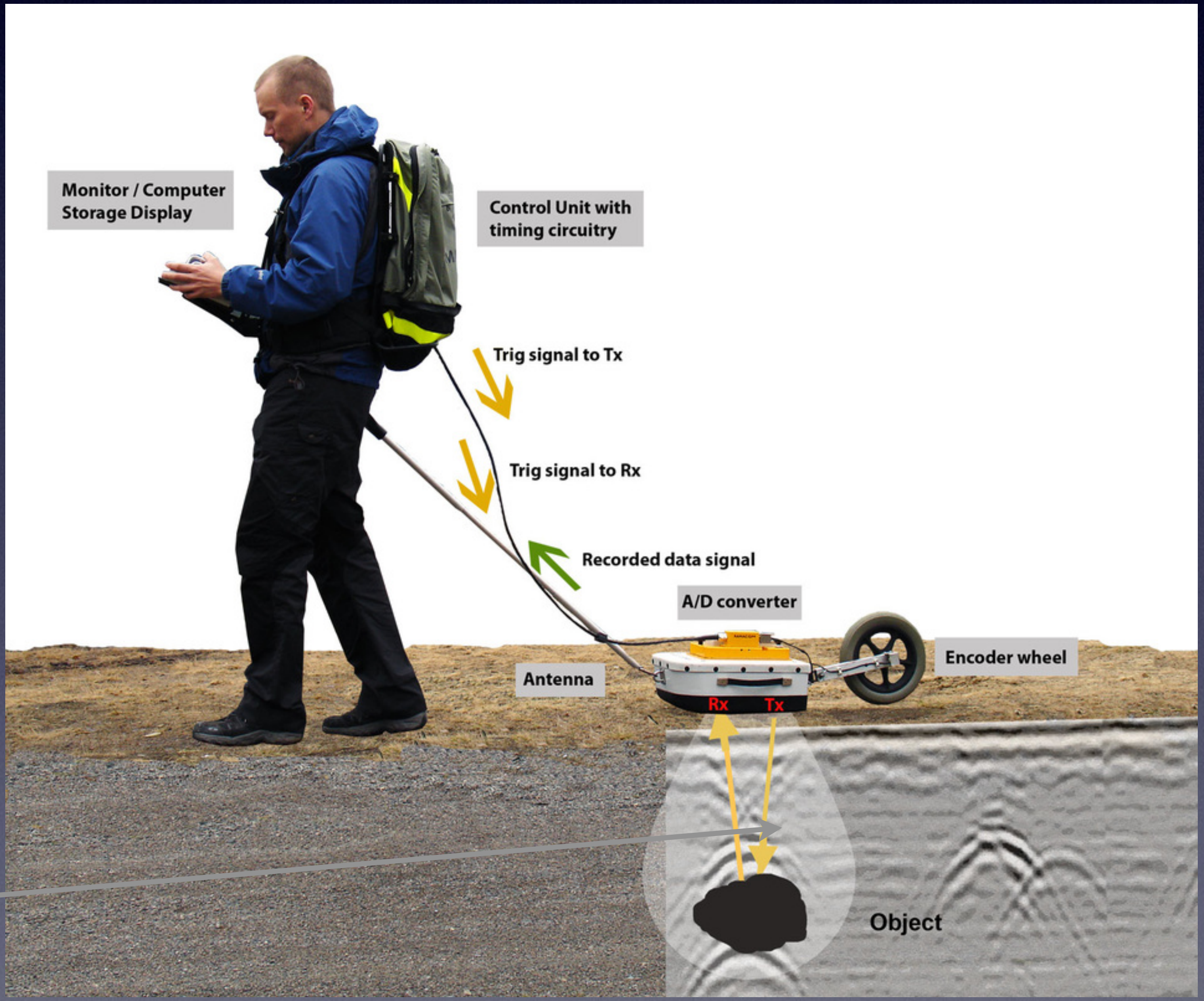
SIGNALS IN A SINGLE GPR TRACE



Electro-magnetic methods

GEORADAR antenna

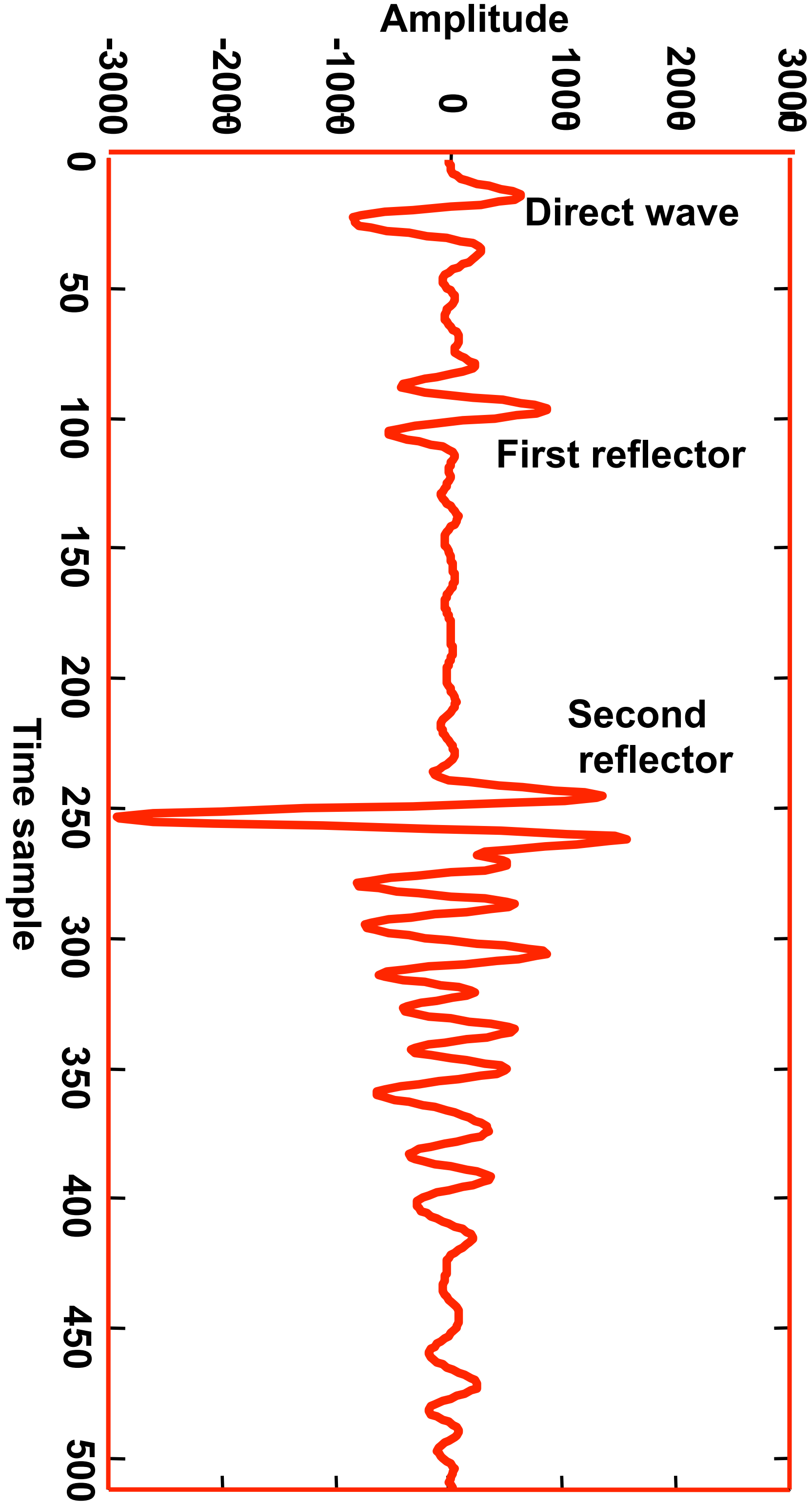




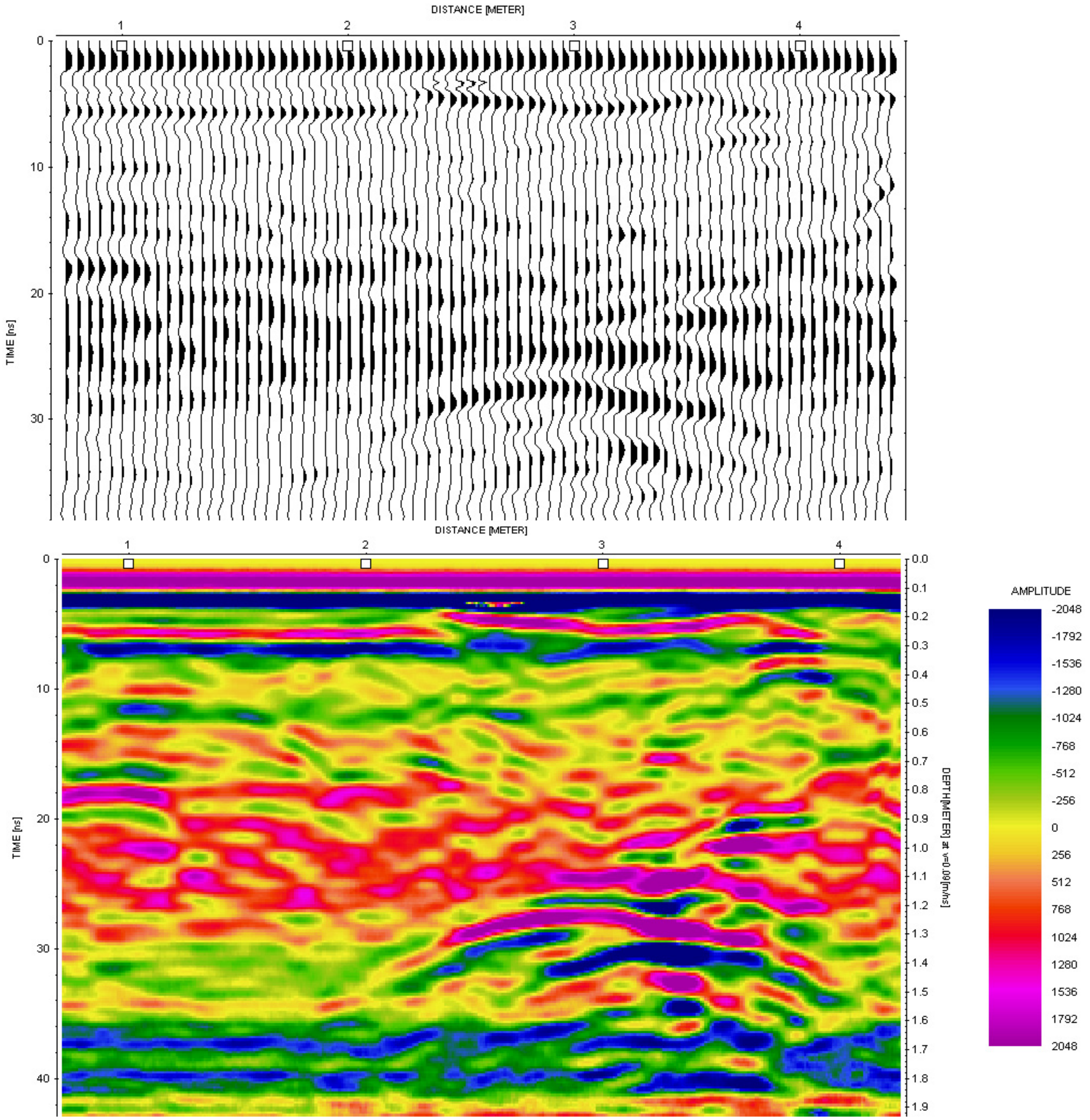
RADARGRAM
Studying
The REFLECTION OF EM WAVES
due to dielectric contrasts

RADARGRAM

A real GPR trace

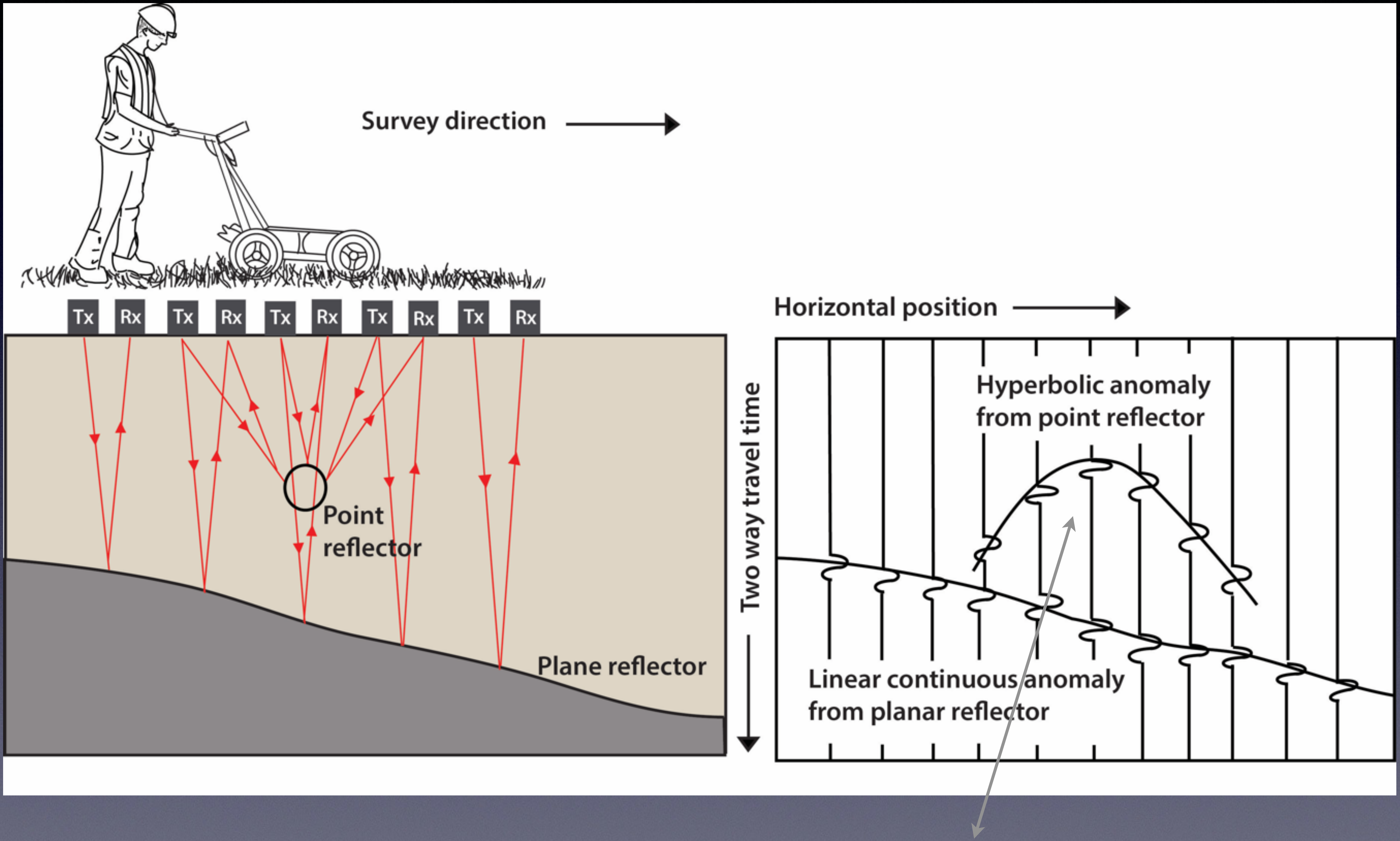


With modern fast systems, many traces can be collected with a continuous acquisition



Electro-magnetic methods

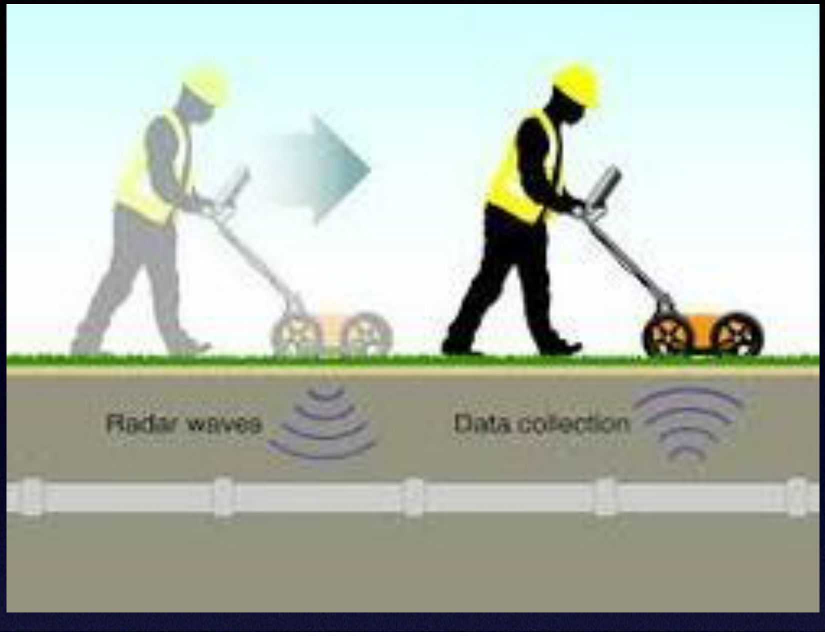
GEORADAR

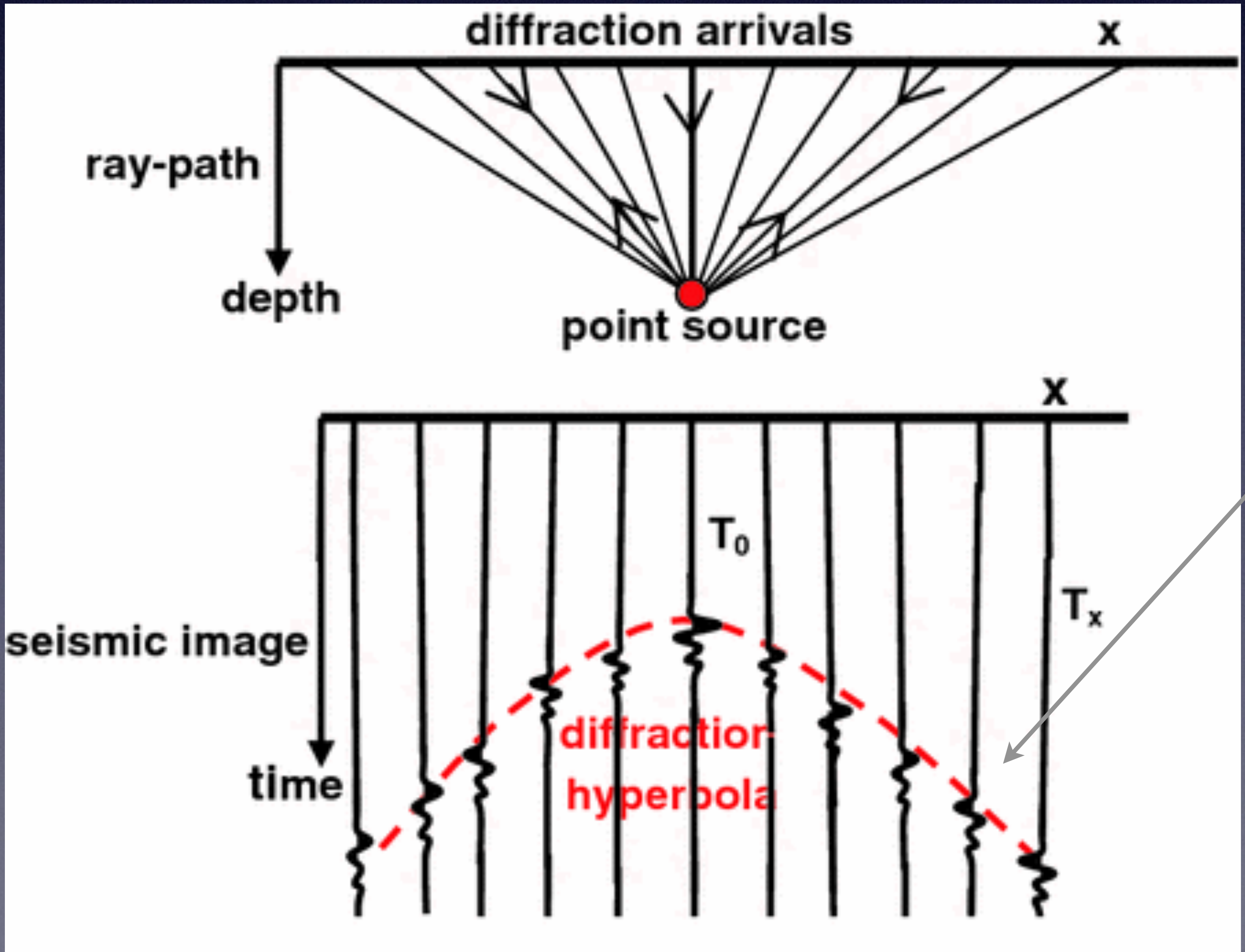


Diffraction Hyperbola

Electro-magnetic methods

GEORADAR





Diffraction Hyperbola

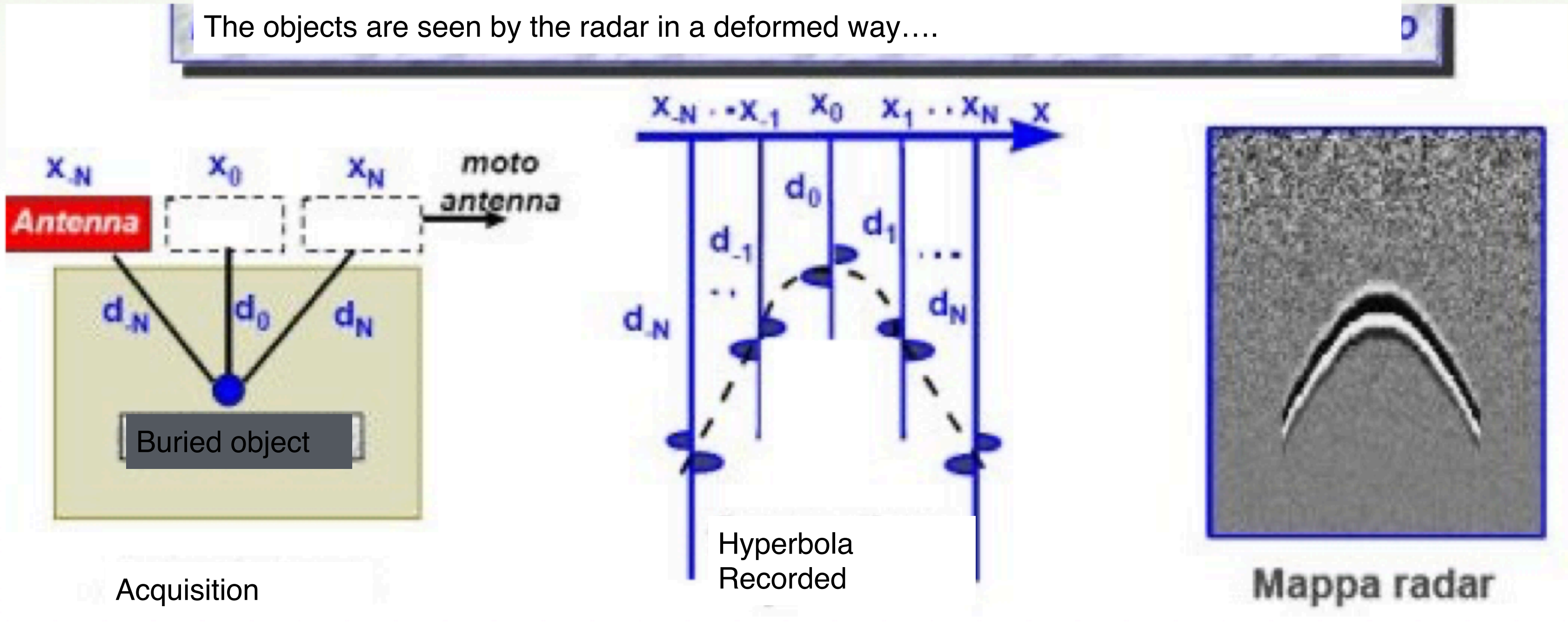
same processing
of seismic
exploration

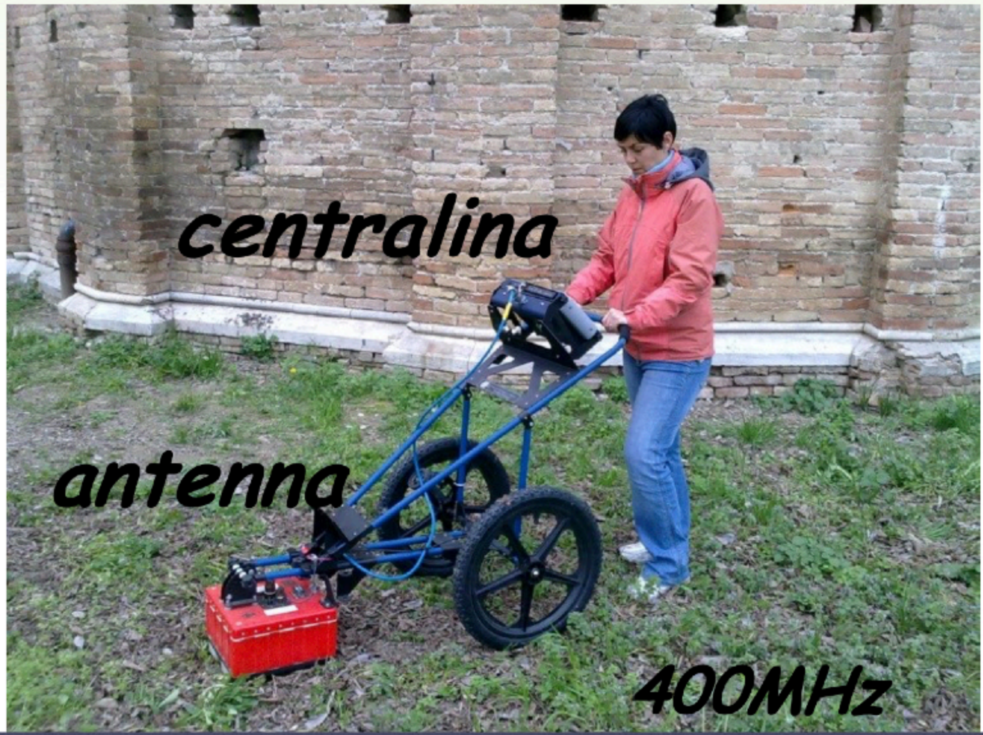
$$T^2x = T^20 + X^2 / V^2$$

Electro-magnetic methods

GEORADAR

GEORADAR

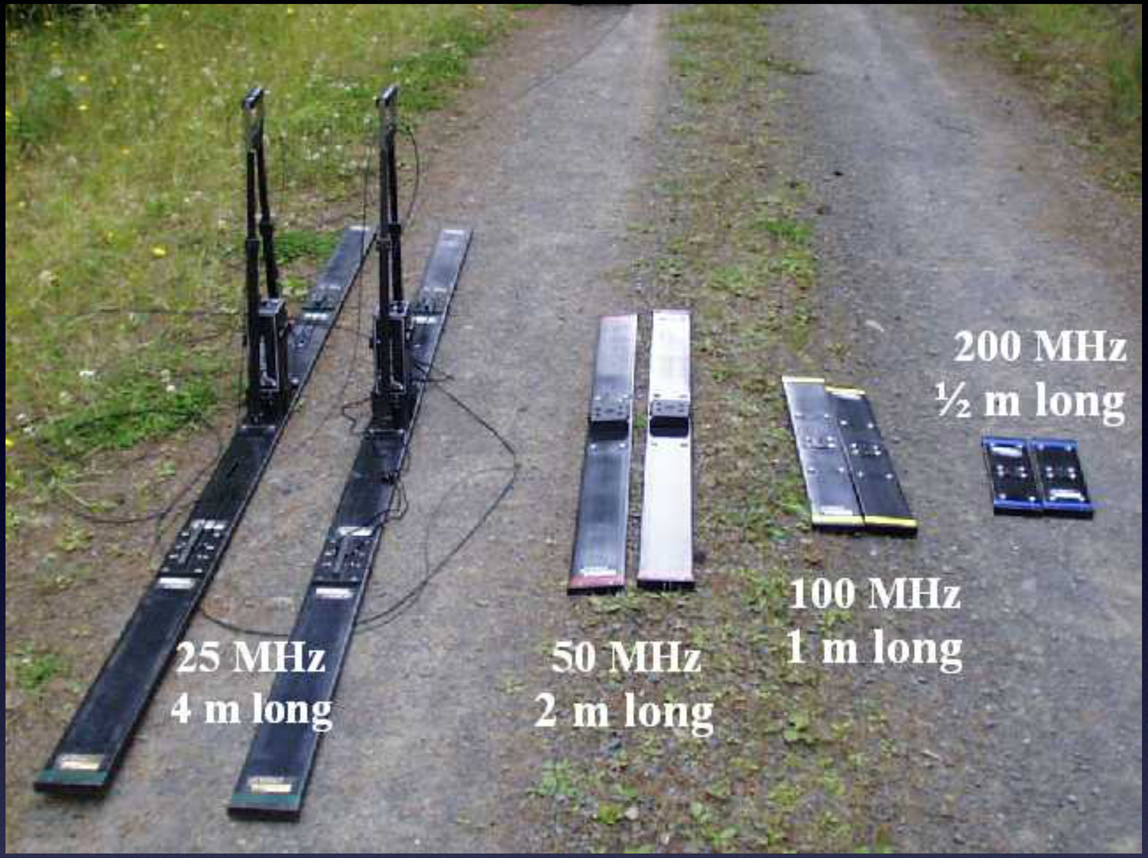

The objects are seen by the radar in a deformed way….

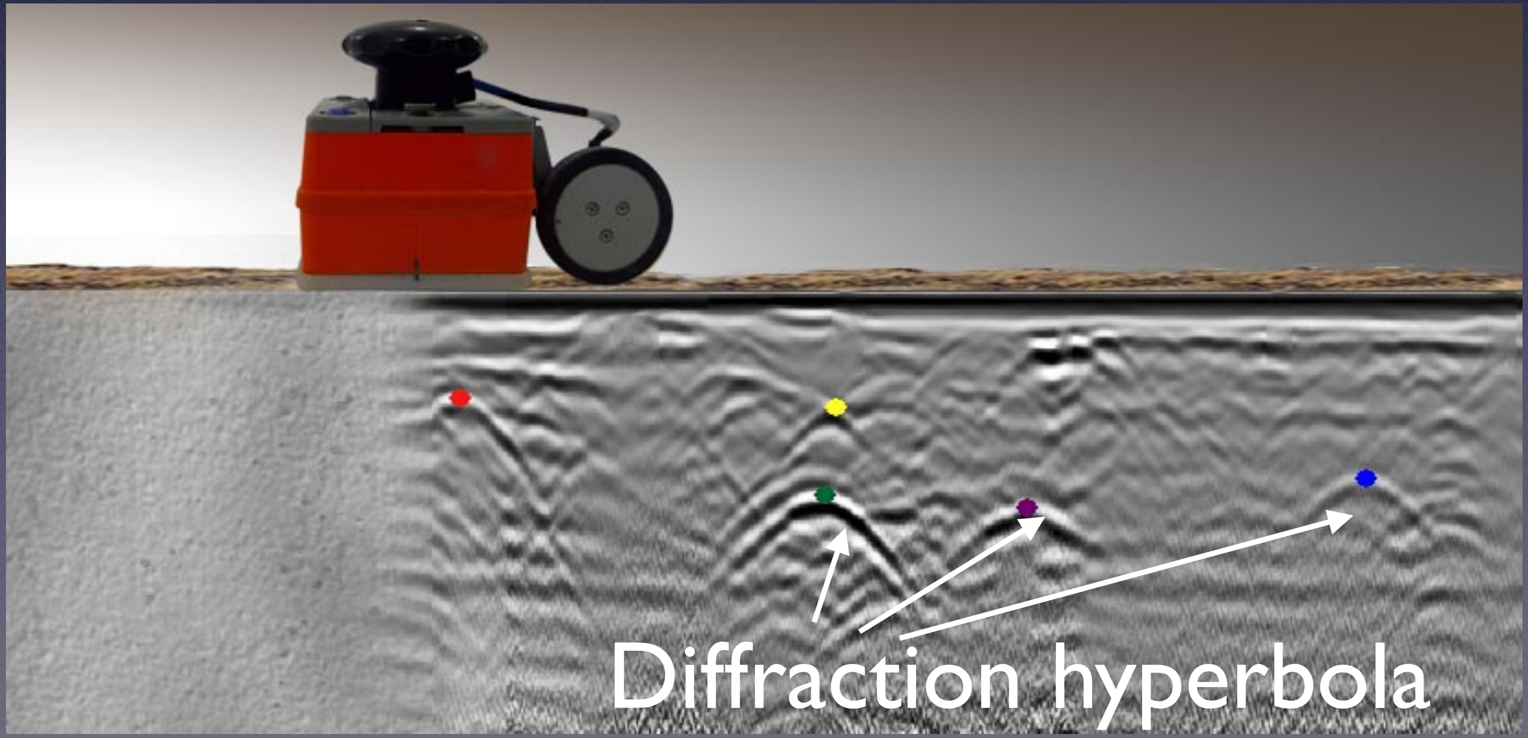


Electro-magnetic methods

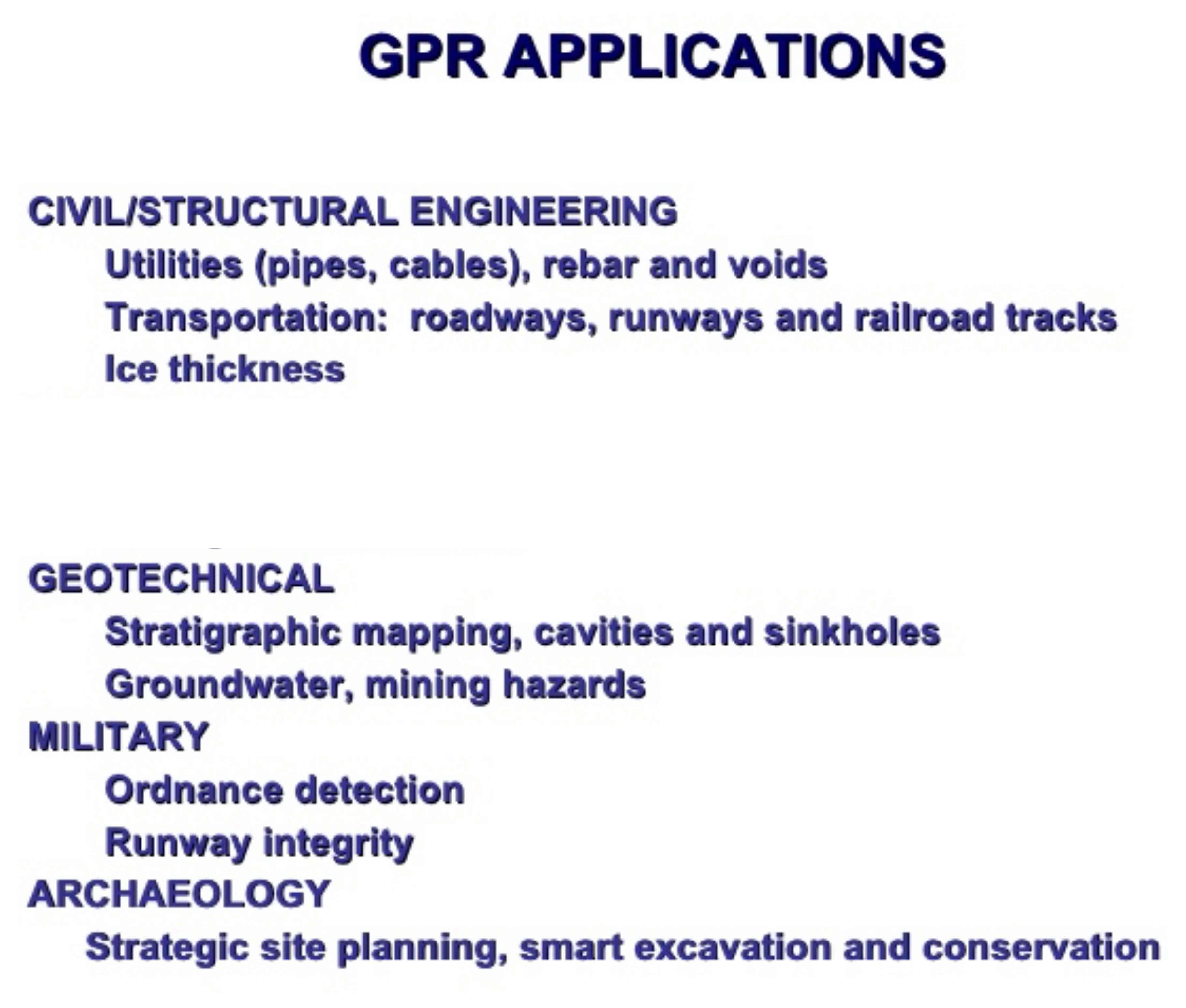
GEORADAR

Several antennas for several targets





Main use:
shallow buried objects detection



GPR APPLICATIONS

CIVIL/STRUCTURAL ENGINEERING

- Utilities (pipes, cables), rebar and voids
- Transportation: roadways, runways and railroad tracks
- Ice thickness

GEOTECHNICAL

- Stratigraphic mapping, cavities and sinkholes
- Groundwater, mining hazards

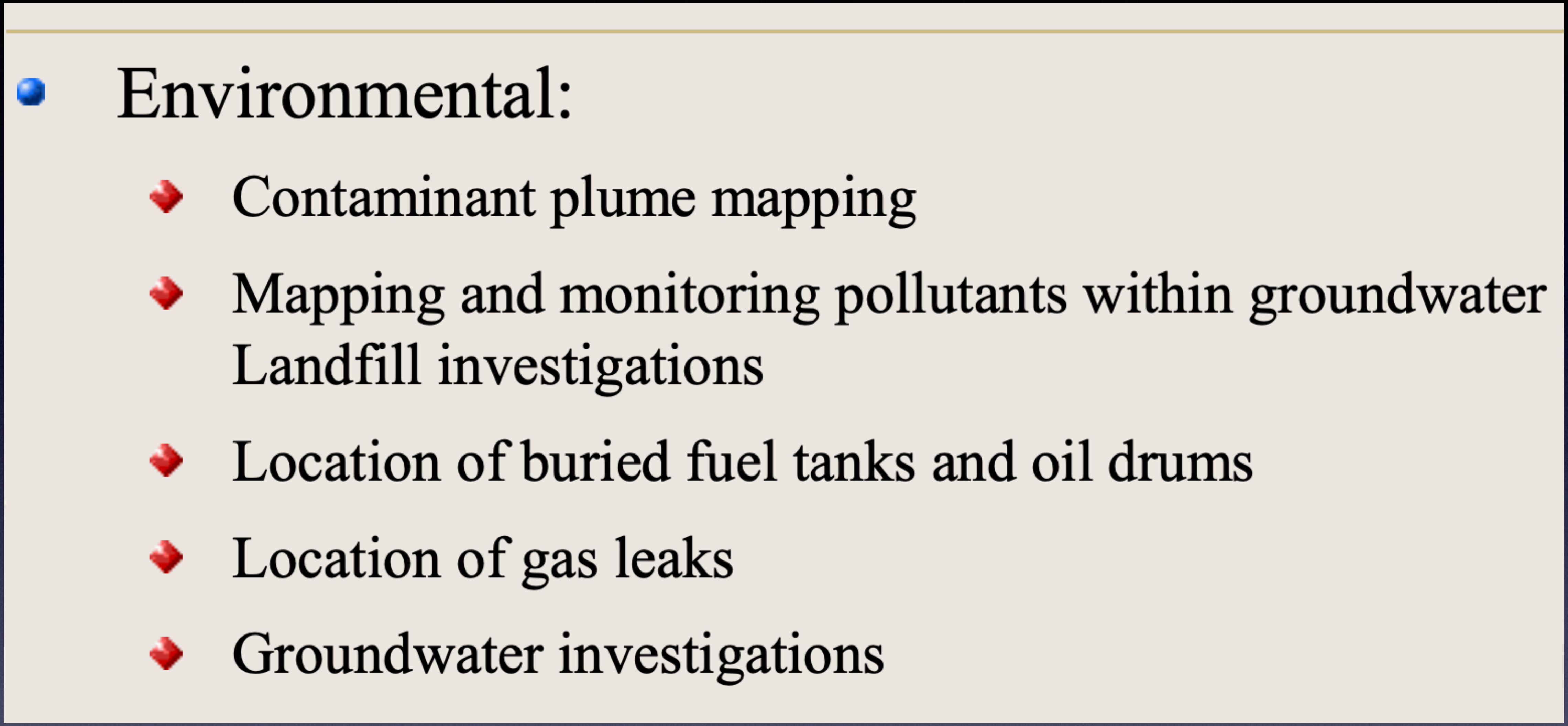
MILITARY

- Ordnance detection
- Runway integrity

ARCHAEOLOGY

- Strategic site planning, smart excavation and conservation

GPR APPLICATIONS



- Environmental:
    - Contaminant plume mapping
    - Mapping and monitoring pollutants within groundwater Landfill investigations
    - Location of buried fuel tanks and oil drums
    - Location of gas leaks
    - Groundwater investigations

Electro-magnetic methods

GEORADAR

Several antennas for several targets

Probes for GPR

MONOSTATIC

(Emitter and receiver in the same probe)

BI- STATIC

(Emitter and receiver separated)

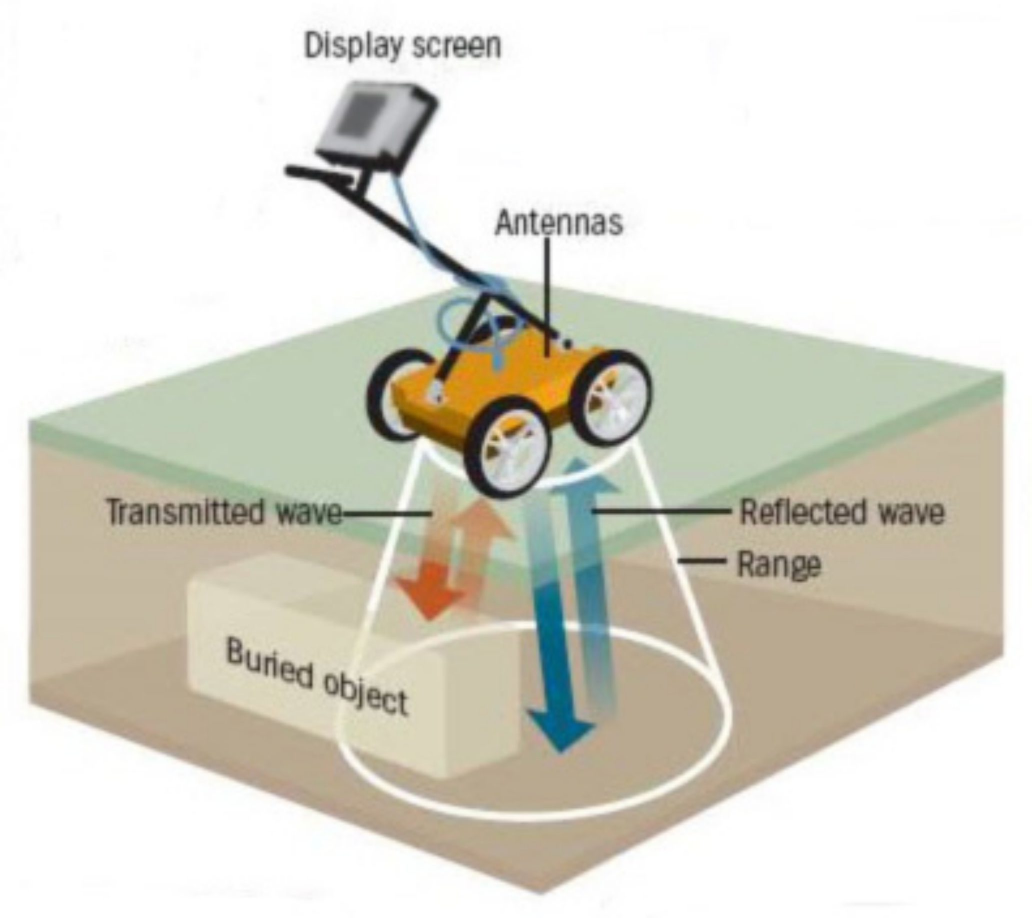
Electro-magnetic methods

GEORADAR

Several antennas for several targets

MONOSTATIC

(Emitter and receiver in the same probe)

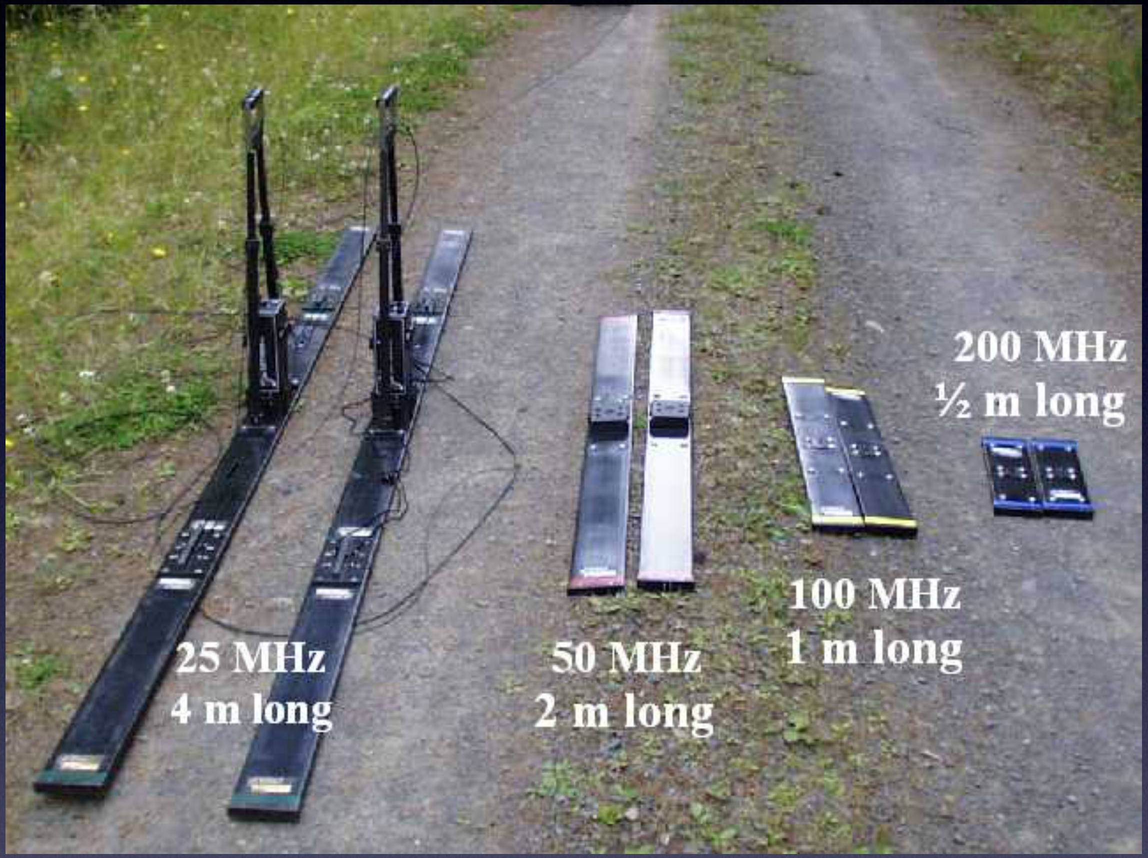


Quick, comfortable, excellent for engineering purposes

Electro-magnetic methods

GEORADAR

Several antennas for several targets



BI- STATIC

(Emitter and receiver separated)

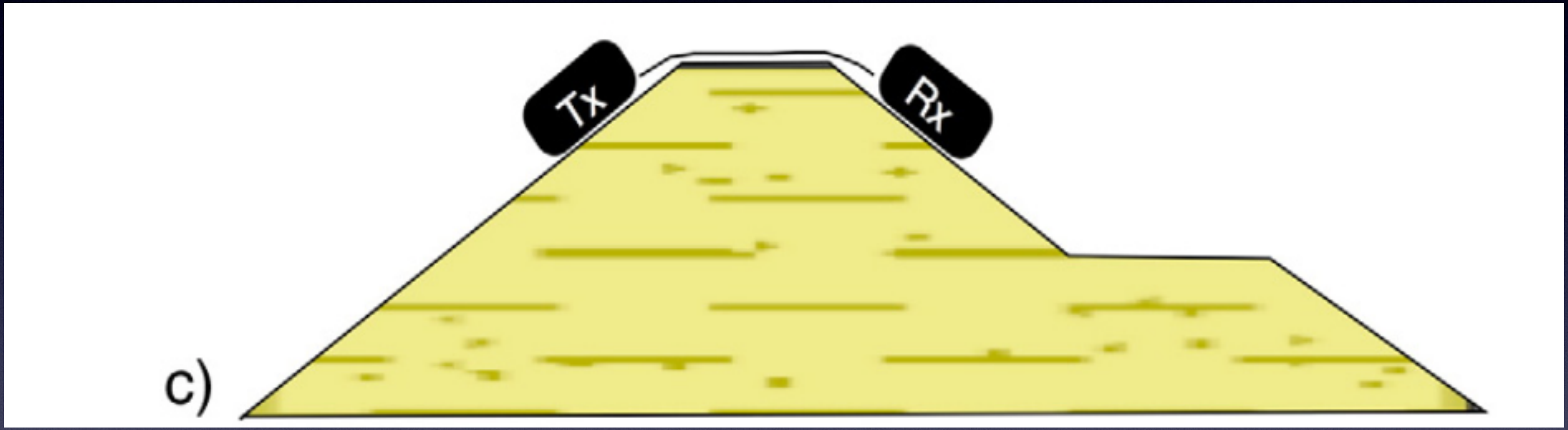
We can

<u>measure the Radar wave transmission velocity</u>

Electro-magnetic methods

GEORADAR

BI- STATIC



‘Transparence method’

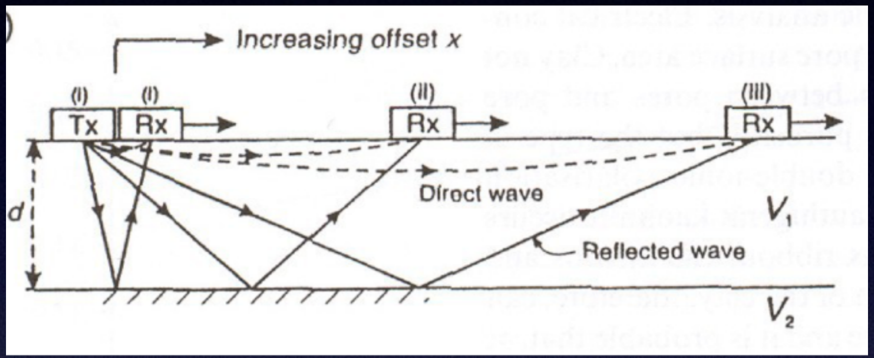
GEORADAR

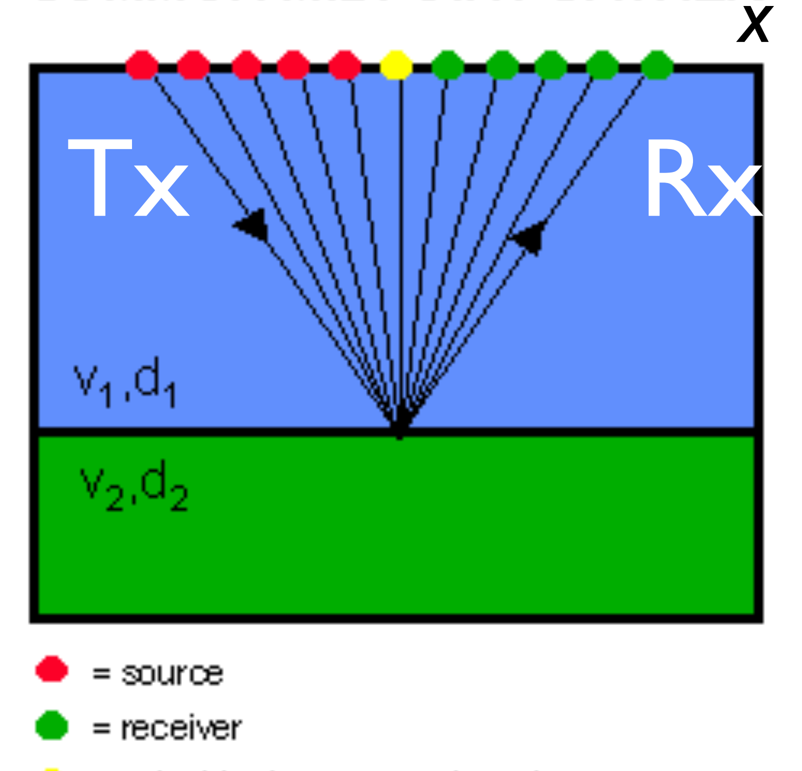
BI- STATIC

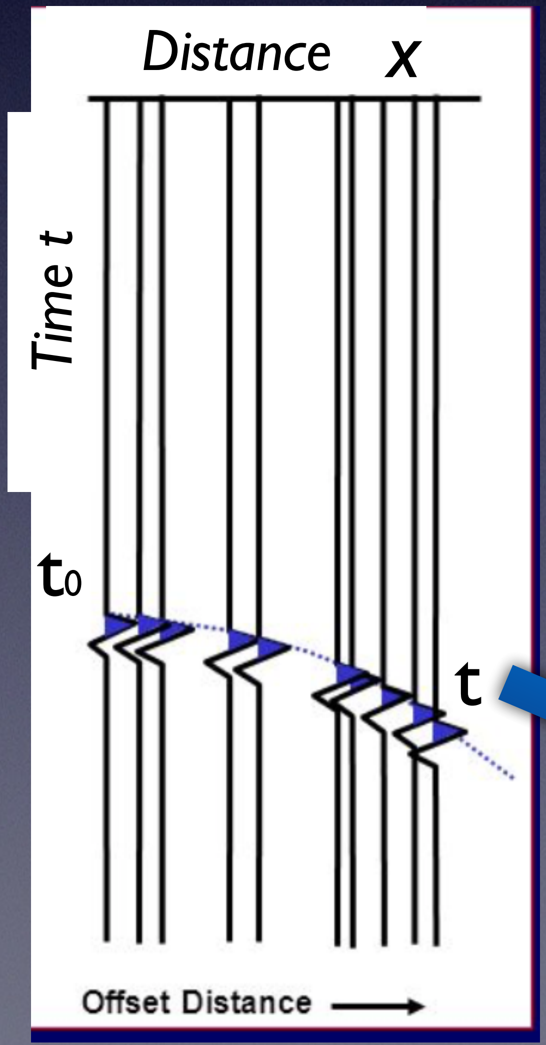
(Emitter and receiver separated)

<u>measure the Radar wave transmission velocity</u>

Es. Method COMMON MID POINT (CMP)







$$v = \frac{c}{\sqrt{\varepsilon_r}}$$

$$T^2_x = T^2_0 + X^2 / V^2$$

GEORADAR

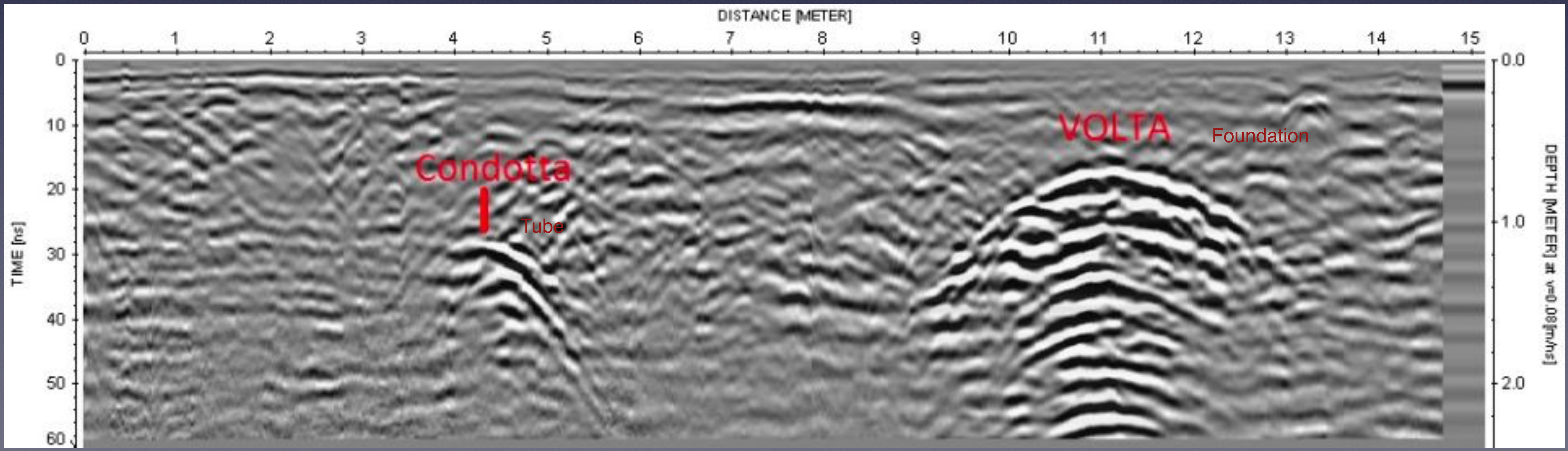
$$v = \frac{c}{\sqrt{\varepsilon_r}}$$

Info about material

Info about moisture content

Form time-RADARGRAM
To depth RADARGRAM (MIGRATION)

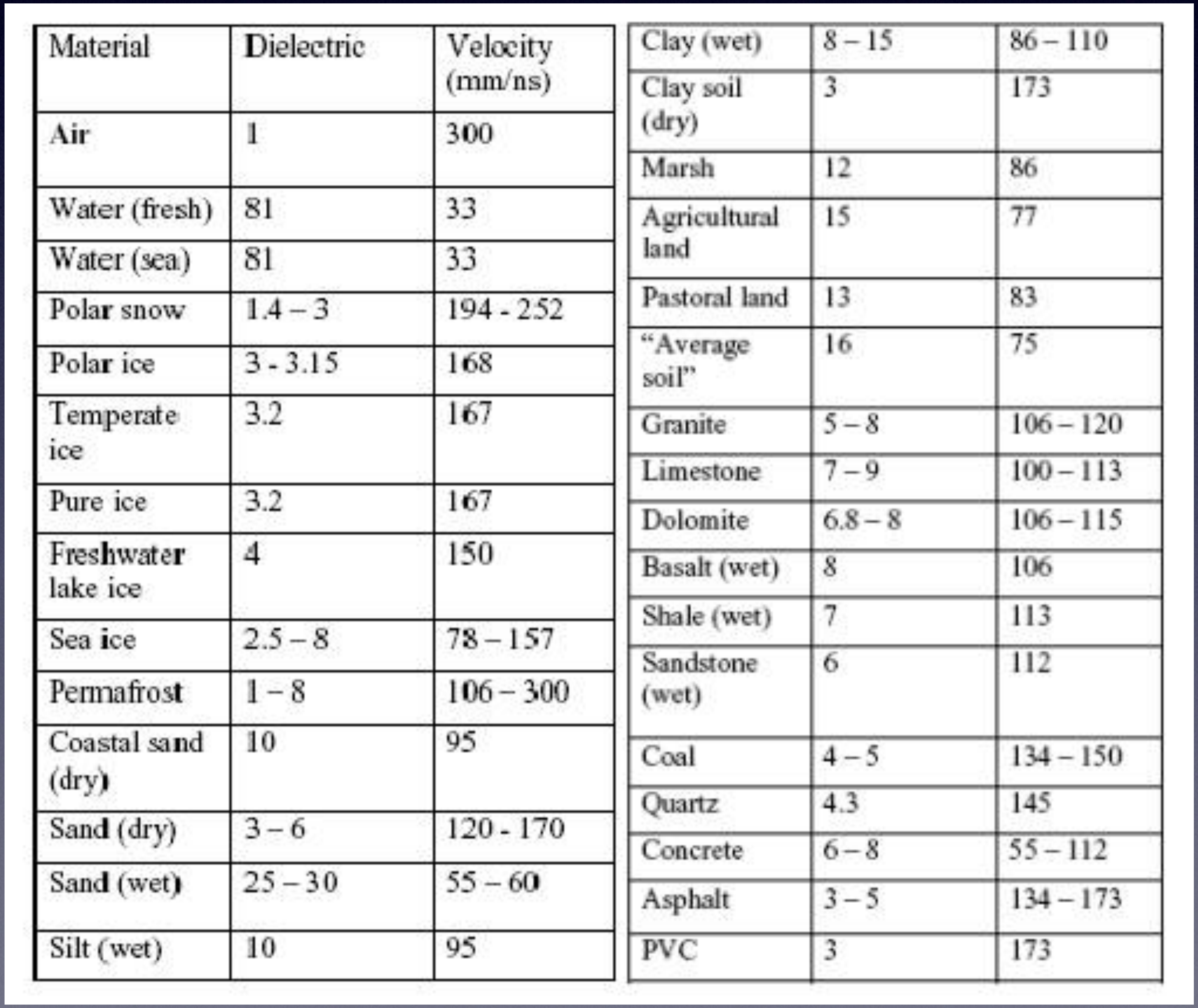
$v = dx/dt$



GEORADAR

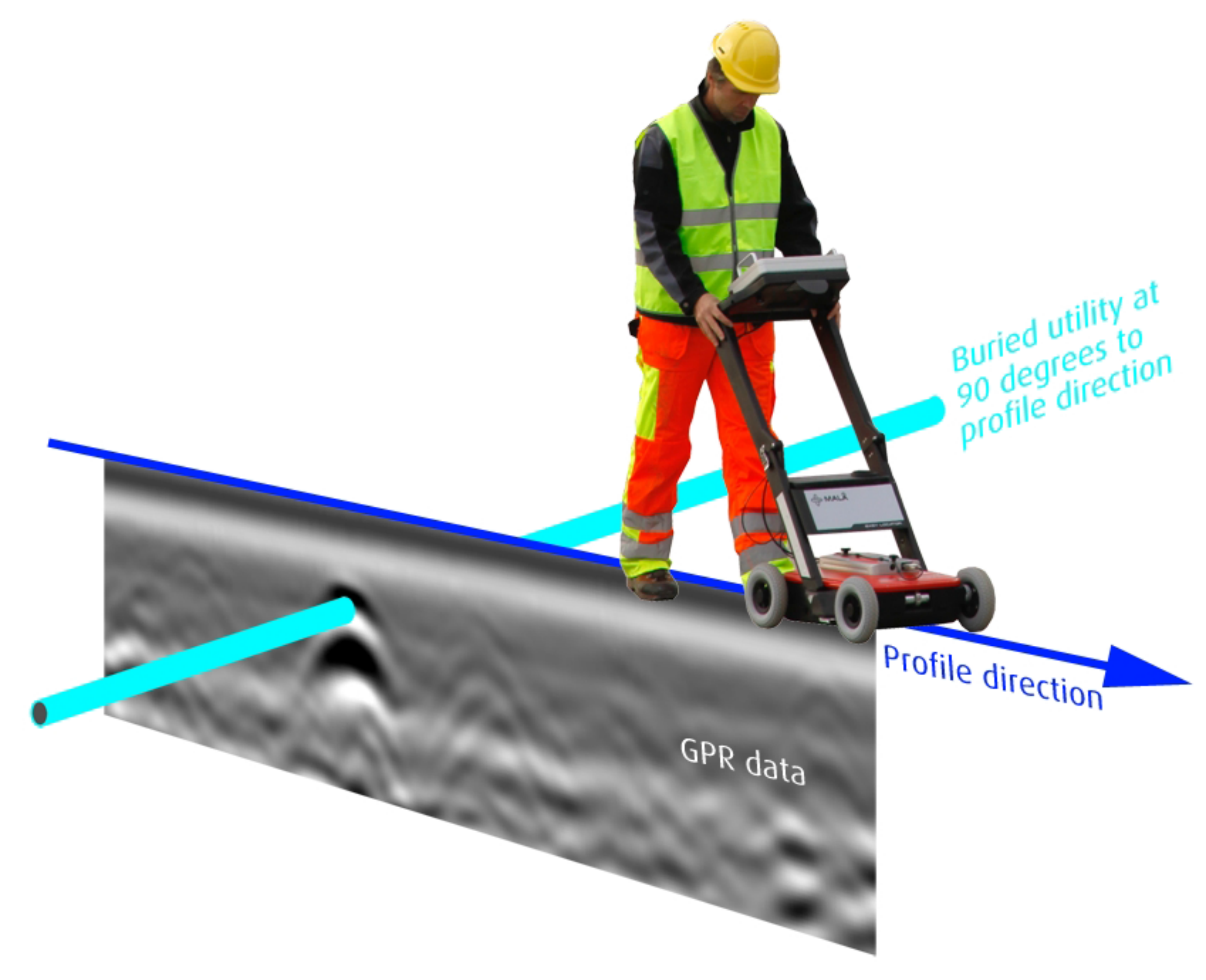
Form time-RADARGRAM
To depth RADARGRAM (MIGRATION)

Otherwise use vel. From tab values



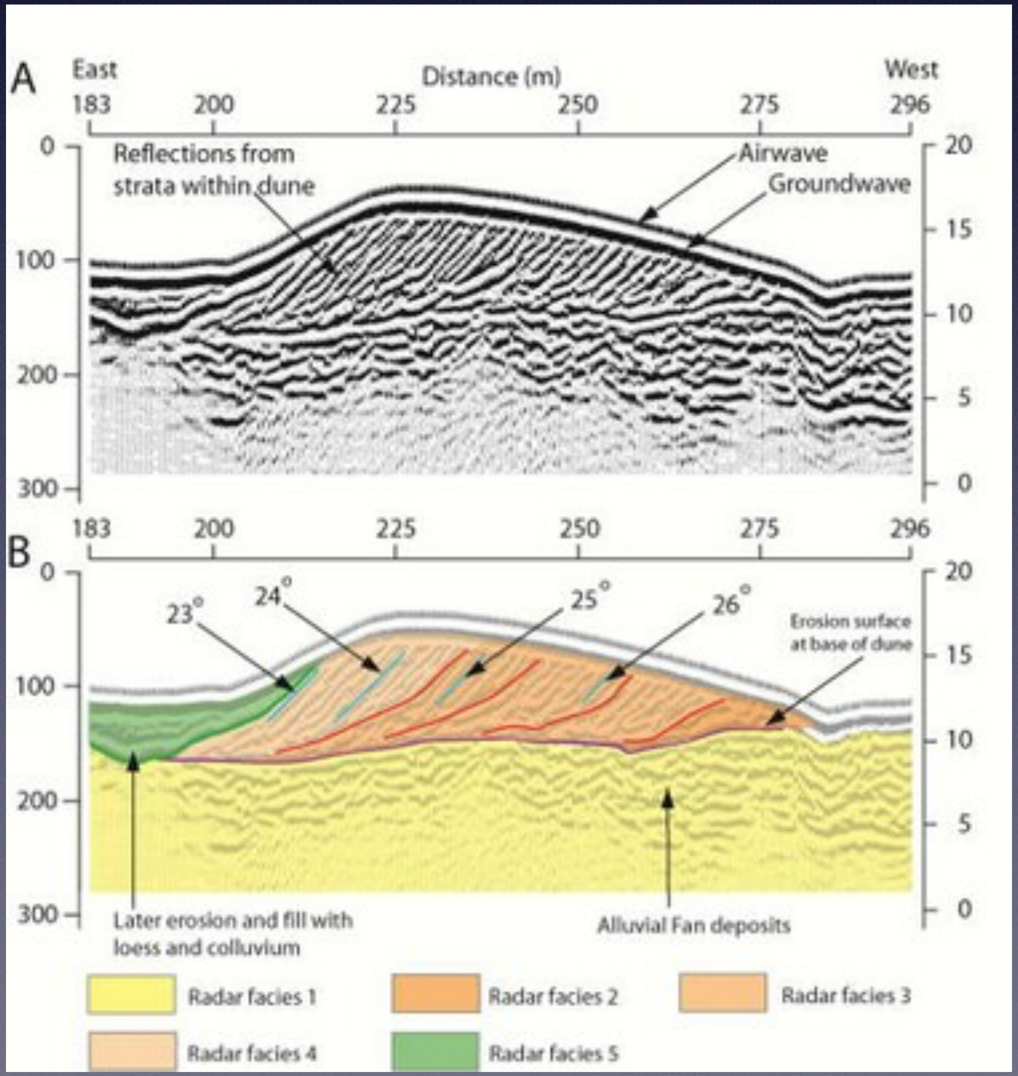
Material	Dielectric	Velocity (mm/ns)
Air	1	300
Water (fresh)	81	33
Water (sea)	81	33
Polar snow	1.4 – 3	194 - 252
Polar ice	3 - 3.15	168
Temperate ice	3.2	167
Pure ice	3.2	167
Freshwater lake ice	4	150
Sea ice	2.5 – 8	78 – 157
Permafrost	1 – 8	106 – 300
Coastal sand (dry)	10	95
Sand (dry)	3 – 6	120 - 170
Sand (wet)	25 – 30	55 – 60
Silt (wet)	10	95
Clay (wet)	8 – 15	86 – 110
Clay soil (dry)	3	173
Marsh	12	86
Agricultural land	15	77
Pastoral land	13	83
"Average soil"	16	75
Granite	5 – 8	106 – 120
Limestone	7 – 9	100 – 113
Dolomite	6.8 – 8	106 – 115
Basalt (wet)	8	106
Shale (wet)	7	113
Sandstone (wet)	6	112
Coal	4 – 5	134 – 150
Quartz	4.3	145
Concrete	6 – 8	55 – 112
Asphalt	3 – 5	134 – 173
PVC	3	173

GEORADAR

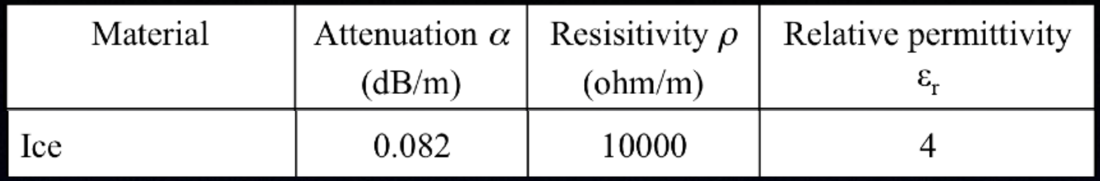


Looking for buried tunnel, tanks, etc.

Geological study



GEORADAR glaciers study

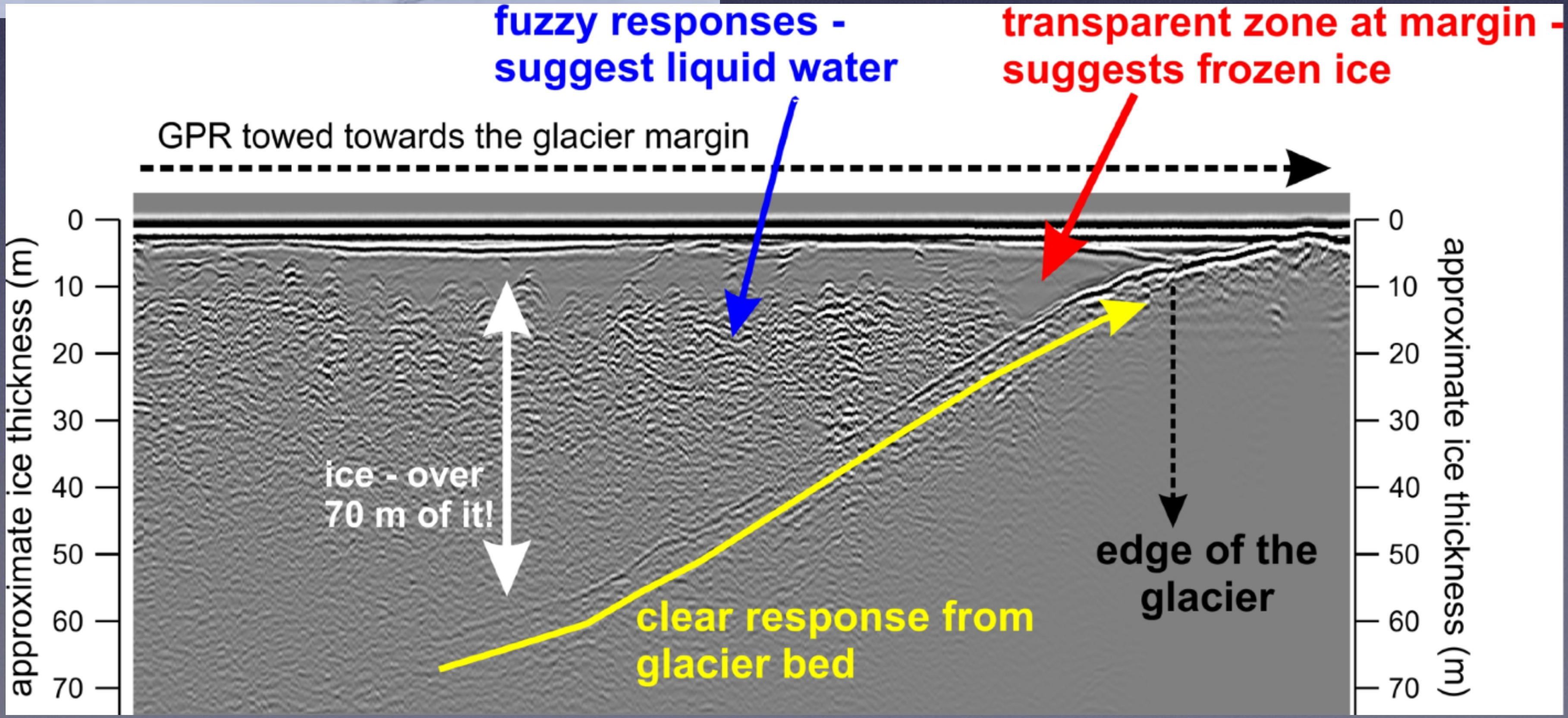


Material	Attenuation α (dB/m)	Resisitivity ρ (ohm/m)	Relative permittivity ε_r
Ice	0.082	10000	4

Ice is very resistive

<< Attenuation

>> Penetration



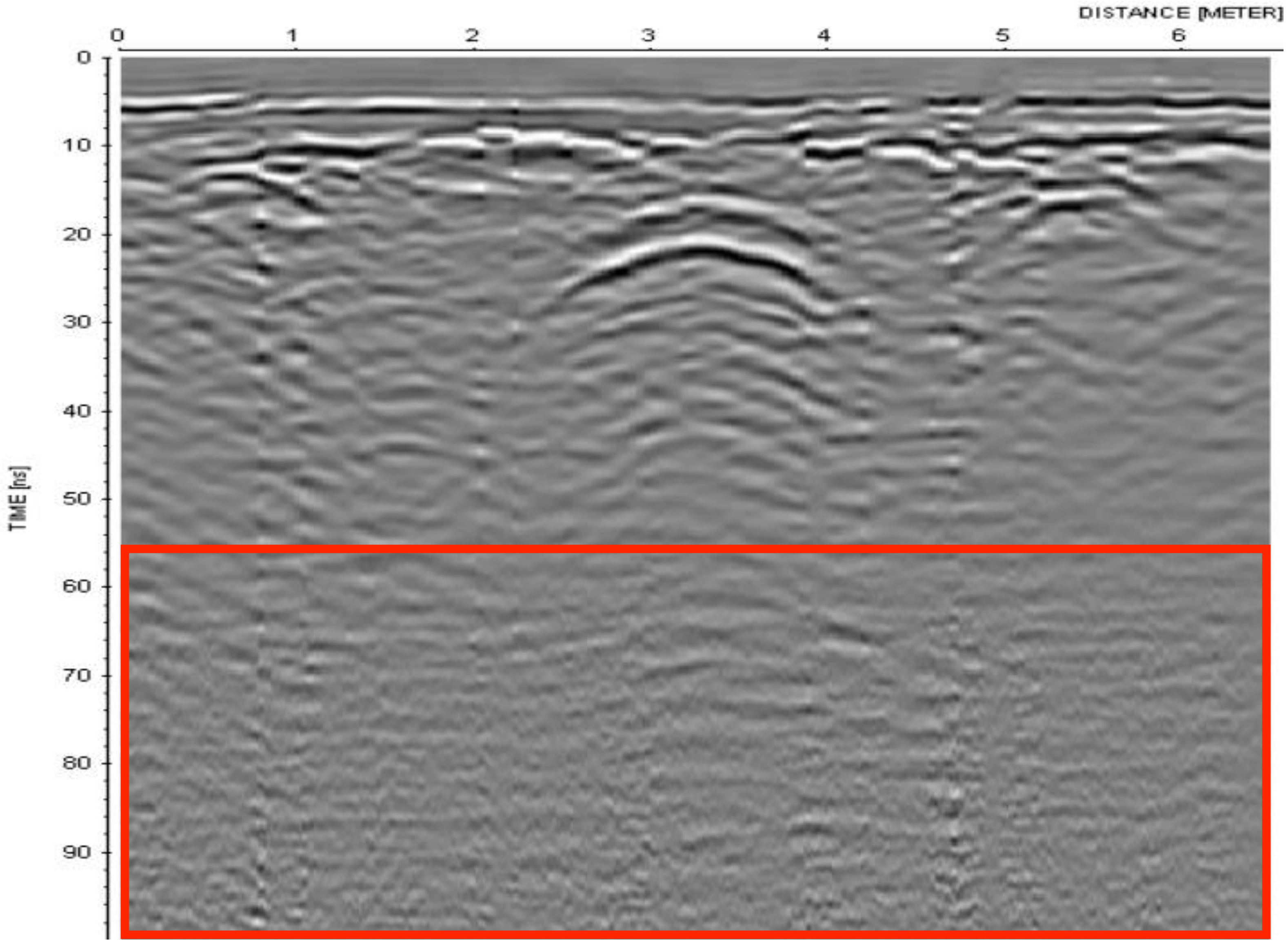
GEORADAR for road pavements

GEORADAR in tunnel

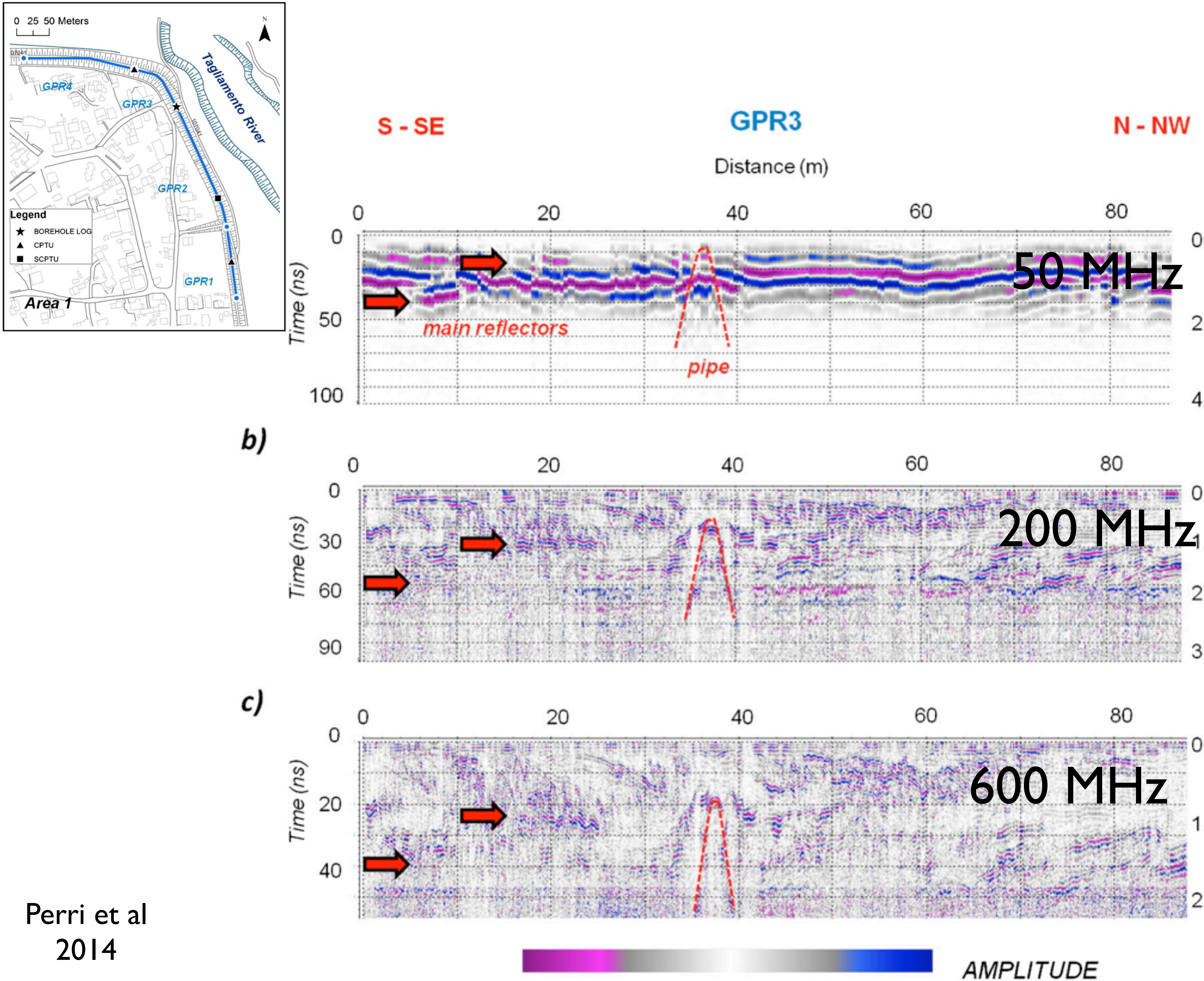
INVESTIGATION DEPTH

ρ = 10 Ωm ε=20 v=0.07m/ns α=38 dB/m
ρ = 200 Ωm ε=5 v=0.13m/ns α=0.38 dB/m

100dB system: respectively 2.6m and 26 m
respectively 40ns and 200ns



Dependence on the frequency

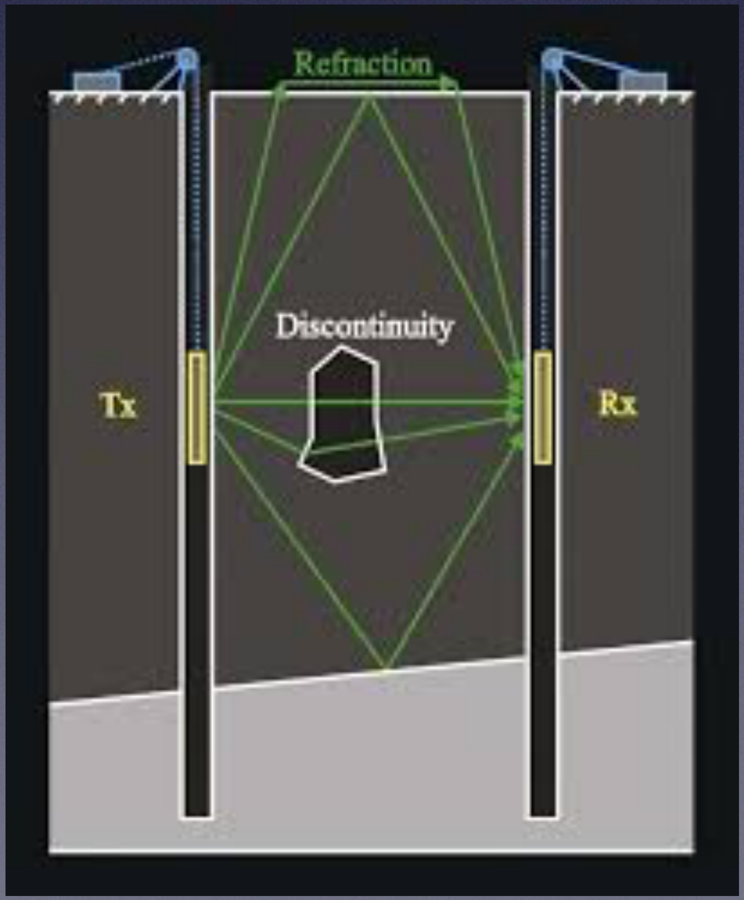


Perri et al
2014

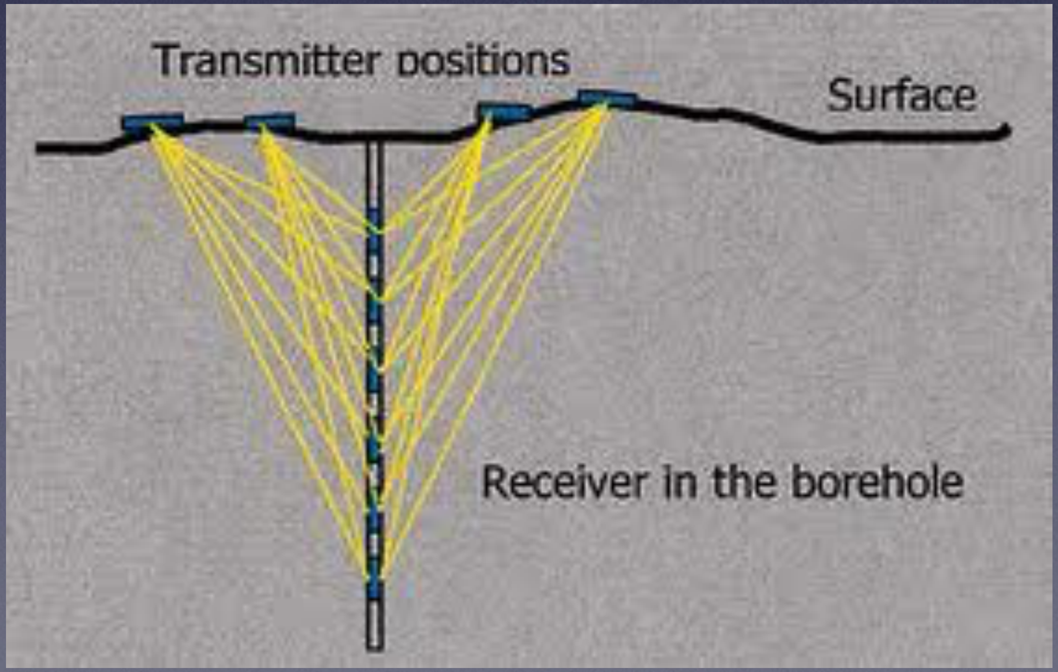
GEORADAR In pozzo

BOREHOLE GPR

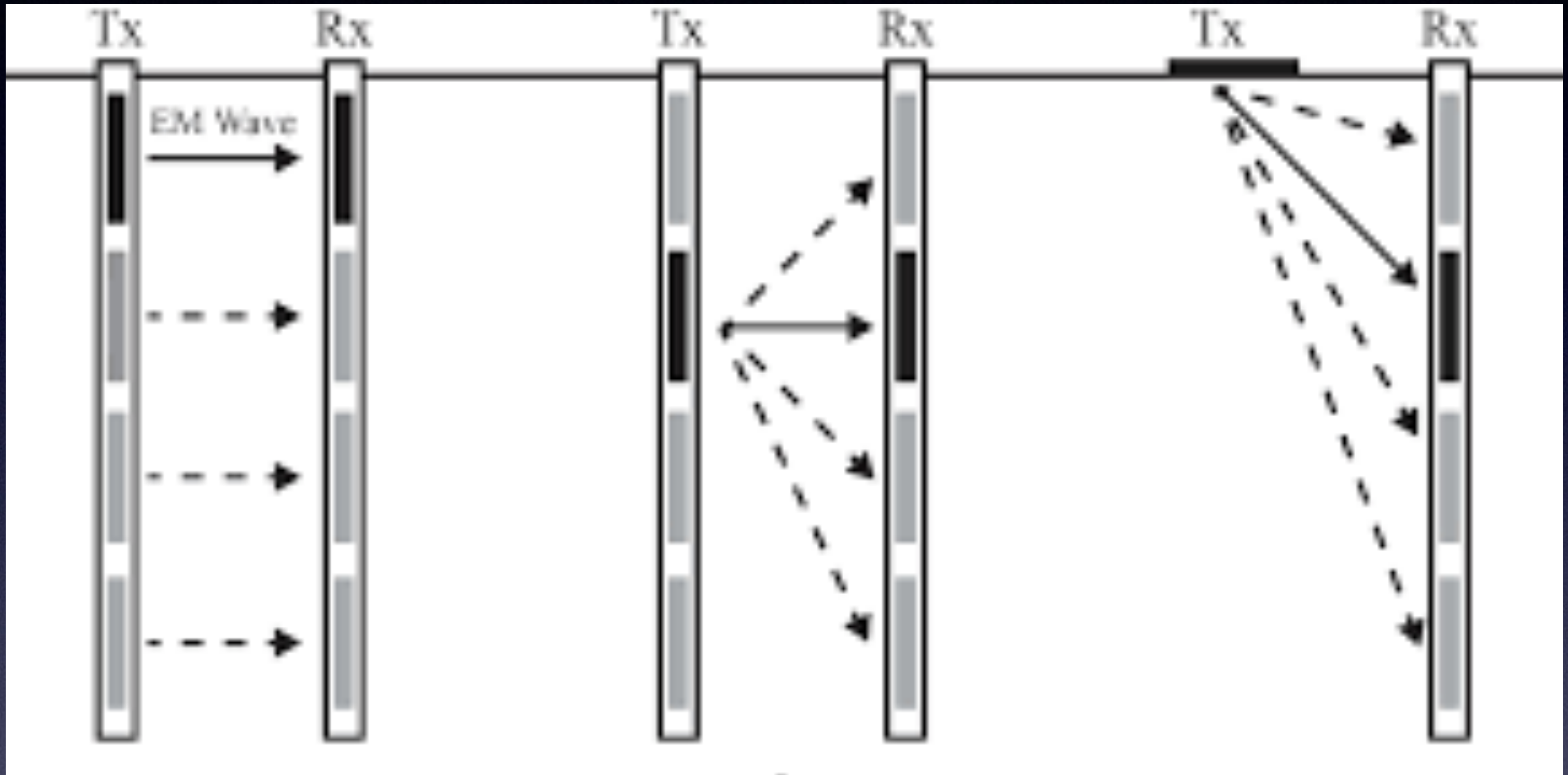
Cross Borehole



Single Borehole



BOREHOLE GEORADAR



Zero Offset Profile ZOP

Multiple Offset Gather MOG

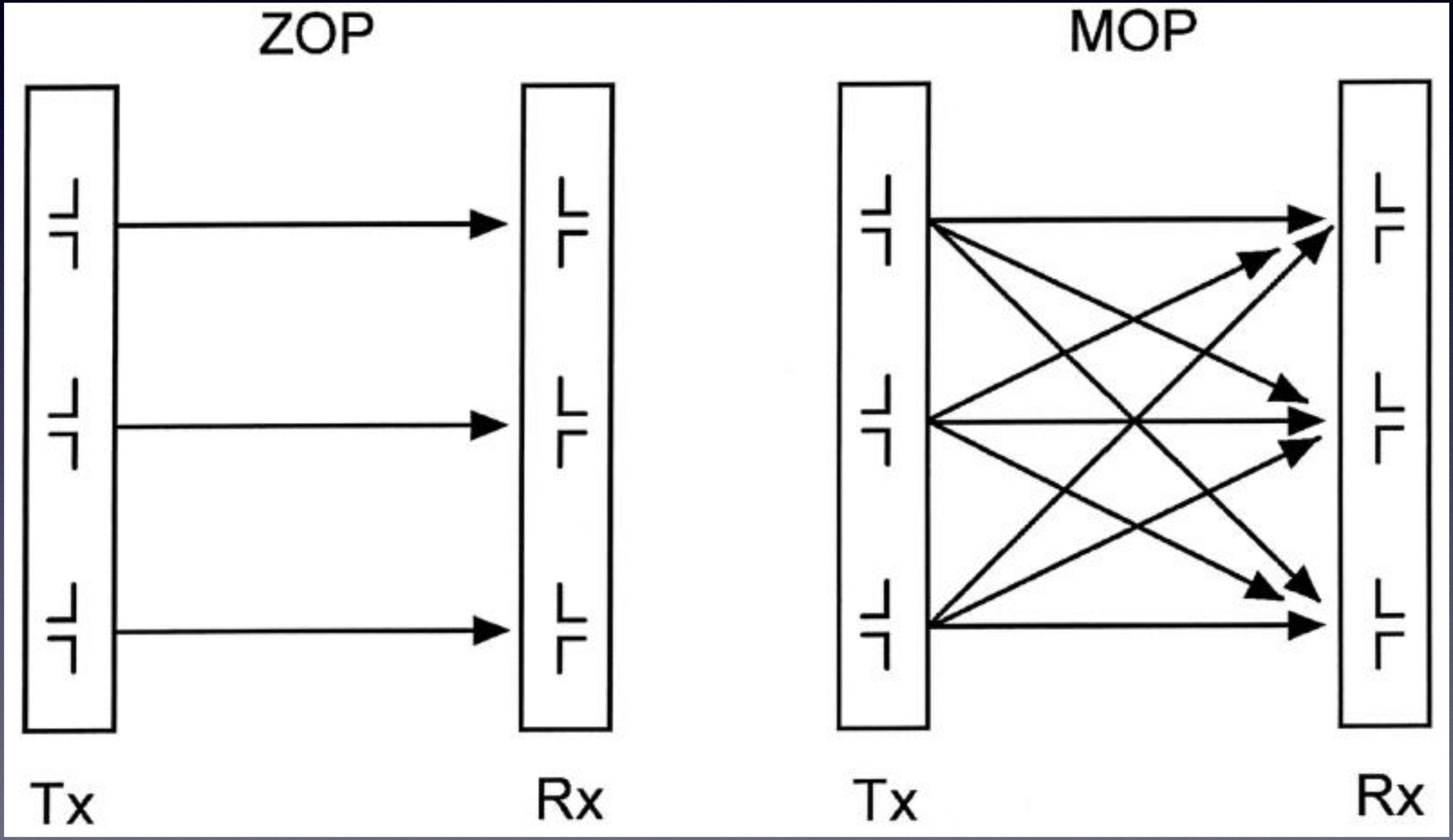
Vertical Radar Profile VRP

Different Configurations

BOREHOLE GEORADAR

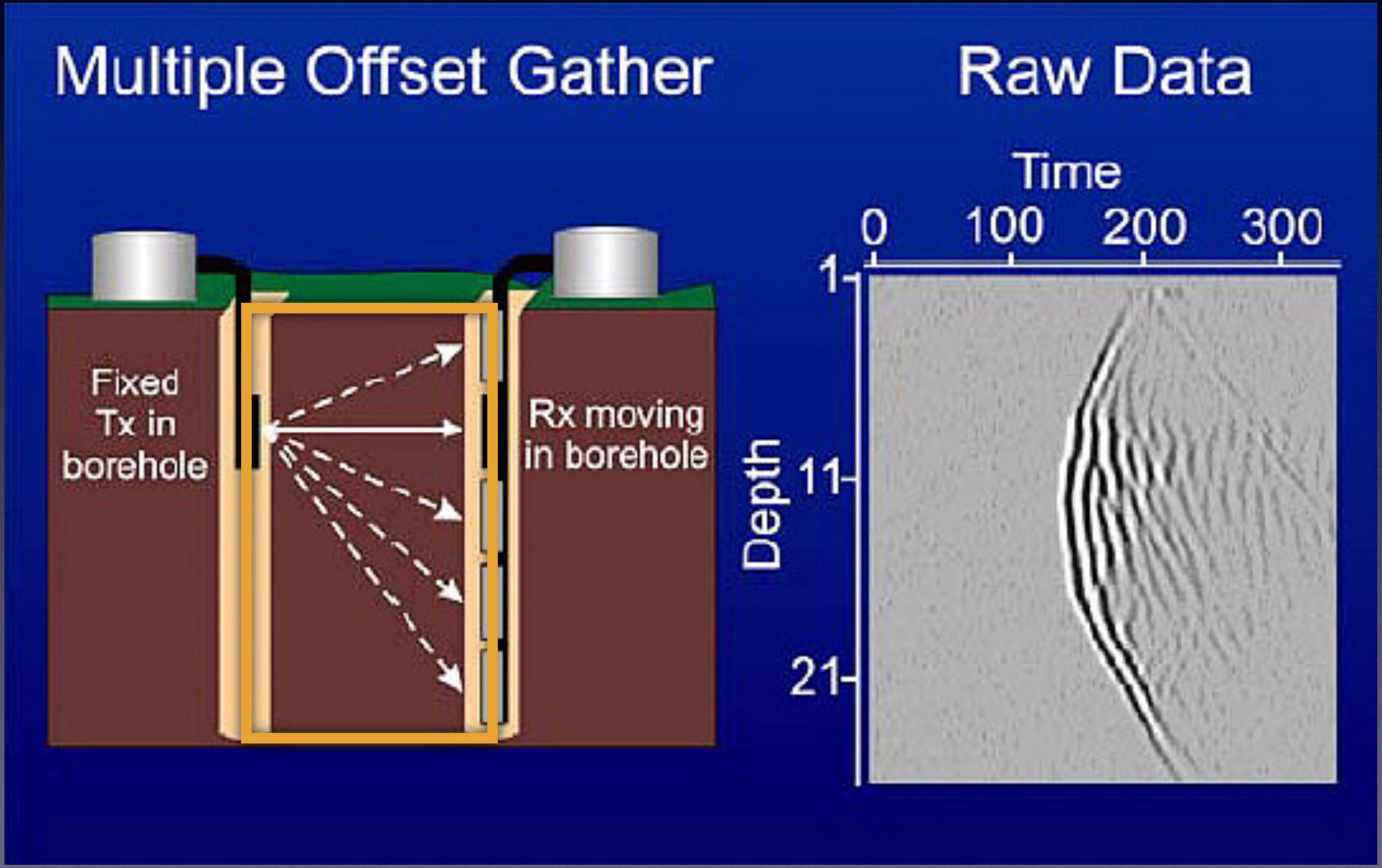
ZERO OFFSET PROFILE

MULTI OFFSET PROFILE



BOREHOLE GEORADAR

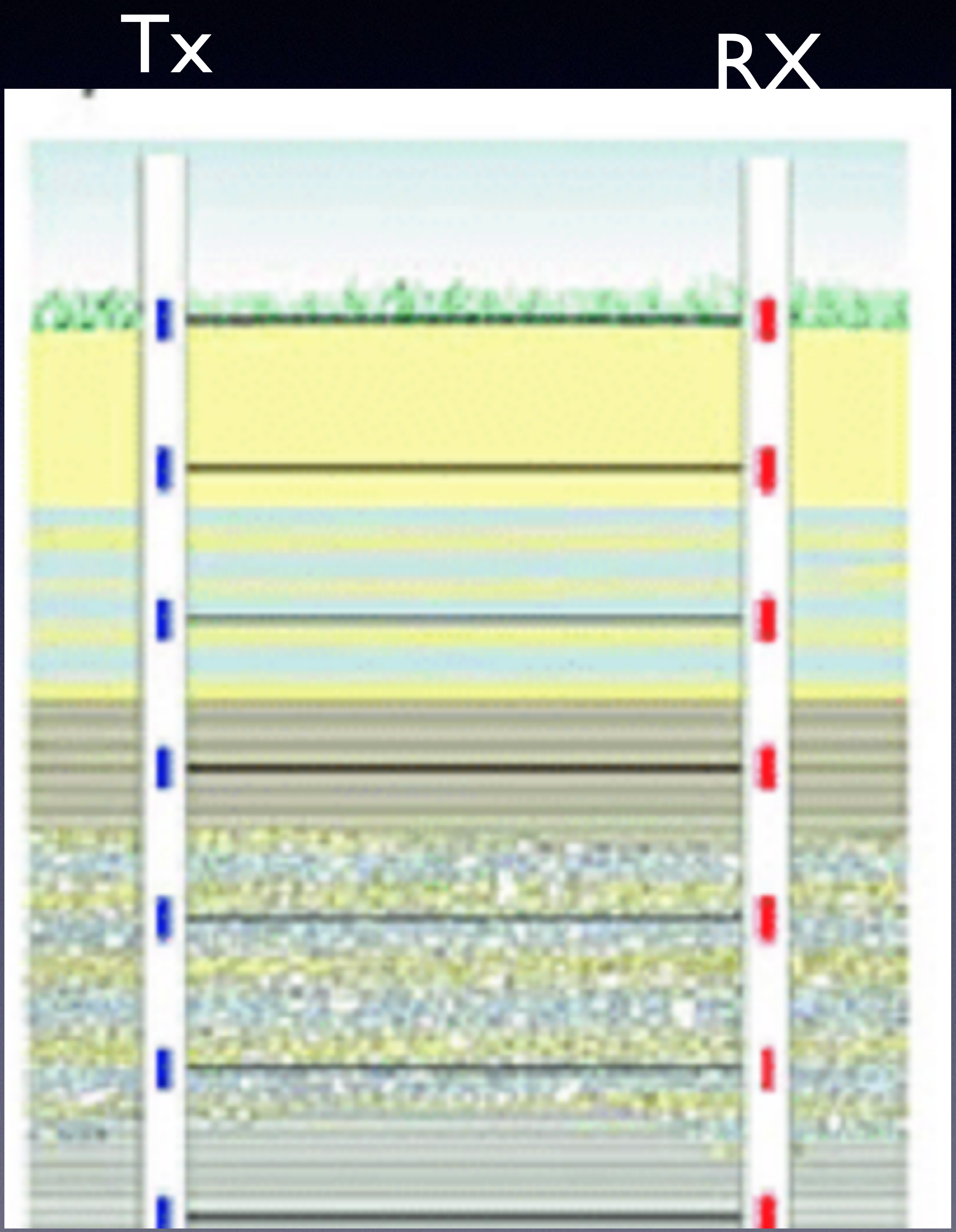
MULTI OFFSET PROFILE



BEST
Resolution
Method
Between
The 2 boreholes

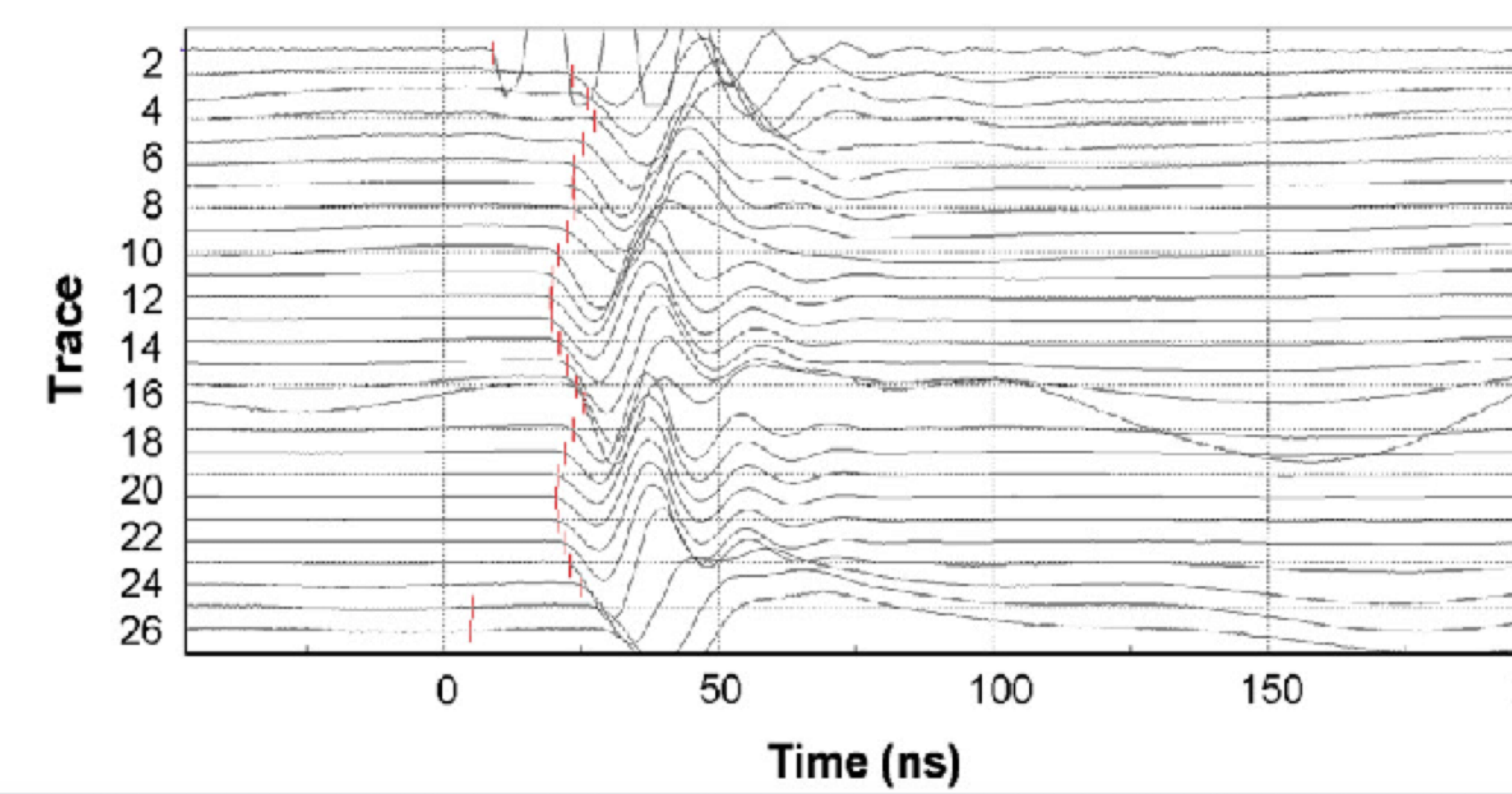
BOREHOLE GEORADAR

Zero Offset Profile



x (m)

Picking of radar wave first arrivals

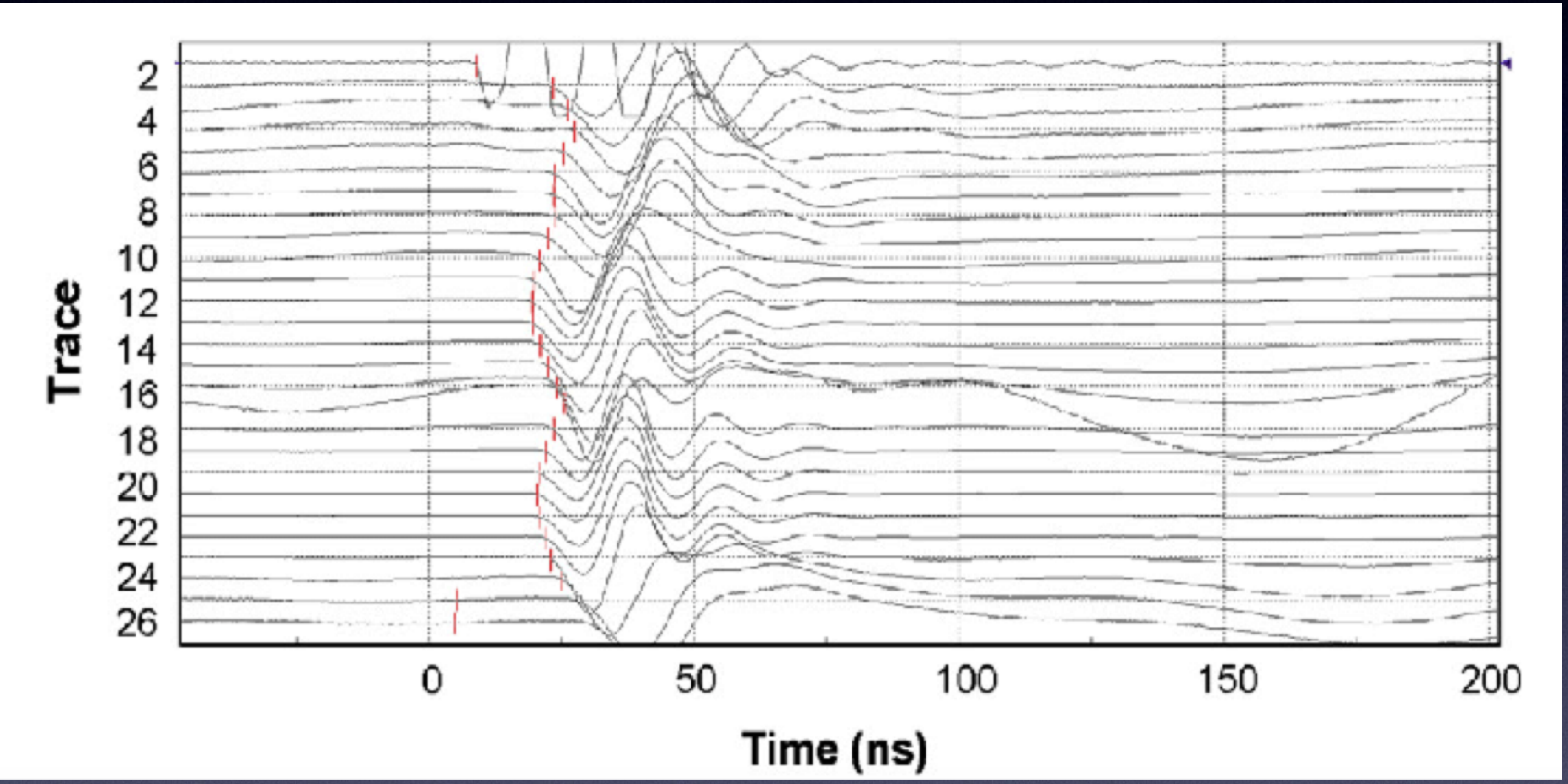


velocity of propagation

Electro-magnetic methods

GEORADAR

Picking of radar wave
first arrivals



velocity of propagation

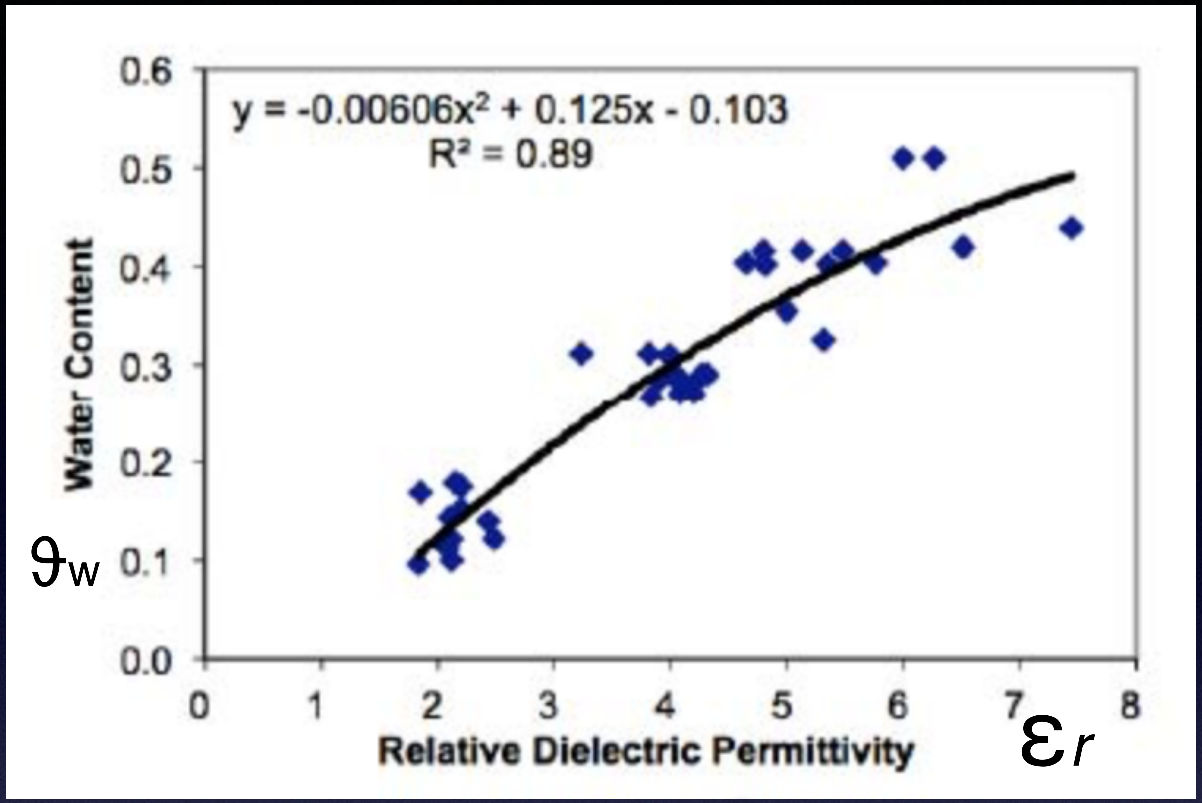
For Environmental
Applications

GPR can be used
To assess
Dielectric changes
(Velocity changes)

WATER CONTENT

Electro-magnetic methods

ε_r =f (saturation)



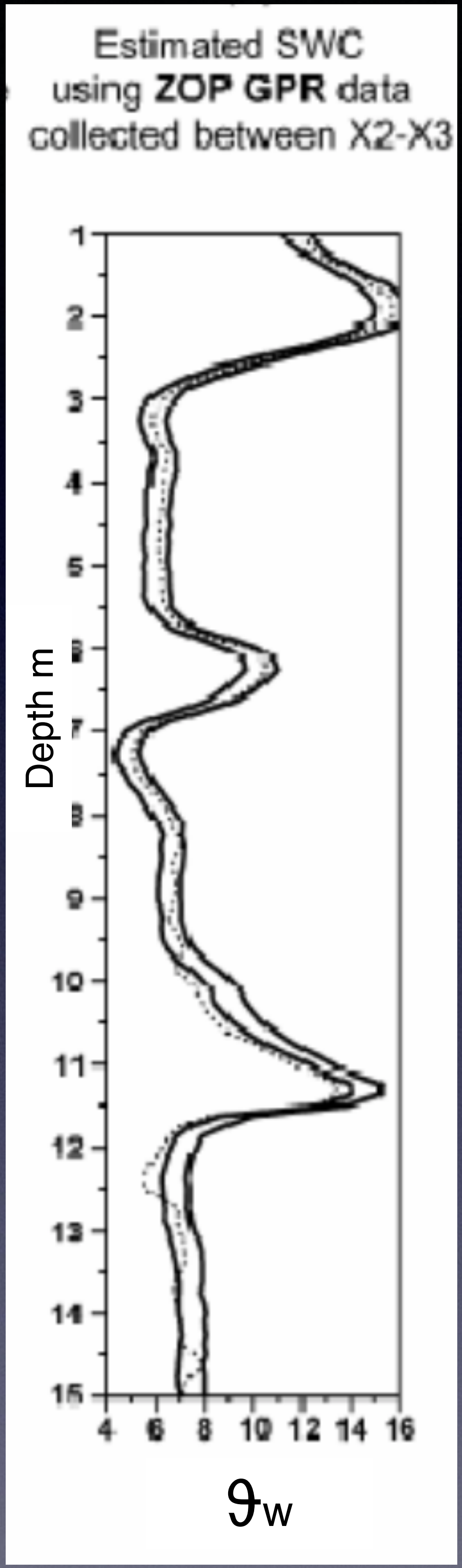
$$v = \frac{c}{\sqrt{\varepsilon_r}}$$

Velocity of Radar wave

$\neq v$ → $\neq$ water content →

$$\theta_w = V_w / V_{total} \; ; \quad \theta_w = \varphi . S_w$$

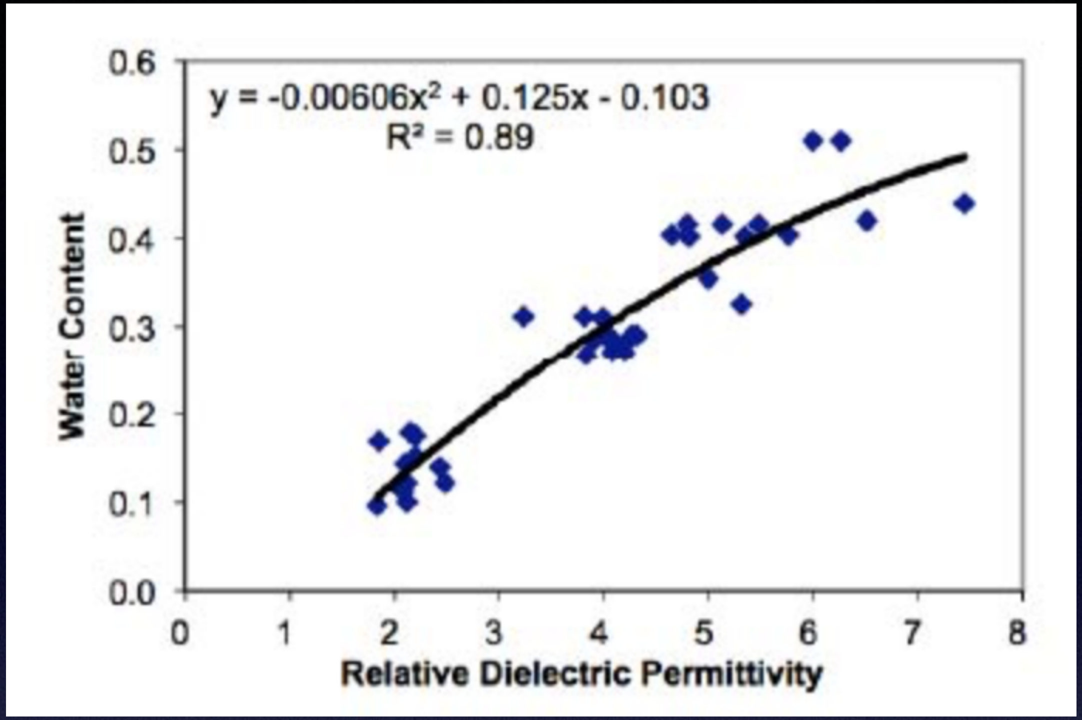
Water Content *Vol. water/Vol. tot* *Porosity * Saturation*



Water content estimated via borehole GPR

Electro-magnetic methods

εr =f (saturation)



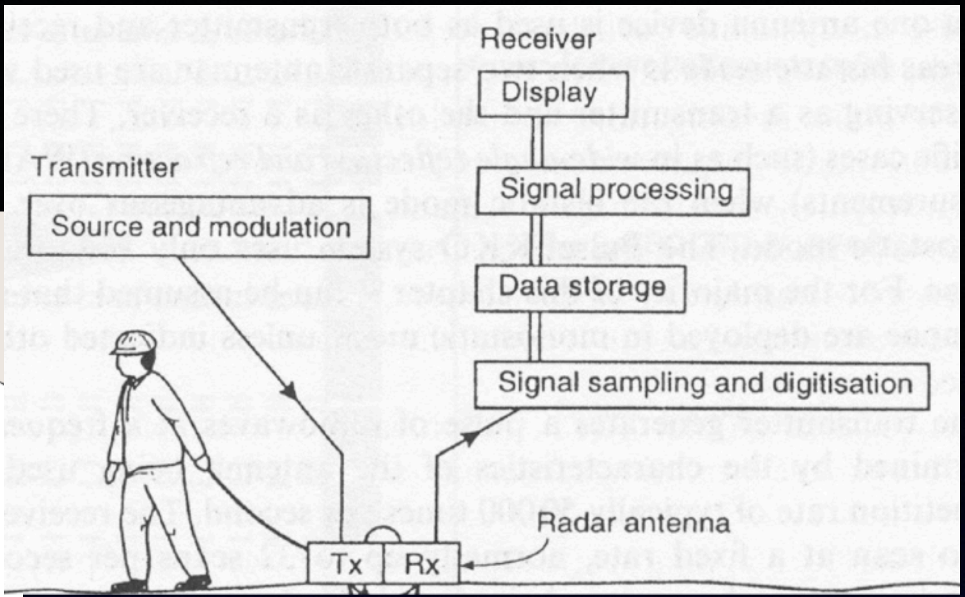
Theta from Topp (1980)

$$\vartheta = 0,\ 053\varepsilon + 0,\ 0292\varepsilon^{2}\ 0,\ 00055\varepsilon^{3} + 0,\ 0000043\varepsilon^{3}$$

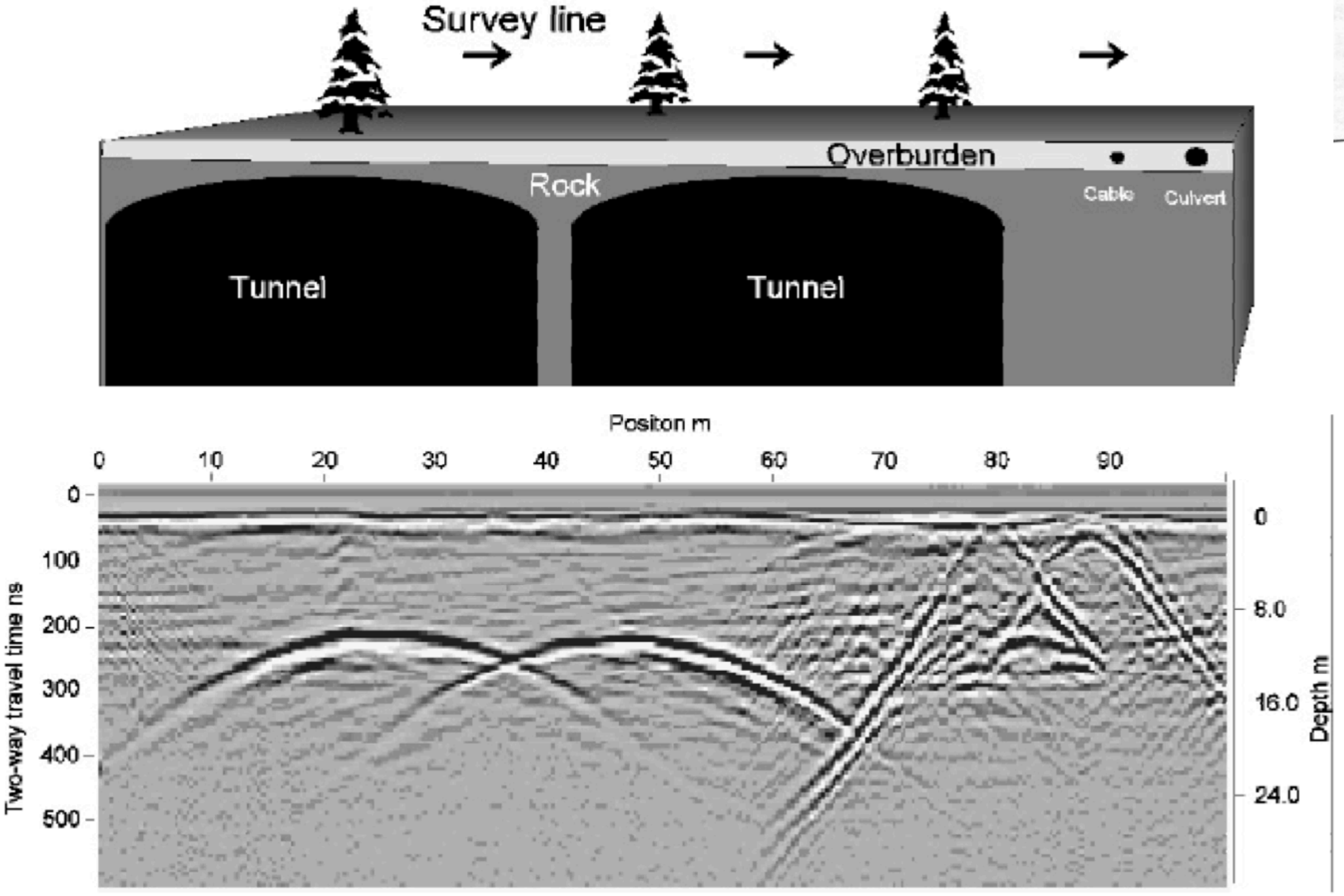
Water Content *Dielectric const.*

We can estimante water changes
and different liquid phases with GPR

GPR case histories



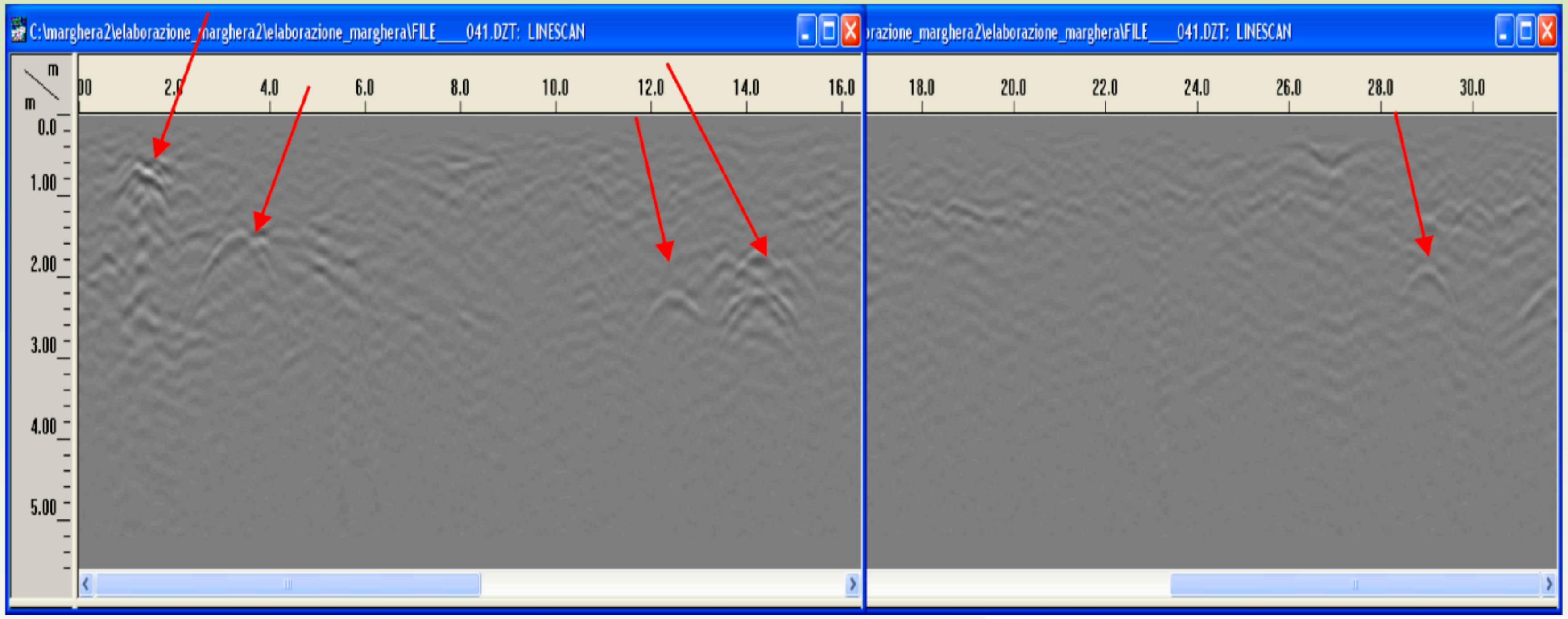
- Detecting tunnels (Sweden)



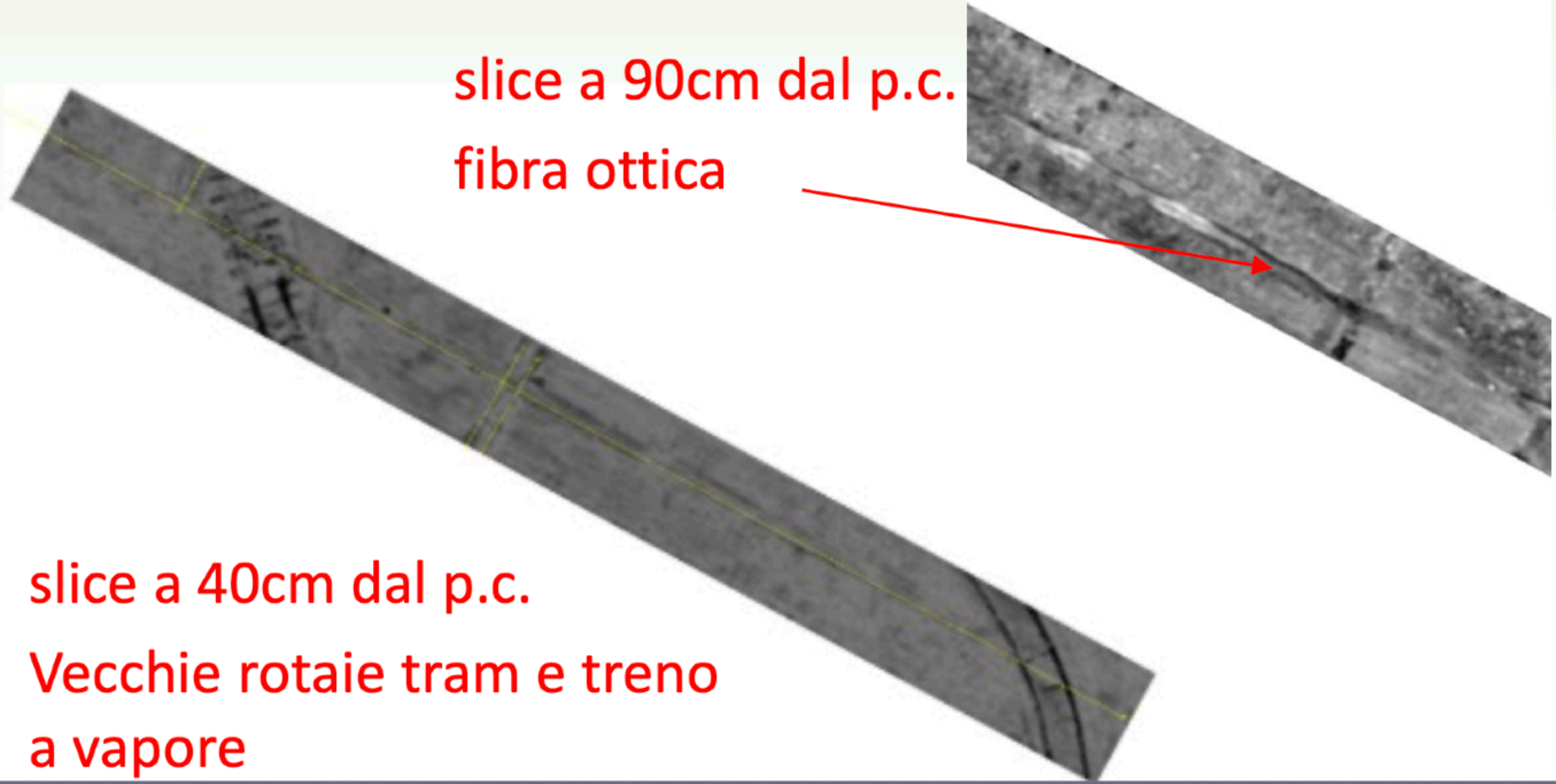
- **50-Mhz GPR locates two tunnels at 11 meters depth**
- **GPR locates a cable and culvert**
- **GPR defines overburden thickness**

Es. ricerca sottoservizi in area industriale

2D



3D



slice a 90cm dal p.c.

fibra ottica

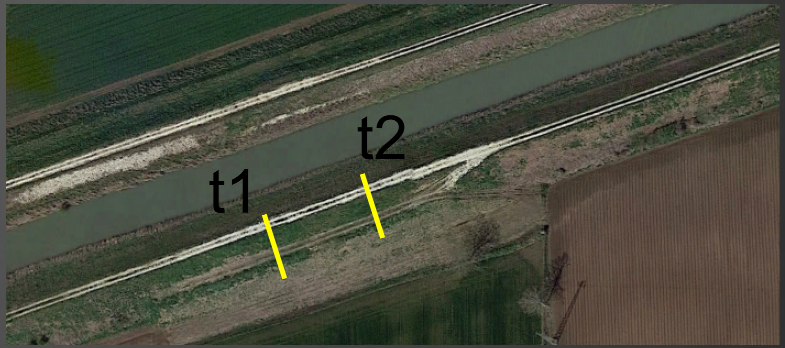
slice a 40cm dal p.c.

Vecchie rotaie tram e treno a vapore

Rizzo et al

4. GPR results

Same position of transversal ERT sections T1 and T2

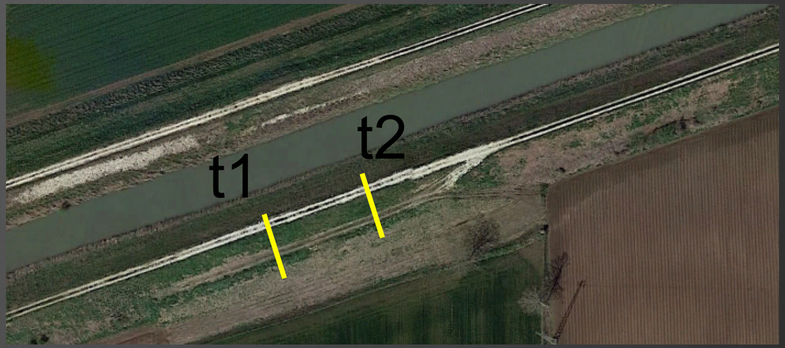


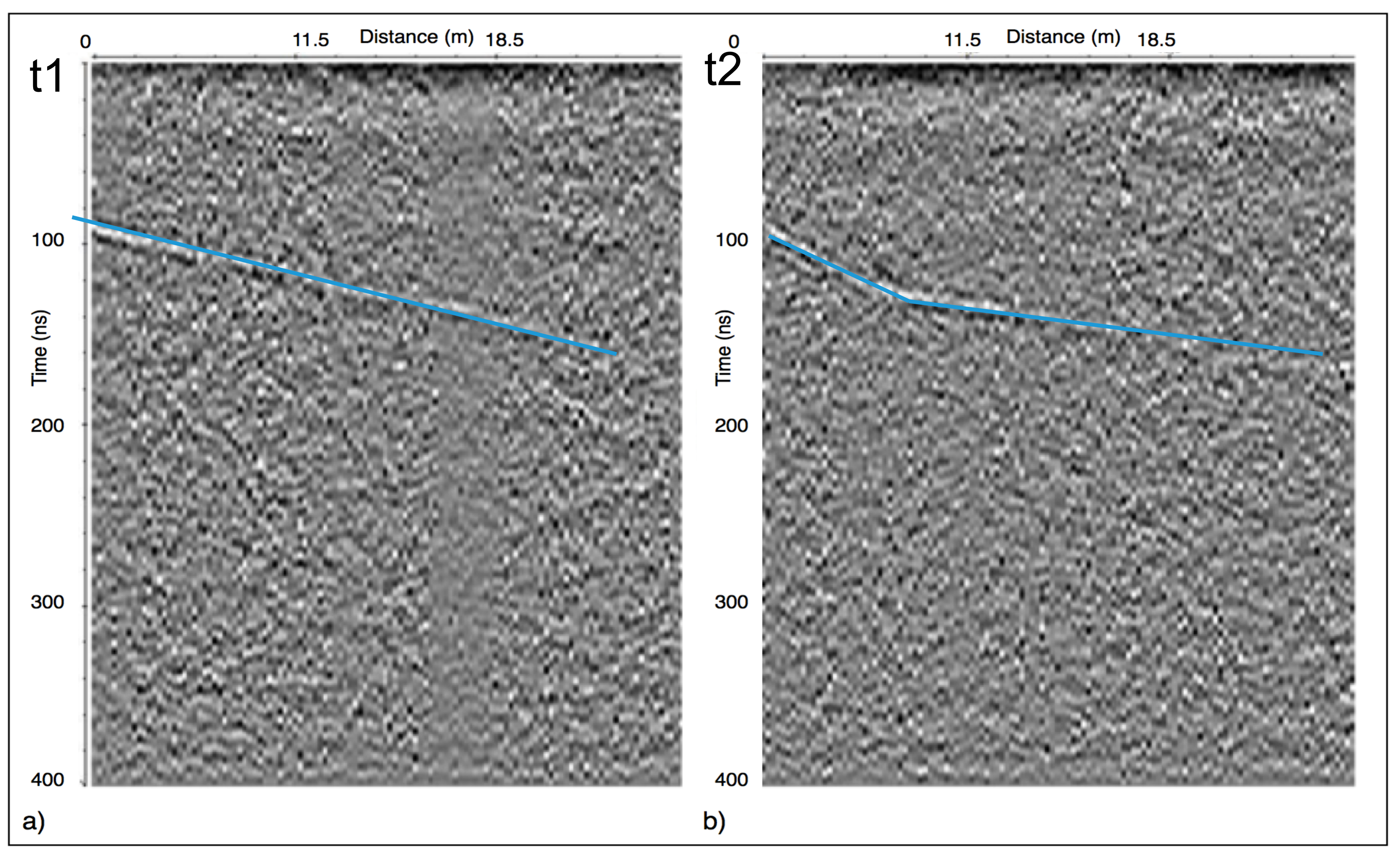
- Bi-static profile
- Tx and Rx on internal and external sides of the levee (ZOP)
- 100 Mhz antennas

4. GPR results

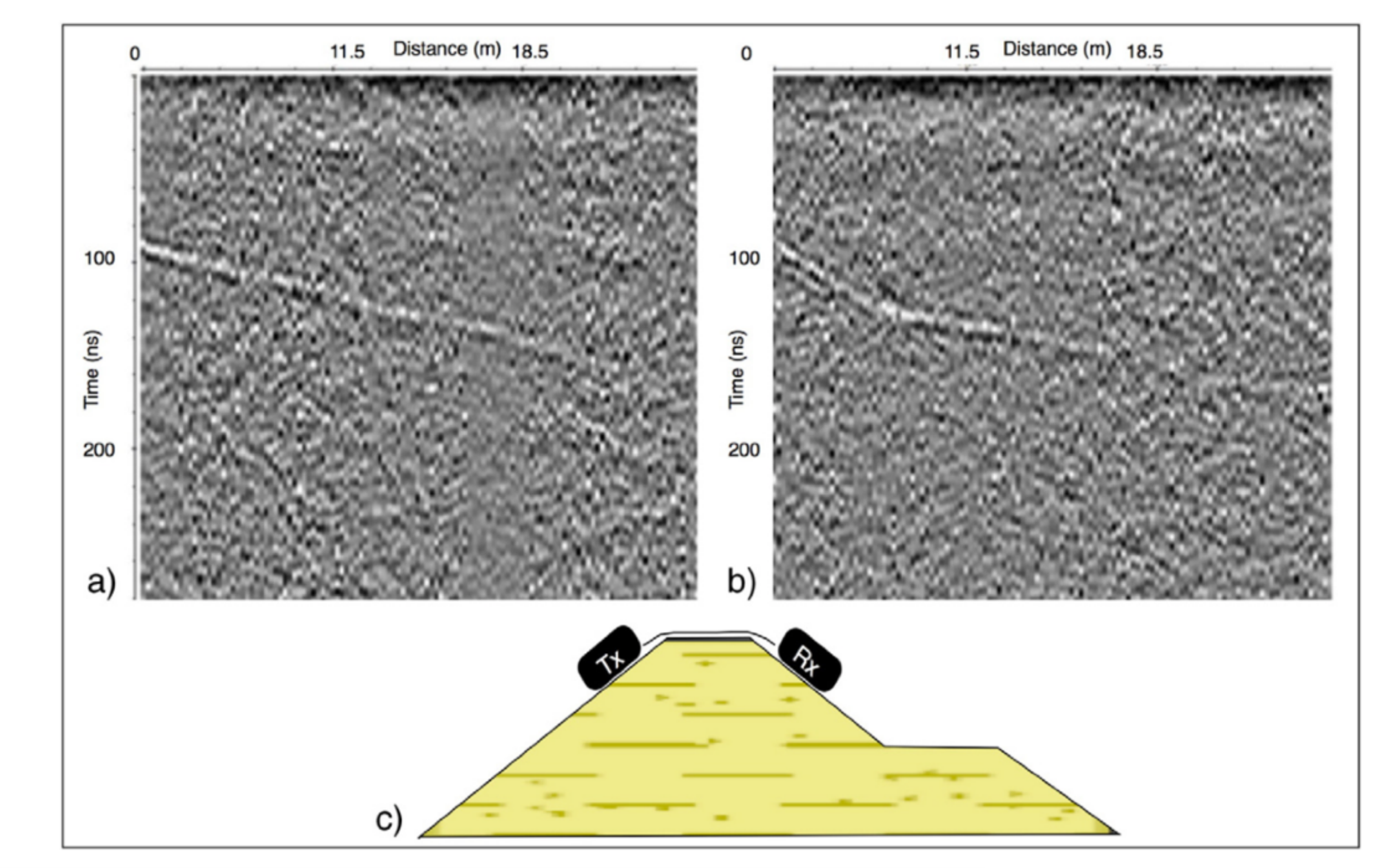
Conductive core - noisy data

First pick arrival for (ε) estimation



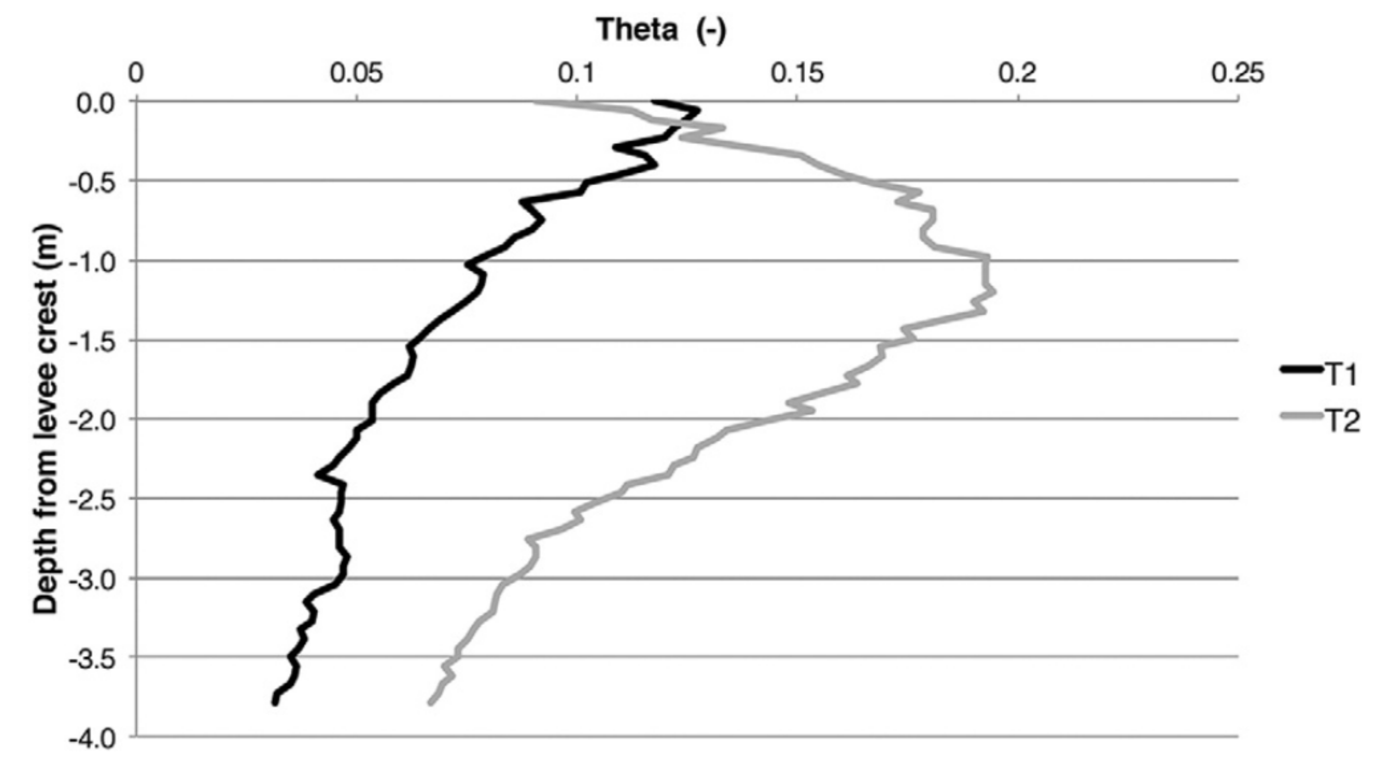


GPR on levees



Estimation of
Water content θ
In the levee

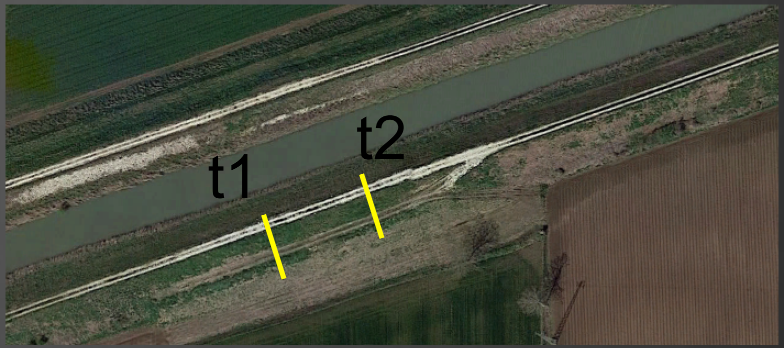
Leakages
seeking…



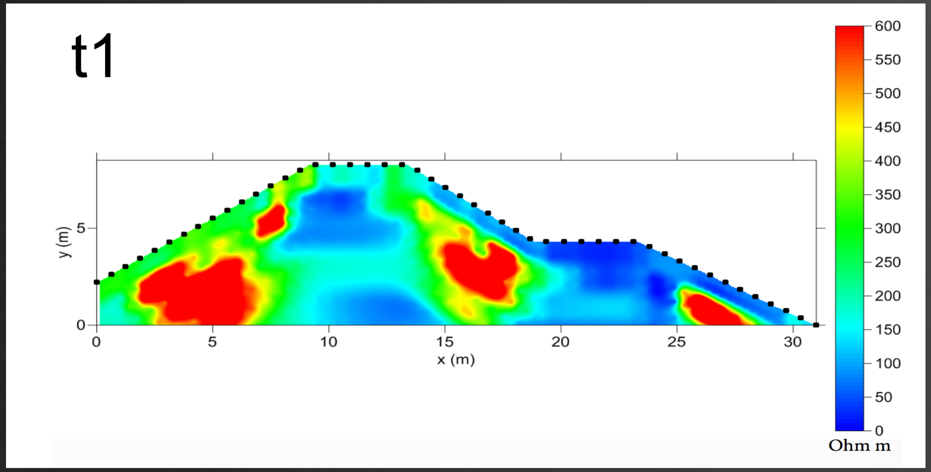
4. GPR results

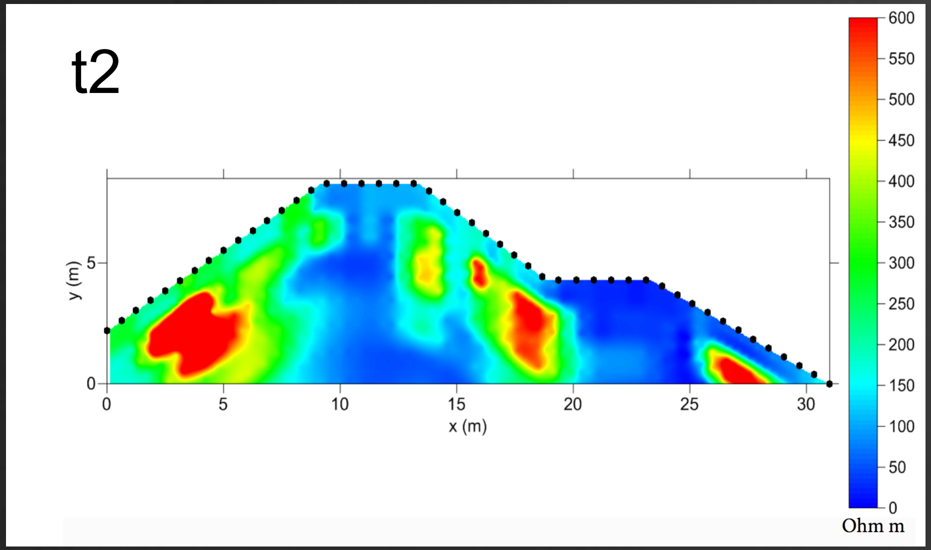
Theta from Topp (1980)

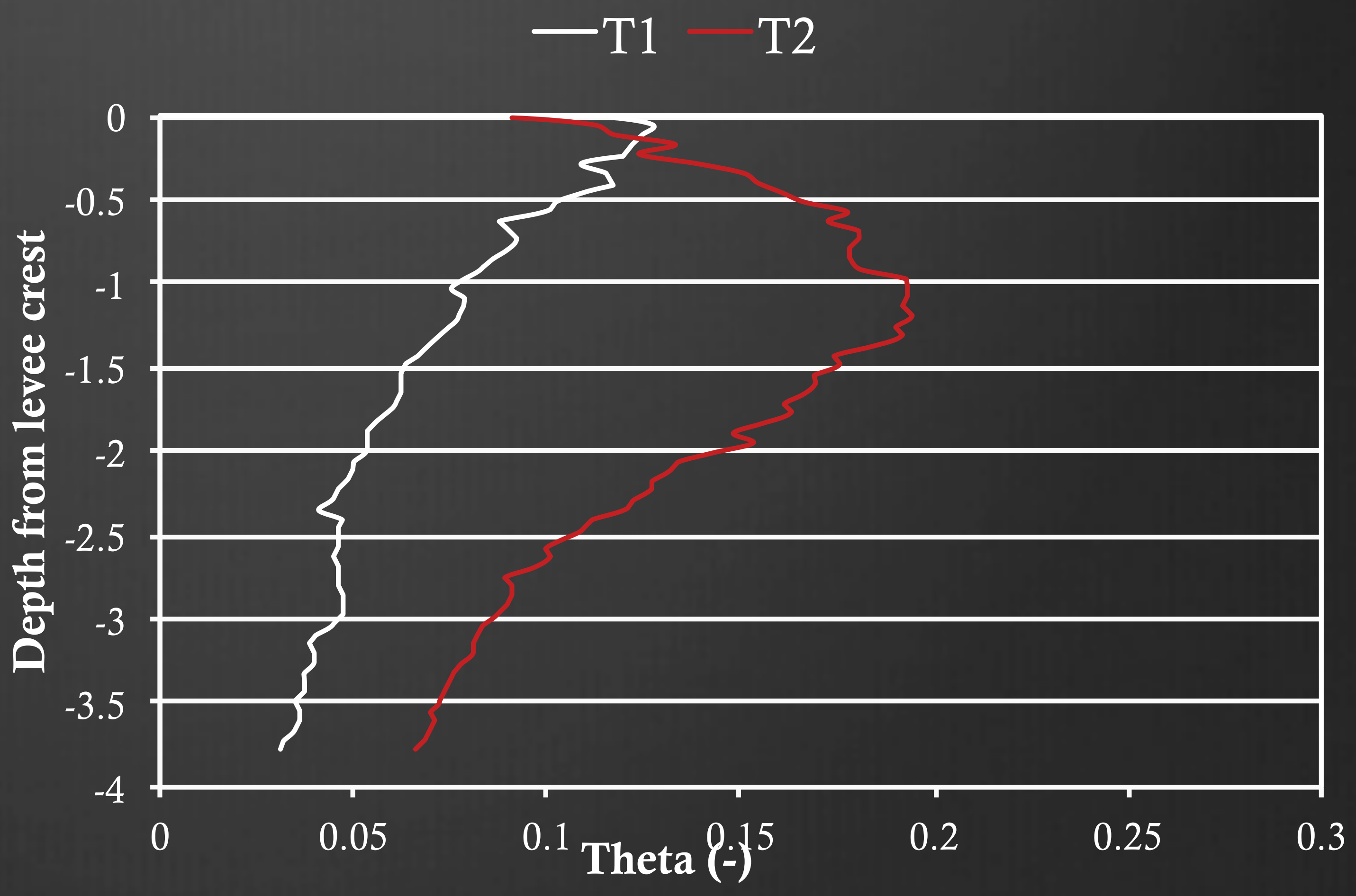
$$\vartheta = 0,053\varepsilon + 0,0292\varepsilon^2\ 0,00055\varepsilon^3 + 0,0000043\varepsilon^3$$



> Theta in stronger concrete septum





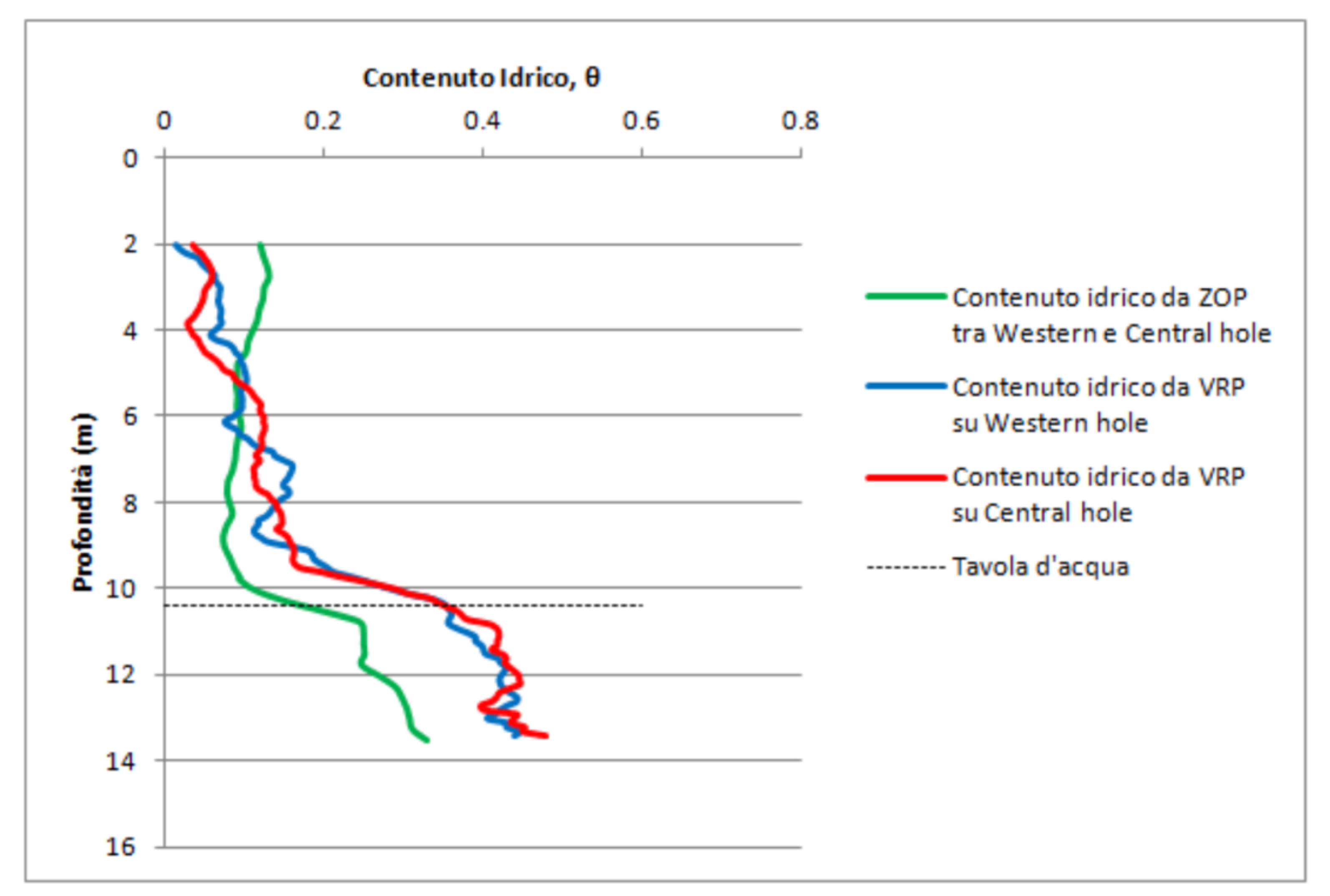


es. Trecate (No)

$\varepsilon_r = f\ (saturation)$

$\varepsilon_r = f\ (fluid)$

$$v = \frac{c}{\sqrt{\varepsilon_r}}$$



Watertable

Pollutant

RADAR attributes

Not only diffraction

Amplitude-related attributes are the most common attributes in GPR applications.
The time derivative of instantaneous amplitude (i.e. the time rate of change of the envelope) can further emphasize interfaces and discontinuities, and help the identification of reflections thus increasing the overall resolution and interpretability.

Cosine of instantaneous phase help check lateral spatial continuity/ discontinuity of reflections, such attribute images weak and strong events with equal strength.

The dominant frequency of the processed GPR section returns the instantaneous dominant frequency from the frequency spectrum of GPR data, that is, the frequency with the highest amplitude in specified windows. E.g. We can note a general attenuation trend due to the altered debris layer.

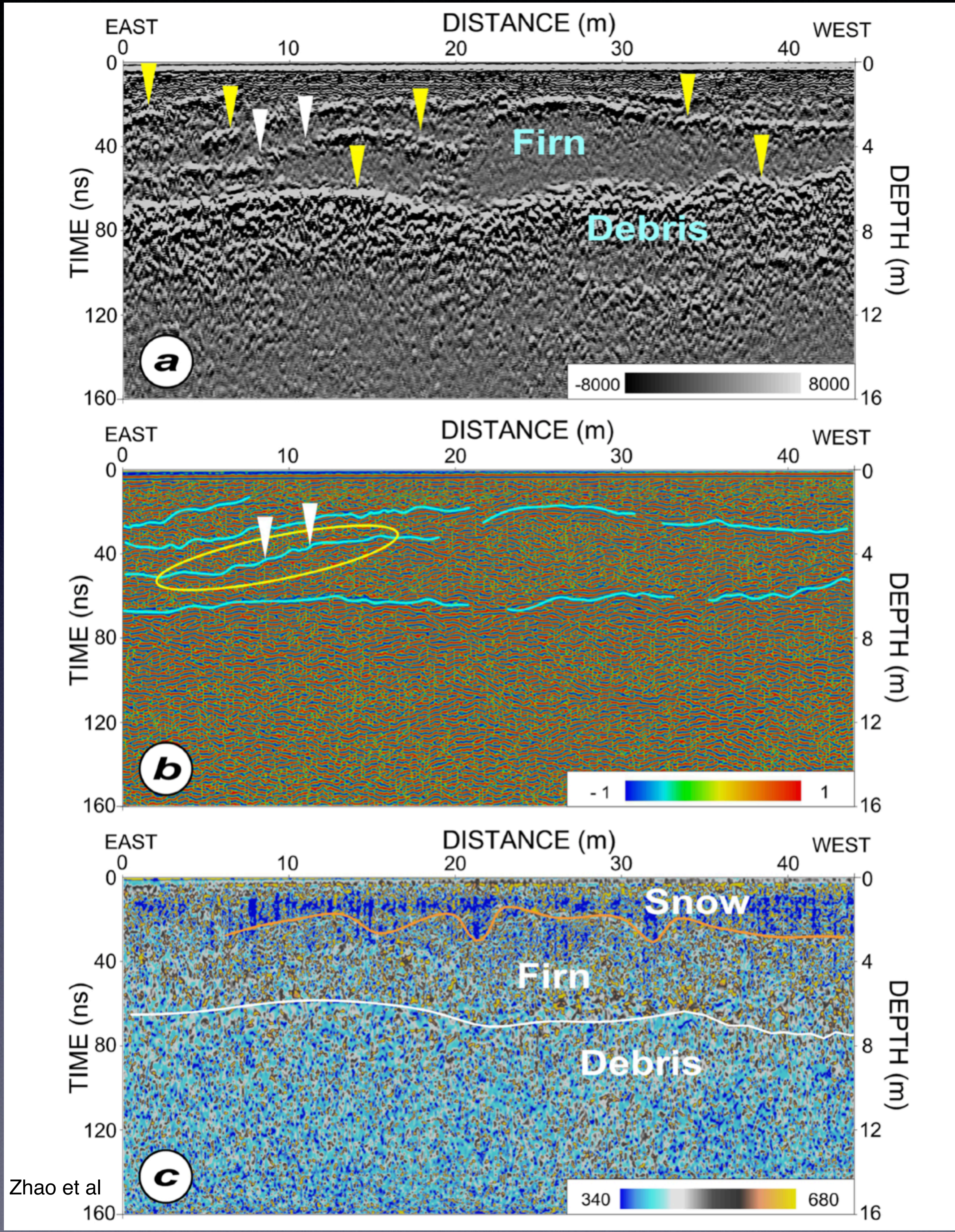
RADAR attributes

Glacier example

(a) Amplitude first derivative

(b) cosine of the instantaneous phase

(c) dominant frequency



Zhao et al

Radar Logistic

Method	Probe	Resolution	Depth
GPR	50MHz - Ghz	cm -m	cm - 50m

COST: - GPR 50-100k

RADAR GPR methods

Equipments

RADAR GPR methods

Main builders:

MALA (Sweden)

Pulsekko (Canada)

IDS (Italy)

GSSI (Usa)

RADAR GPR methods

MONO static

Bi static

IDS (Italy)

Pulsekko (Canada)

RADAR GPR methods

MONO static

IDS (Italy)

PRO

Maybe the top
Quality RADAR in terms
Of s/n ratio

CONS

Cost, only mono static

RADAR GPR methods

Bi static

Pulsekko (Canada)

PRO

Huge polyvalence

Can be linked to borehole
Radar, different frequencies antenna

Or fixed in a trolley and become
Monostatic

CONS

Quality of imaging

Electrical and EM methods

Methods	Properties	Aim
Electric surveys	Electric resistivity	Subsoil imaging, Hydrological surveys, Caves, dynamic of fluids, …
EM- methods	Electric conductivity	Environmental studies, archeology, Agriculture aims,…
Radar GPR	Dielectric permittivity	Subsoil target, Voids, archeology, glaciology, roads,…