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Geophysical methods in geoscience and near surface geophysics
Ground Penetrating Radar

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Italiadomani

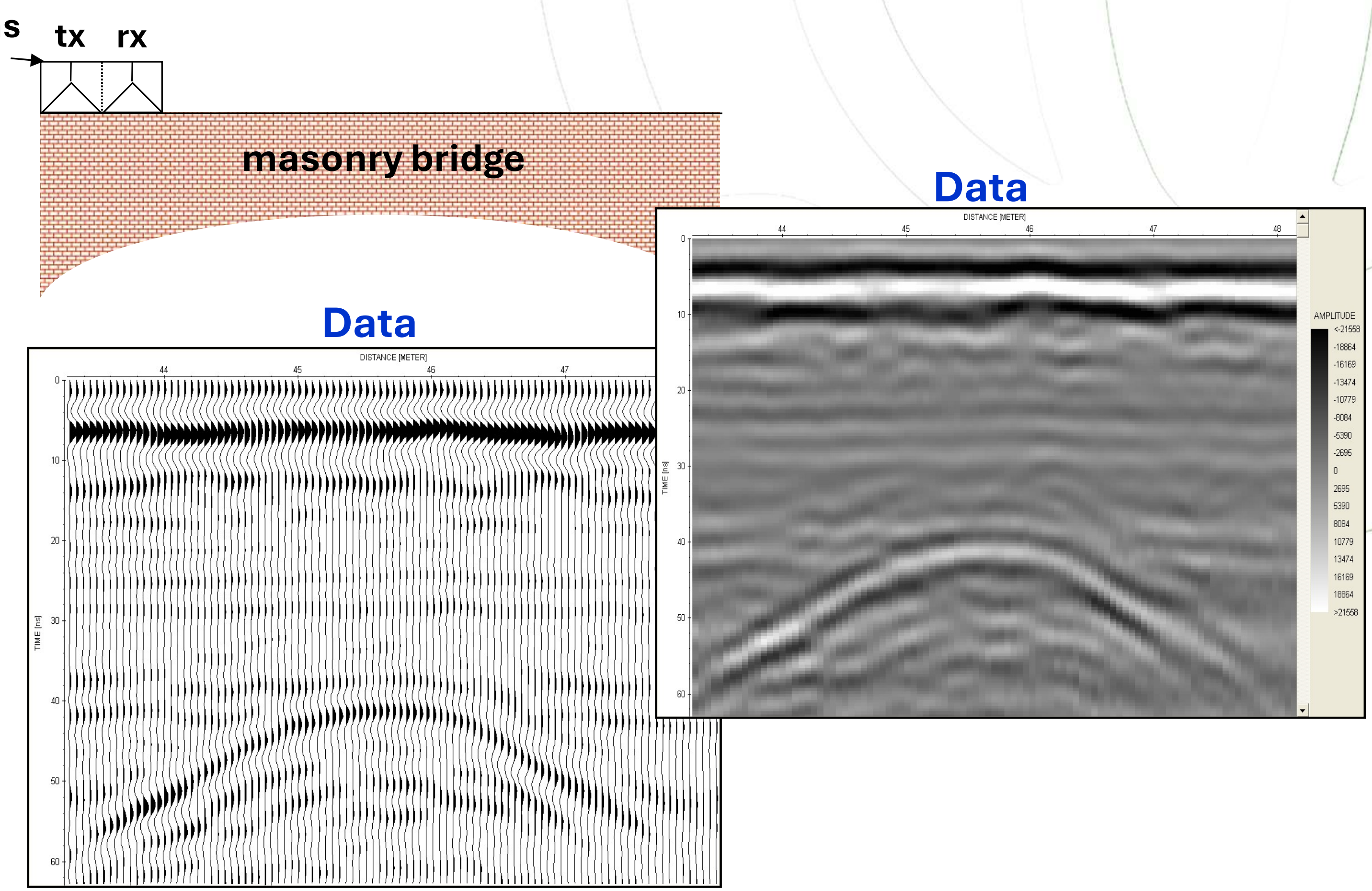
Syllabus

Ground Penetrating Radar (6 hours):

- Principles of operation of the GPR technique
- Electrical permittivity
- Reflection and transmission coefficients
- Directivity of antennas
- Spatial aliasing
- Radargram
- Velocity analysis in the GPR case
- Application examples

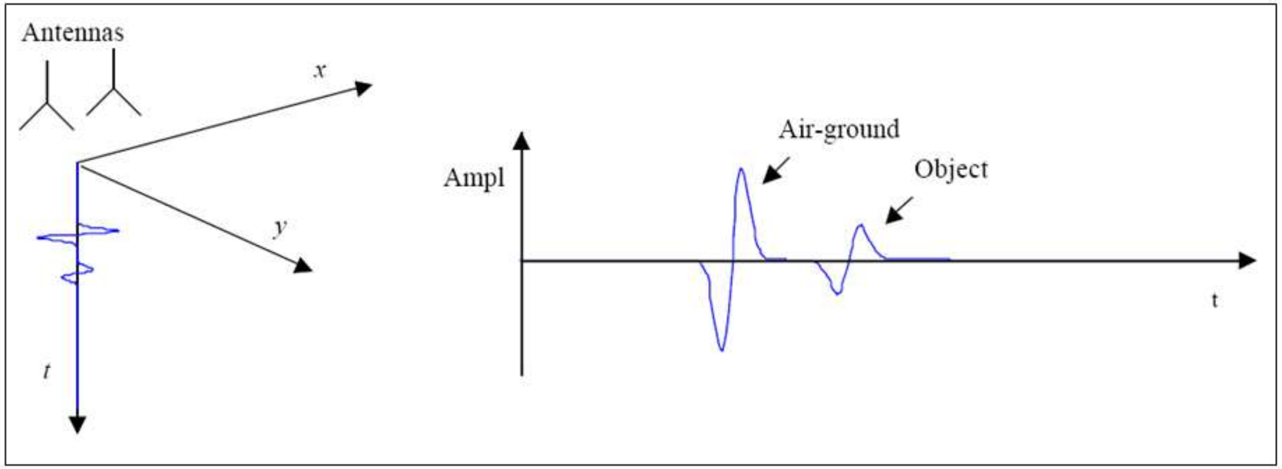
GPR (Ground Penetrating Radar) method

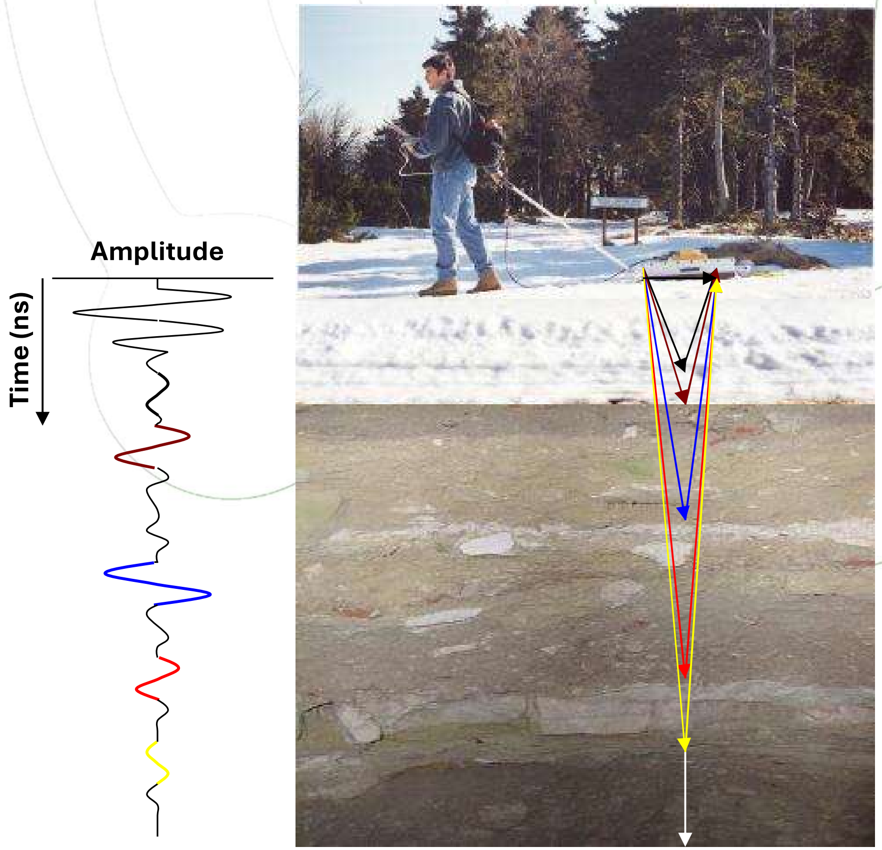
Acquisition



A-scan (1D-radar survey)

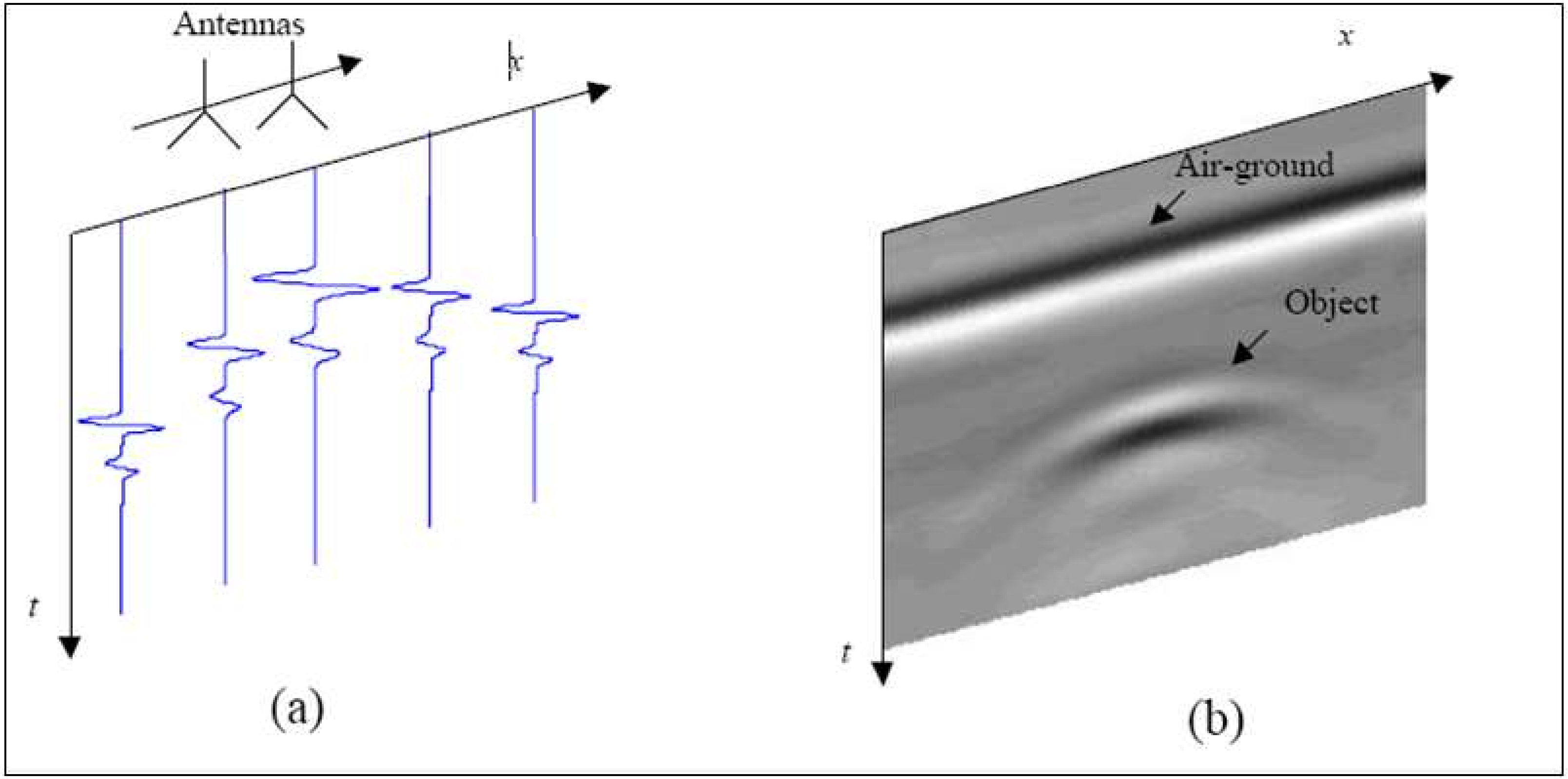
Configuration and representation of an A-scan.





(Scheers, 2001, U.C. Louvain)

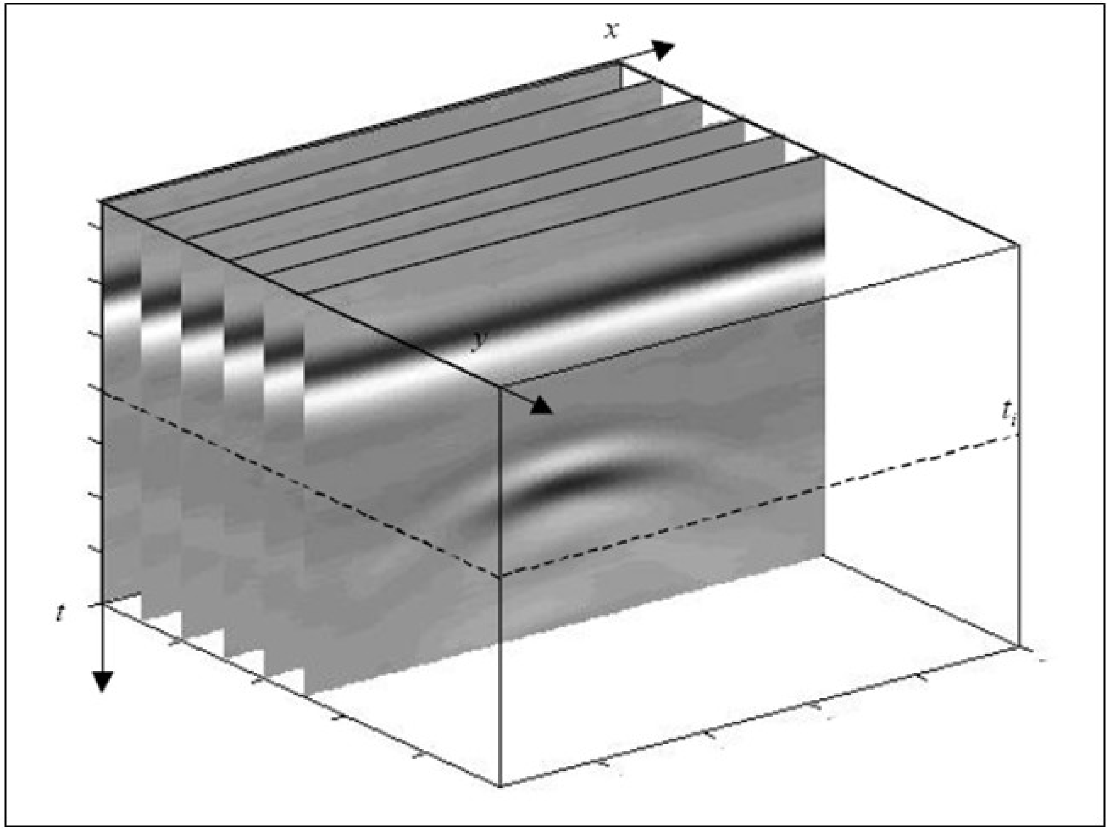
B-scan (2D-radar survey)



(a) Multiple A-scans forming a B-scan. (b) Representation of a B-Scan on a grey-scale.

(Scheers, 2001, U.C. Louvain)

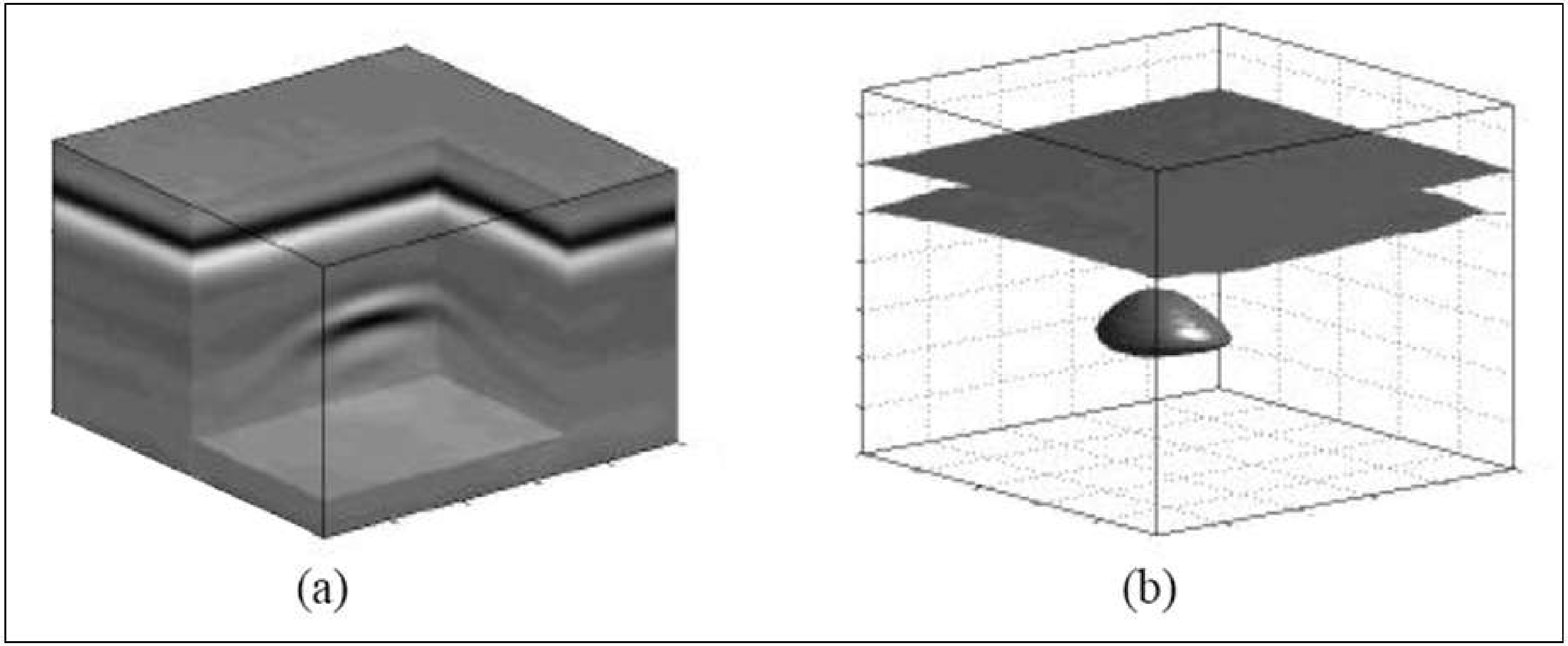
C-scan (3D-radar survey)



(Scheers, 2001, U.C. Louvain)

Multiple parallel B-scans forming a C-scan.

C-scan (3D-radar survey)

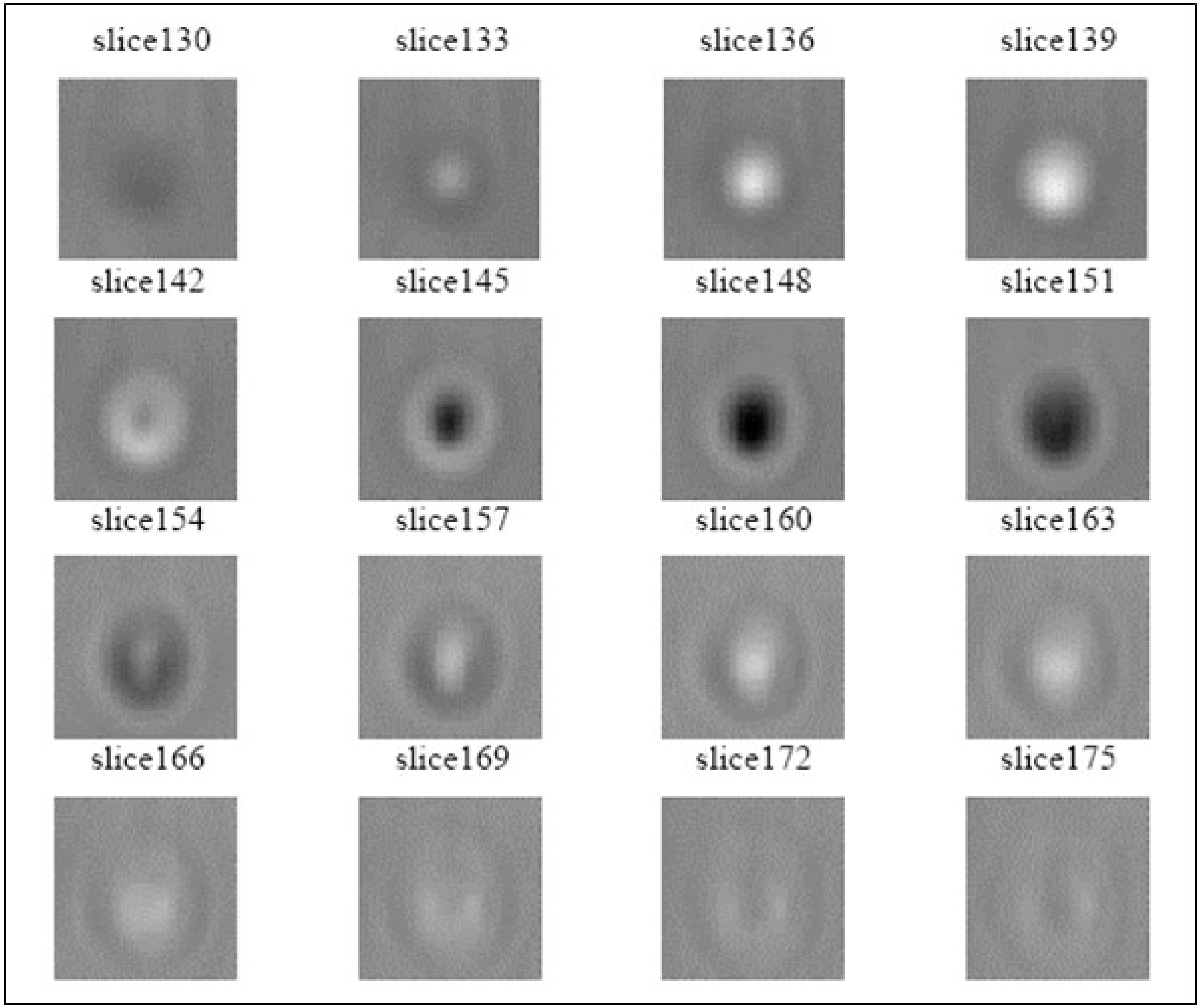


(a) Arbitrary cut in the 3-D volume. (b) Iso-surface representation.

(Scheers, 2001, U.C. Louvain)

C-scan (3D-radar survey)

Representation of a C-scan by horizontal slices at different depths.



(Scheers, 2001, U.C. Louvain)

Theory

Maxwell equations: $\nabla \wedge \vec{E} = -\mu \frac{\partial \vec{H}}{\partial t}$ $\nabla \wedge \vec{H} = \sigma \vec{E} + \varepsilon \frac{\partial \vec{E}}{\partial t}$

Since: $\nabla \wedge (\nabla \wedge \vec{V}) = \nabla(\nabla \cdot \vec{V}) - \nabla^2 \vec{V}$

$$\nabla \wedge (\nabla \wedge \vec{E}) = \nabla(\nabla \cdot \vec{E}) - \nabla^2 \vec{E} = -\mu \frac{\partial (\nabla \wedge \vec{H})}{\partial t}$$

$\nabla \cdot \vec{E} \rightarrow = 0$

$\nabla \wedge \vec{H} \rightarrow = \sigma \vec{E} + \varepsilon \frac{\partial \vec{E}}{\partial t}$

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

The solution for a wave propagating in direction z in a homogeneous medium with an electric field parallel to x is:

$$E_x(z,t) = E_0 e^{-\gamma z} e^{jwt}$$

$$\gamma = \sqrt{jw\mu\sigma - w^2\mu\varepsilon} = \alpha + j\beta$$

β → *phase constant*

α → *attenuation factor*

$\gamma =$ **propagation constant, is a complex function**

Theory

Thus: $$E_x(z,t) = E_0 e^{-\alpha z} e^{j(wt-\beta z)}$$

For a generic dielectric, permittivity is a complex number: $\varepsilon = \varepsilon' - j\varepsilon''$

Then: $$\gamma = \sqrt{-w^2\mu\varepsilon' + jw^2\mu\varepsilon'' + jw\mu\sigma} \Rightarrow \gamma = jw\sqrt{\mu\varepsilon'\left[1 - j\left(\frac{\varepsilon''}{\varepsilon'} + \frac{\sigma}{w\varepsilon'}\right)\right]}$$

1 $\sigma = 0$ **and** $\varepsilon'' = 0$ → $\alpha = 0$

2 $\sigma = 0$ **and** $\varepsilon'' \ll \varepsilon'$ → $\alpha \cong w\sqrt{\mu\varepsilon'}\frac{\varepsilon''}{2\varepsilon'}$

absorption is proportional to ε'' and to frequency

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3 $\sigma \ll \varepsilon'\omega$ **and** $\varepsilon'' = 0$ → $\alpha \cong \sqrt{\mu\varepsilon'}\,\frac{\sigma}{2\varepsilon'}$

absorption is proportional to σ and to frequency through ε'

4 $\sigma \ll \varepsilon'\omega$ **and** $\varepsilon'' \ll \varepsilon'$ → $\alpha \cong \frac{\sqrt{\mu\varepsilon'}}{2\varepsilon'}(\omega\varepsilon'' + \sigma)$

σ and ε'' are responsible for attenuation **attenuation increases with frequency**

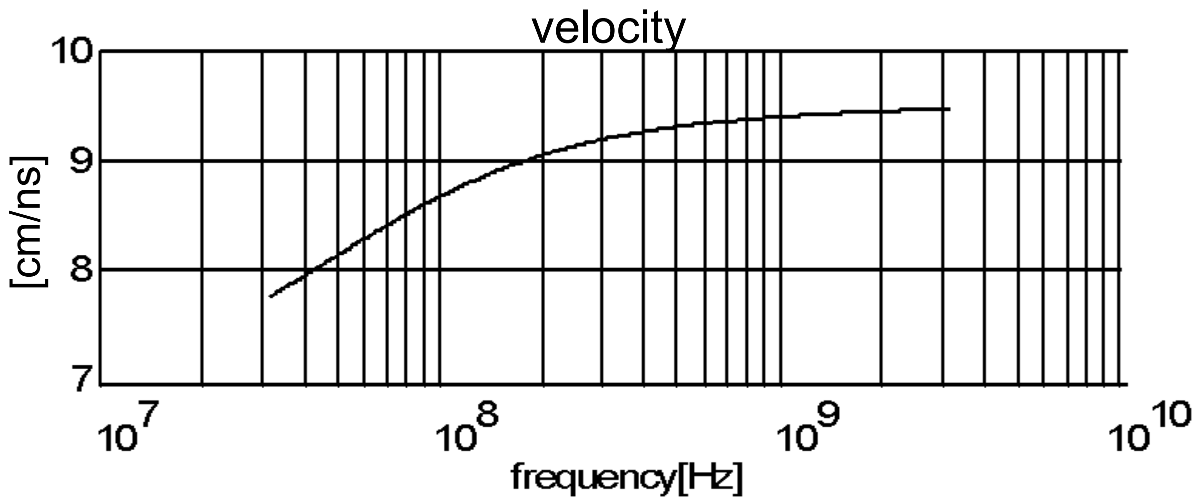
In all the situations: $\beta \cong w\sqrt{\mu\varepsilon'}$ → $v = \frac{\lambda}{T} = \frac{w}{\beta} \cong \frac{1}{\sqrt{\mu\varepsilon'}}$

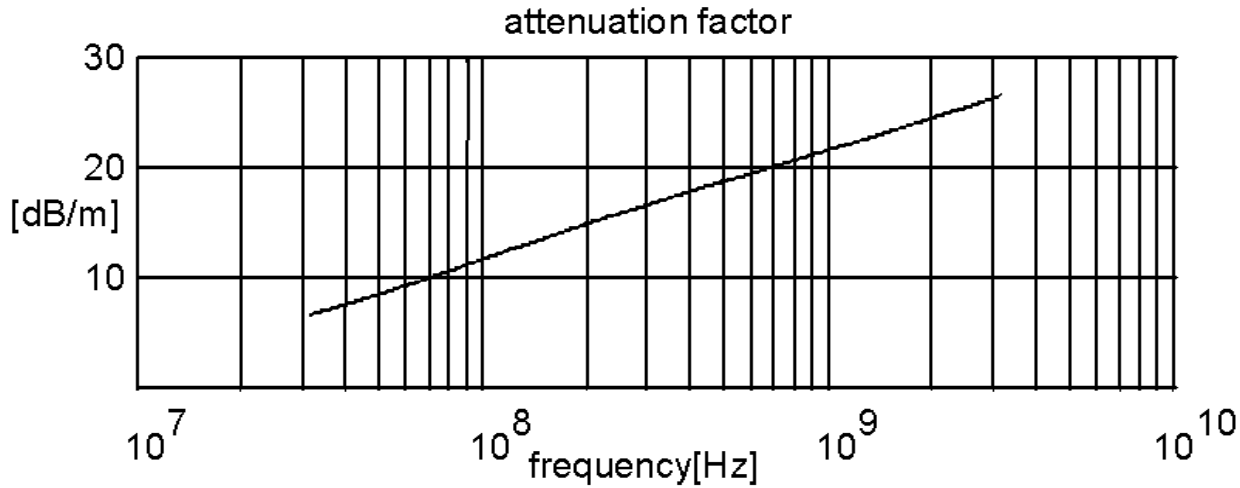
If c indicates the speed of light, i.e., the free space velocity $c = \frac{1}{\sqrt{\mu_0\varepsilon_0'}}$ **then** $v \cong \frac{c}{\sqrt{\mu_r\varepsilon_r'}}$

Since for most rock formations, $\mu_r = 1$ → $v \cong \frac{c}{\sqrt{\varepsilon_r'}}$

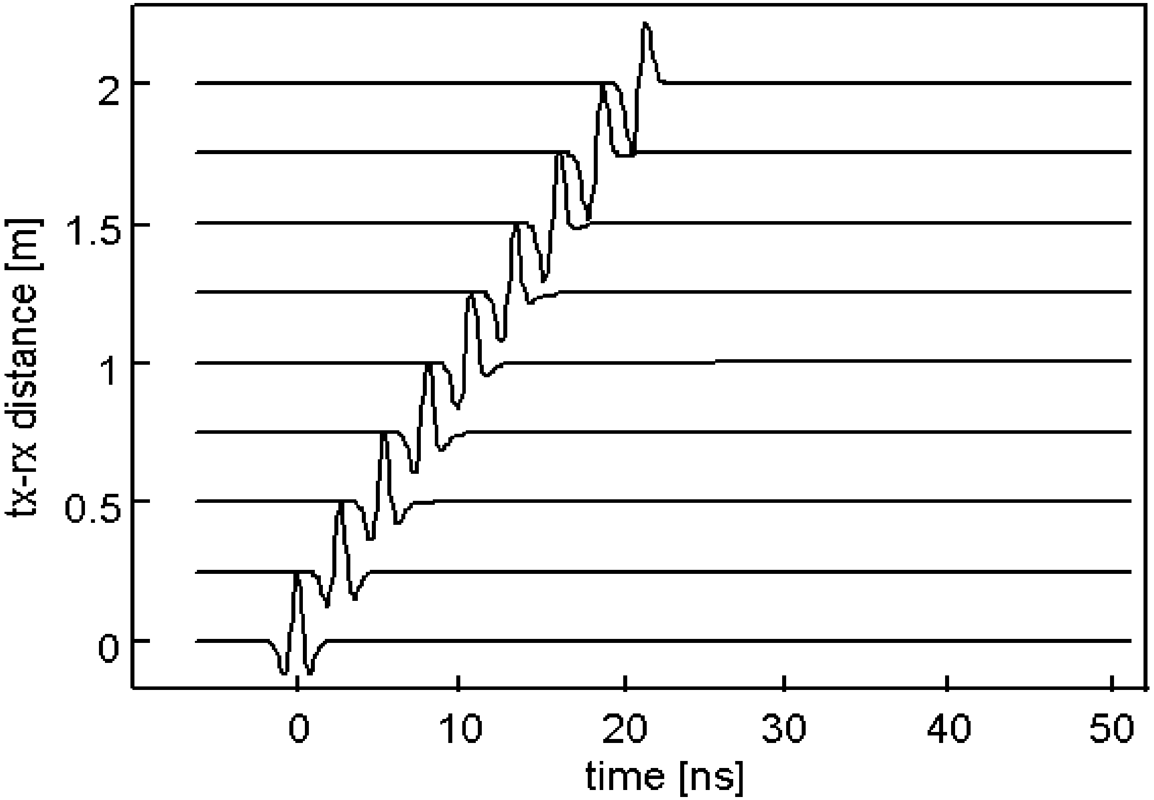
Since ε' generally varies with frequency, radar data suffer from the problem of dispersion

Theory


velocity
10
9
8
7
[cm/ns]
10^7
10^8
10^9
10^{10}
frequency[Hz]


attenuation factor
30
20
[dB/m]
10
10^7
10^8
10^9
10^{10}
frequency[Hz]

Theory



500 MHz Ricker wavelet propagating at different distances through the medium

Reflection and transmission coefficients

When a wave arrives at a surface which separates two media with different electromagnetic characteristics, energy is partially reflected and partially transmitted.

For normal incidence → $R = \frac{Z_2 - Z_1}{Z_2 + Z_1}$ **and** $T = \frac{2Z_1}{Z_2 + Z_1}$ $Z = \sqrt{\frac{jw\mu}{jw\varepsilon + \sigma}}$

Z= **the *electromagnetic impedance***

Any μ or ε or σ contrast between two materials will produce a GPR energy return to the surface.

For perfect dielectric materials: $\sigma = 0$ **and** $\varepsilon'' = 0$ → $Z = \sqrt{\frac{\mu}{\varepsilon'}}$

and considering that for most rock formations, $\mu_r = 1$: → $R = \frac{\sqrt{\varepsilon_{r1}} - \sqrt{\varepsilon_{r2}}}{\sqrt{\varepsilon_{r1}} + \sqrt{\varepsilon_{r2}}}$

Reflection and transmission coefficients

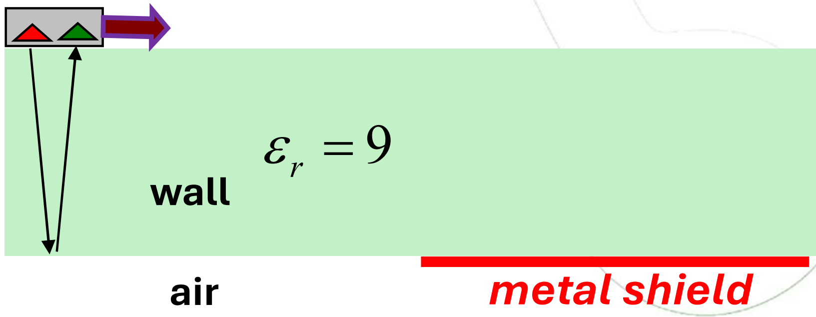
For metal targets: $\sigma \Rightarrow \infty$ → $Z = \sqrt{\dfrac{jw\mu}{jw\varepsilon + \sigma}} \Rightarrow 0$ → $R = \dfrac{Z_2 - Z_1}{Z_2 + Z_1} \Rightarrow -1$

Example

$$R = \frac{\sqrt{\varepsilon_{r1}} - \sqrt{\varepsilon_{r2}}}{\sqrt{\varepsilon_{r1}} + \sqrt{\varepsilon_{r2}}}$$

$$R = \frac{3-1}{3+1} = 0.5$$

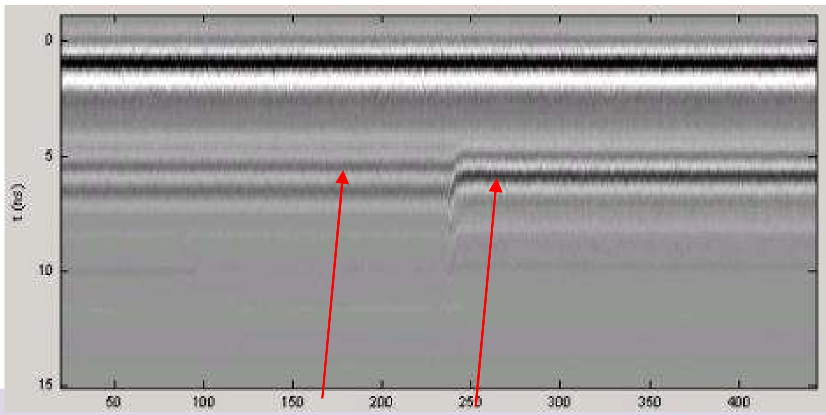
R > 0



Z = 0

R = -1

R < 0

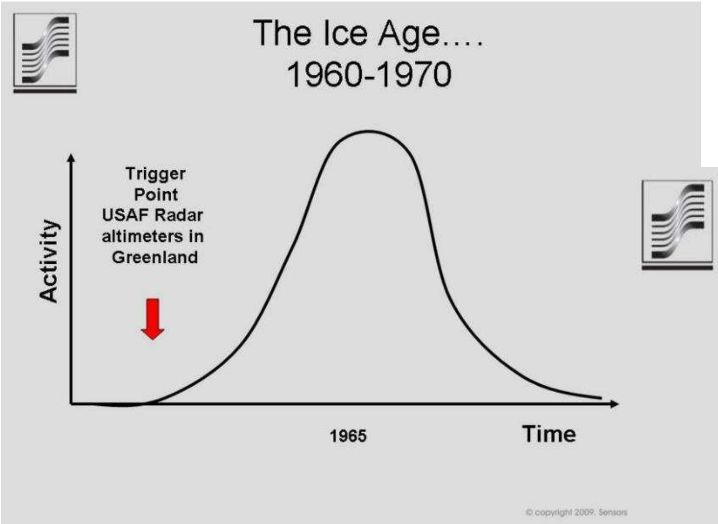


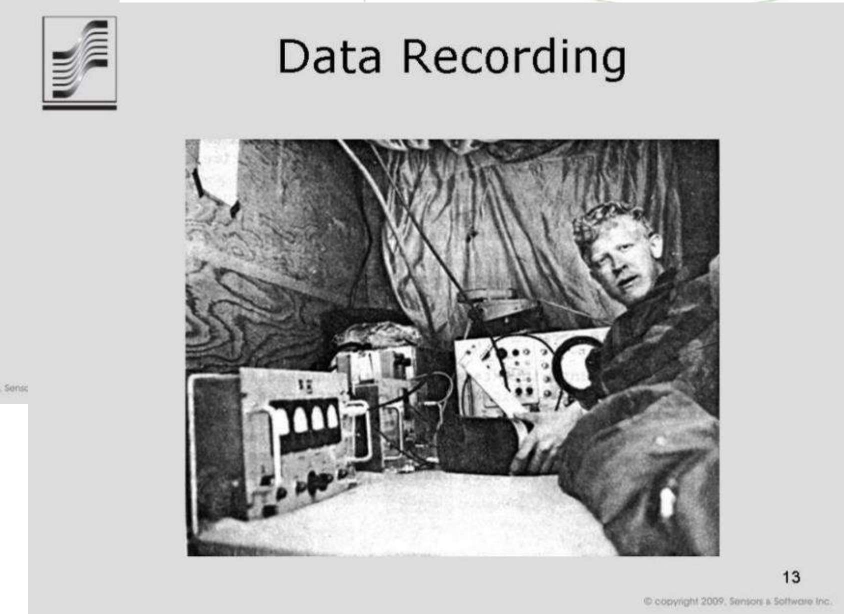
reflections with opposite polarity

Material properties

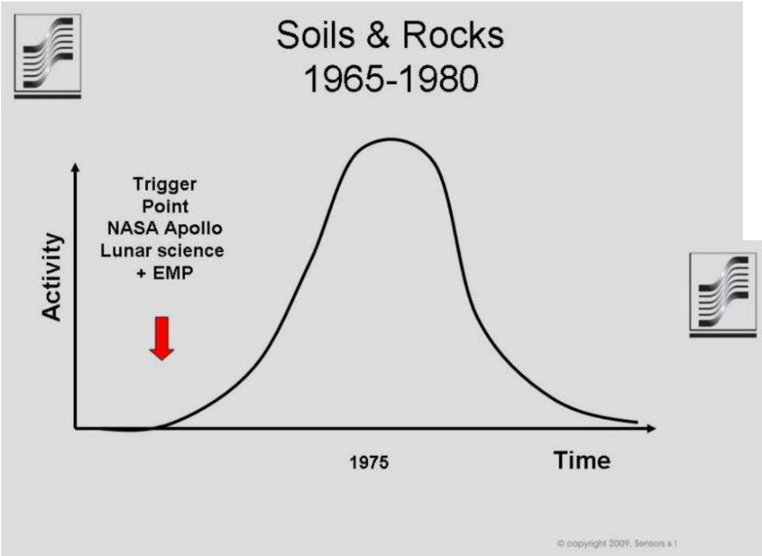
material	ε_r	σ (mS/m)	V (m/ns)	α (dB/m)
air	1	0	0.30	0
distilled water	80	0.01	0.033	2×10^{-3}
fresh water	80	0.5	0.033	0.1
salt water	80	3×10^{4}	0.01	10^{3}
dry sand	3-5	0.01	0.15	0.01
satured sand	20-30	0.1-1.0	0.06	0.03-0.3
limestone	4-8	0.5-2	0.12	0.4-1
shale	5-15	1-100	0.09	1-100
silt	5-30	1-100	0.07	1-100
clay	5-40	2-1000	0.06	1-300
granite	4-6	0.01-1	0.13	0.01-1
dried salt	5-6	0.01-1	0.13	0.01-1
ice	3-4	0.01	0.16	0.01

Data acquisition





Data acquisition



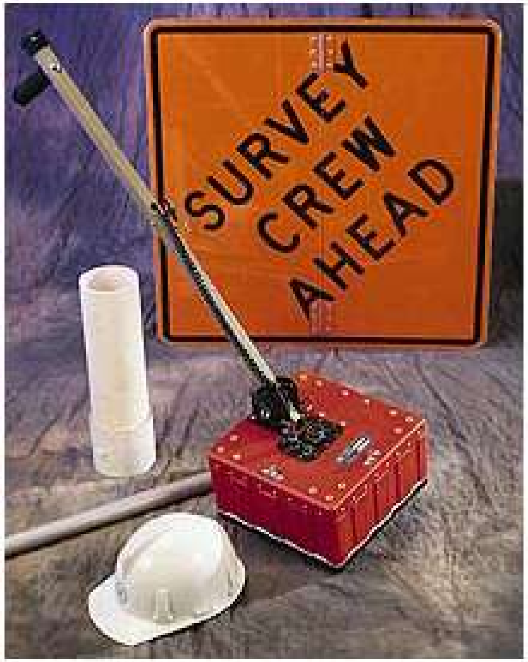
Data acquisition

1971 First commercial GPR by GSSI

1990 First multi-channel GPR by GSSI (SIR10 model)

GSSI system (SIR20)

SIR-10 radar unit



400 MHz antenna

Data acquisition

RAMAC system (100MHz)

RAMAC system (50 MHz unshielded)

Data acquisition

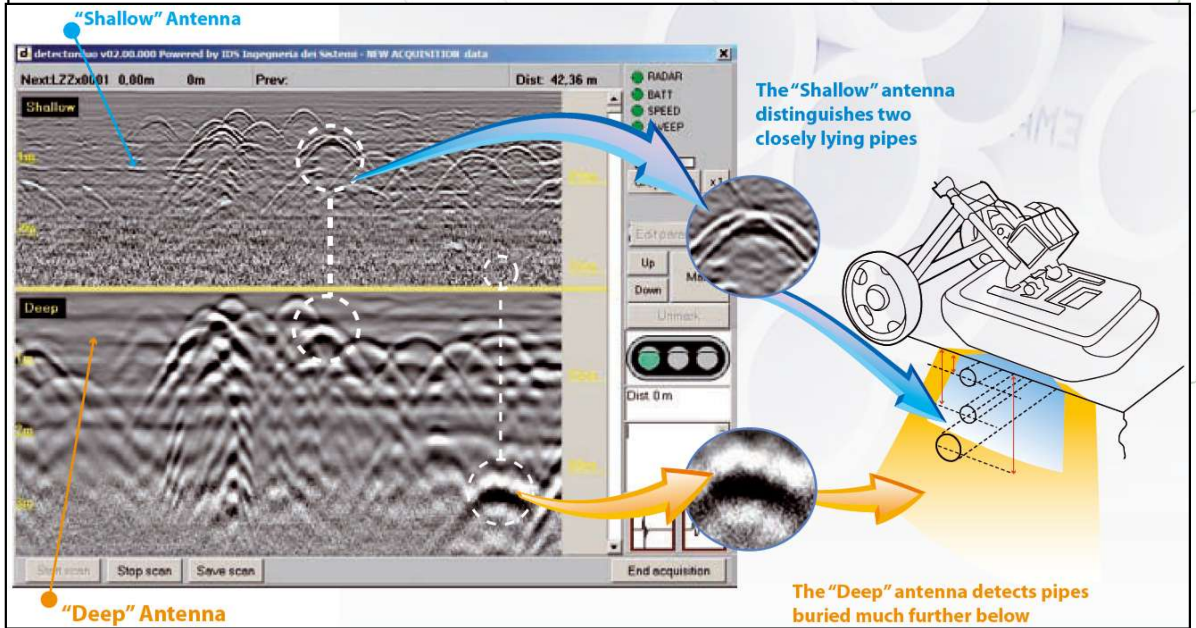
IDS antenna (200 MHz)

Data acquisition

Multi-frequency antennas

Detector DUO (IDS)

250 and 700 *MHz* pairs in one antenna

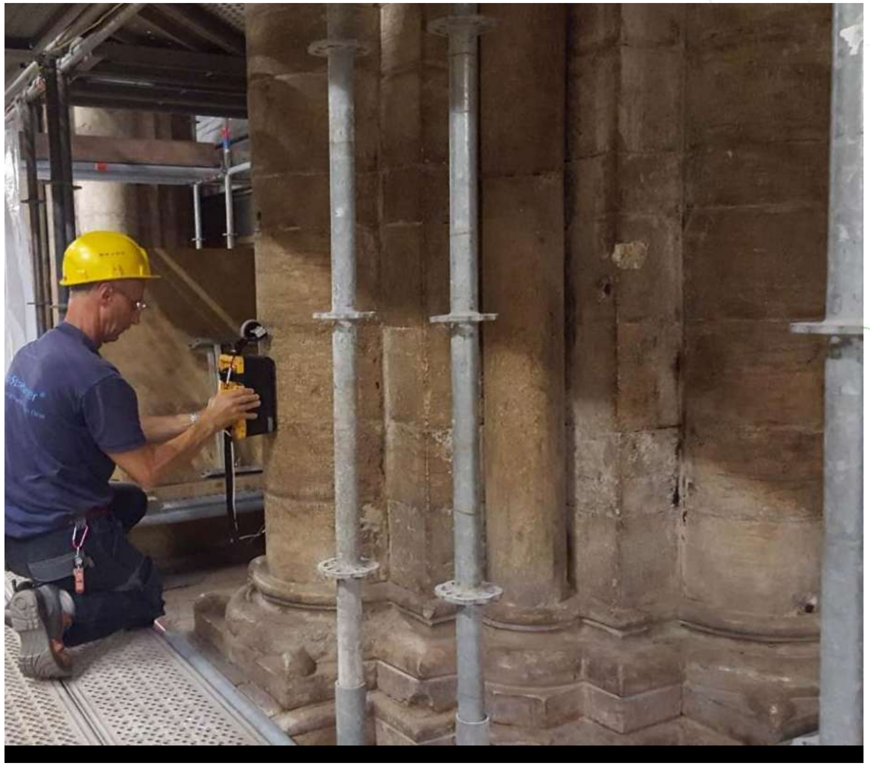


Data acquisition

SnowScan system (500 *MHz*)

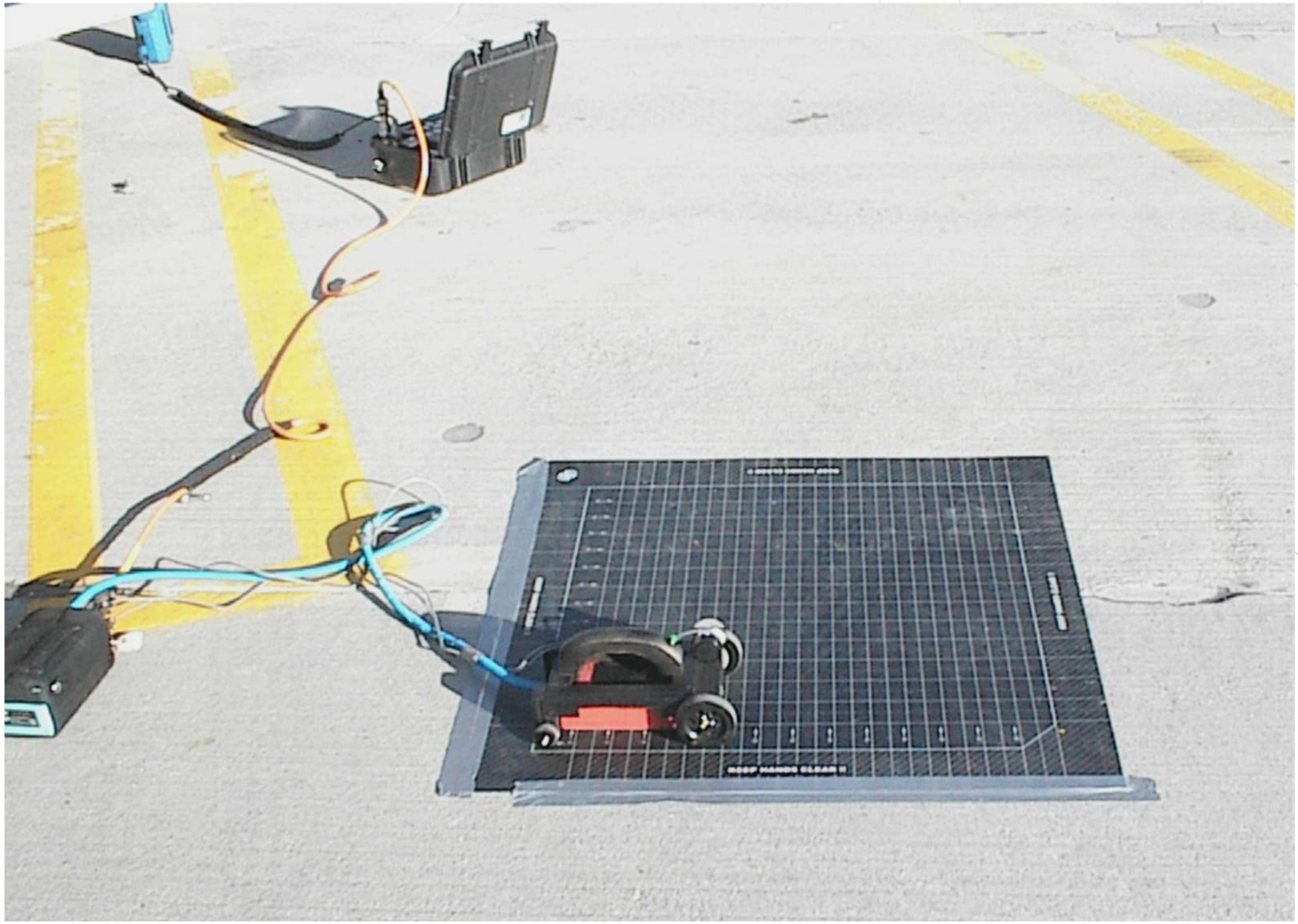
Data acquisition

RAMAC system (1GHz)



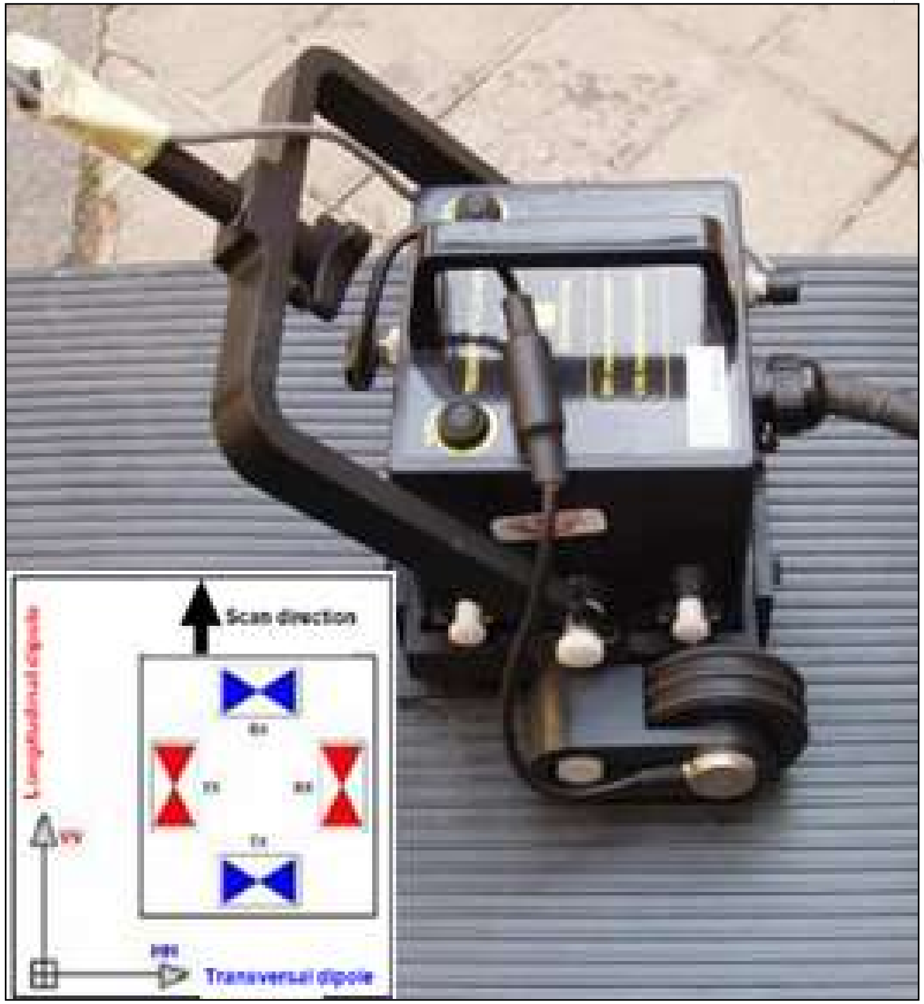
Data acquisition

GSSI system (1.5GHz)



Data acquisition

IDS bipolar antenna (2GHz)



Data acquisition

RAMAC system (borehole antennas)

MALÅ 100MHz Slimhole Borehole Antenna:

Dimensions:

Tx:	189 cm including batteries. Diameter: 40 mm
Weight:	3.3 kg
Rx:	176 cm including batteries. Diameter: 40 mm
Weight:	3.6 kg

The MALÅ 250MHz Borehole Antenna:

Dimensions:

Tx:	129 cm including batteries. Diameter: 48 mm
Weight:	4.75 kg
Rx:	129 cm including batteries. Diameter: 48 mm
Weight:	4.75 kg

Data acquisition

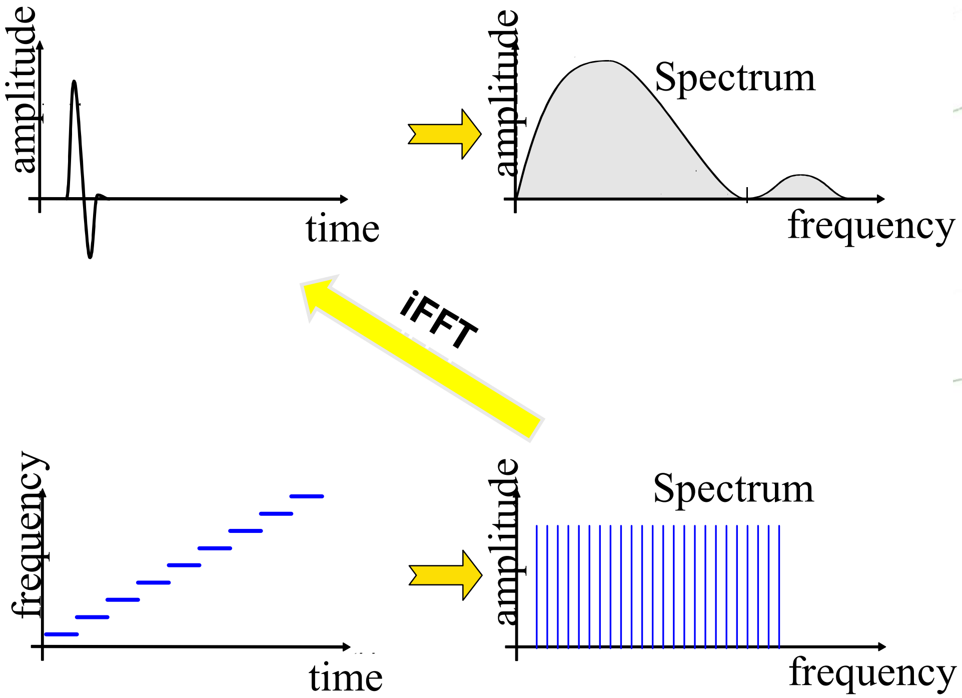
Antenna array systems

Data acquisition

Antenna array systems

Data acquisition

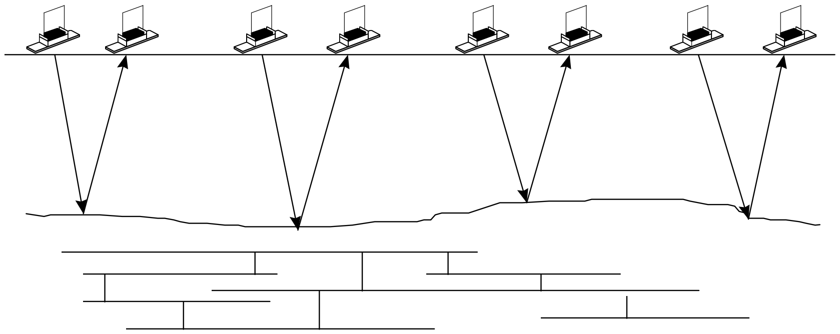
Antenna array systems



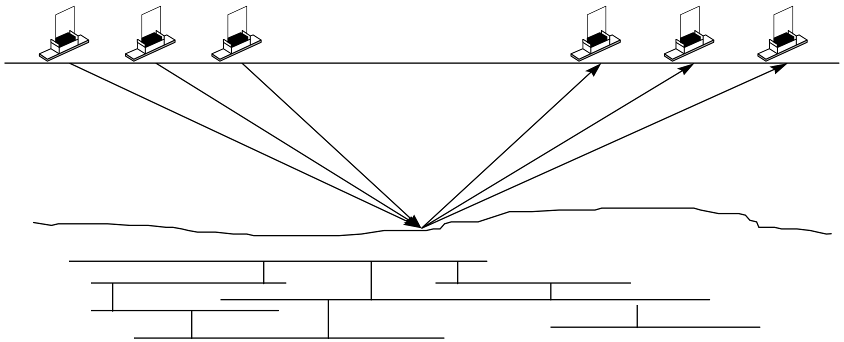
Data acquisition

Data acquisition

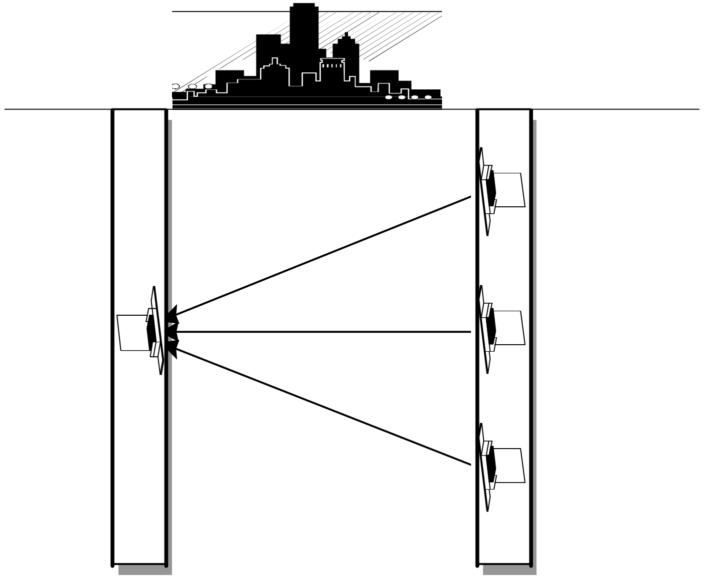
Reflection profile



CMP (Common Mid Point) gather

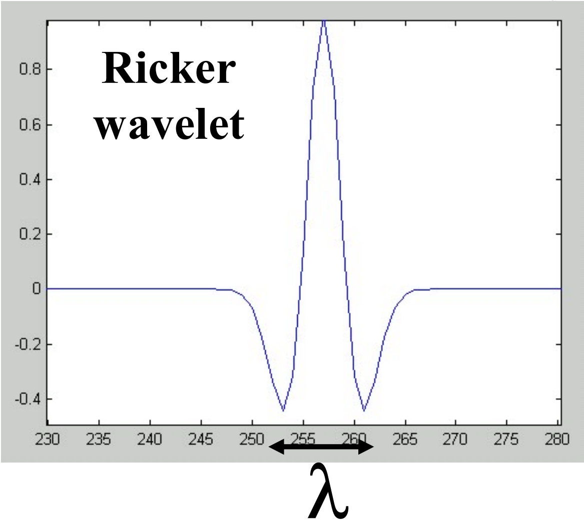


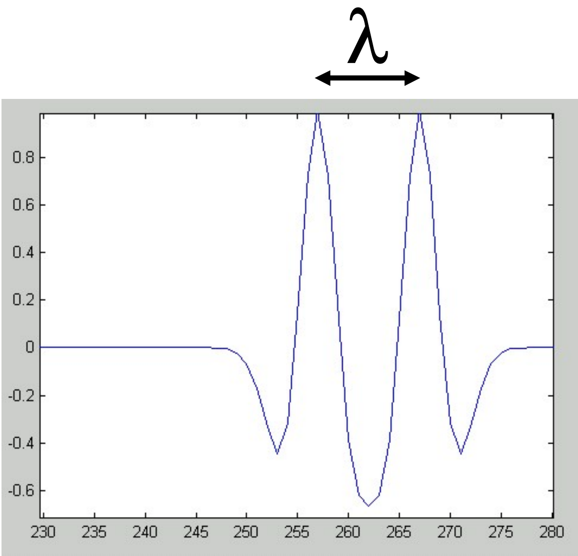
Tomography

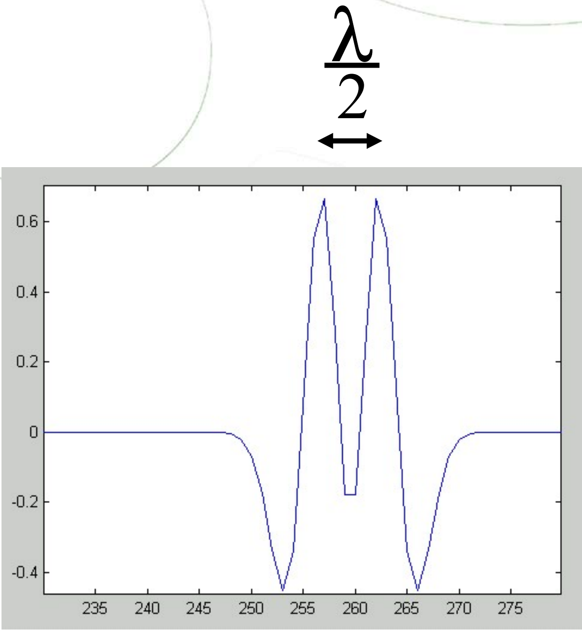


Data acquisition

Frequency vs. Resolution



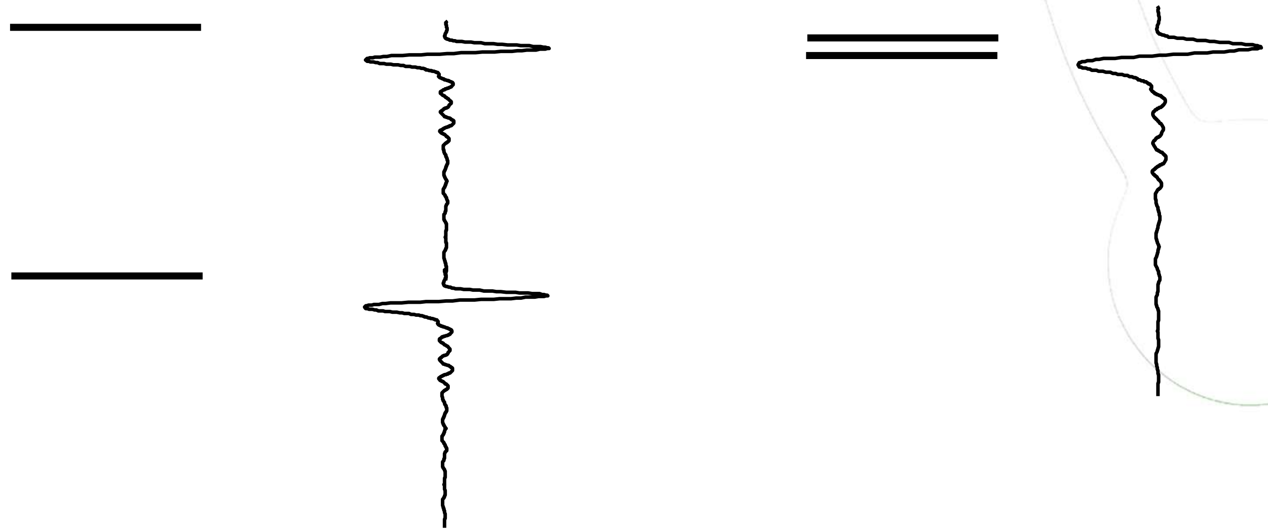


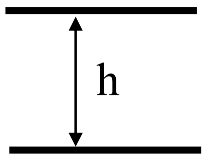


Data acquisition

Frequency vs. Resolution

Vertical resolution



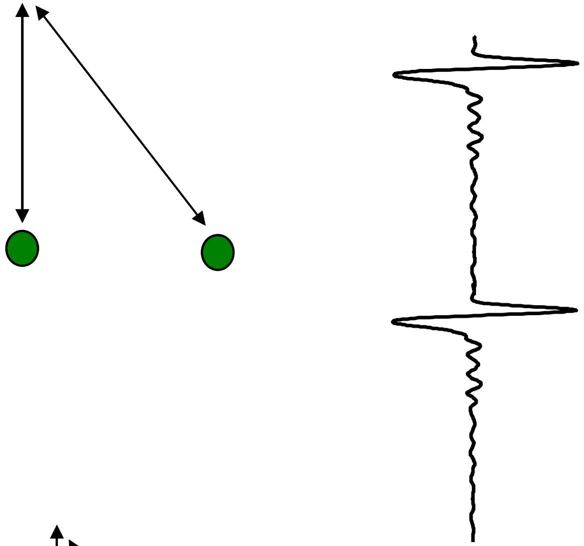


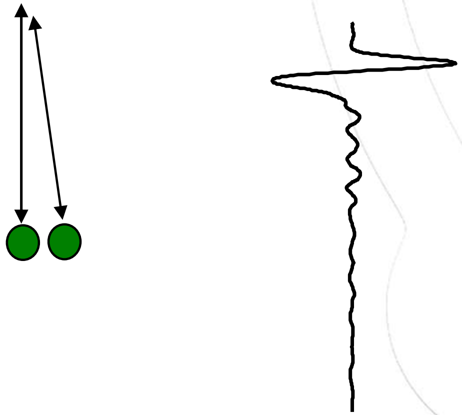
$$\Rightarrow \quad 2h = \frac{\lambda}{2} \quad \Rightarrow \quad h = \frac{\lambda}{4}$$

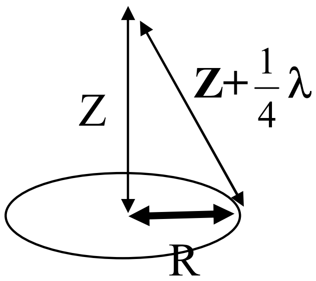
since $\lambda = \frac{v}{f}$ to obtain h as vertical resolution at any depth $\Rightarrow$ $f = \frac{v}{4h}$

Frequency vs. Resolution

Lateral resolution







$$R = \sqrt{\frac{\lambda^2}{16} + \frac{Z\lambda}{2}} \quad \Rightarrow \quad \text{for } Z >> \lambda \quad \Rightarrow \quad R = \sqrt{\frac{Z\lambda}{2}}$$

To obtain *R* as lateral resolution at depth *Z*, ➡

$$f = \frac{Zv}{2R^2}$$

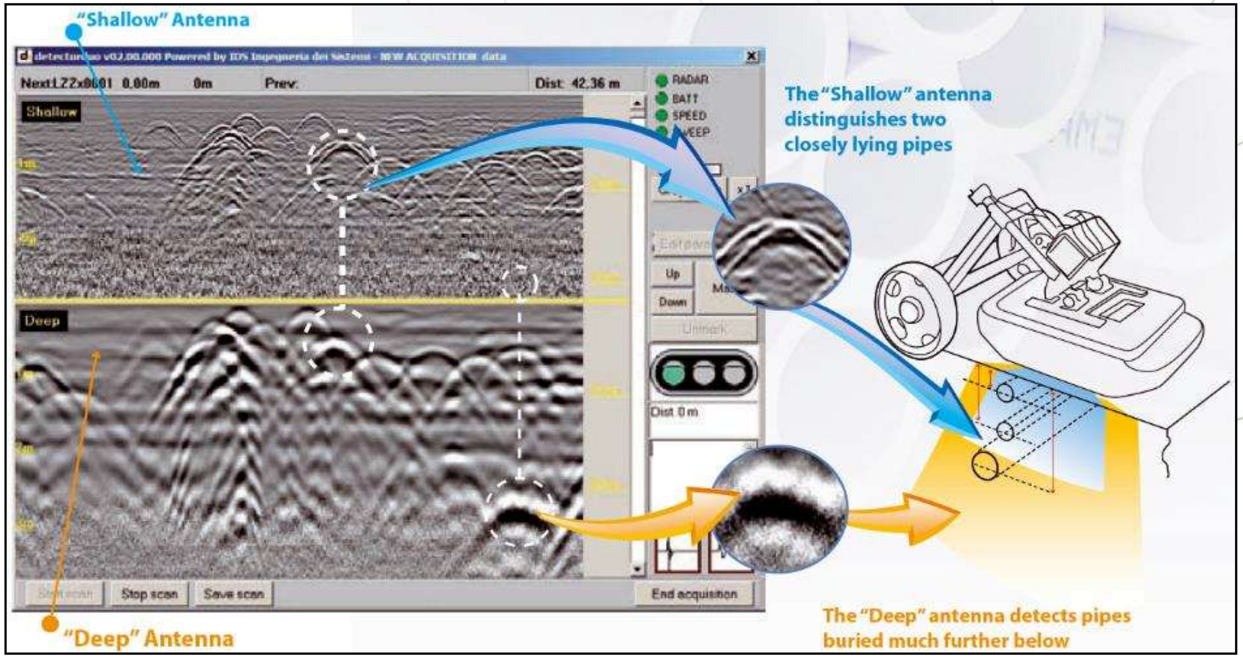
Data acquisition

Frequency vs. Penetration

Since absorption is proportional to frequency:

Penetration (m)	Frequency MHz)
0.5-1.0	1000
1.0-2.0	500
2.0-10	200
5-15	100
10-30	50
30-50	25
50-100	10

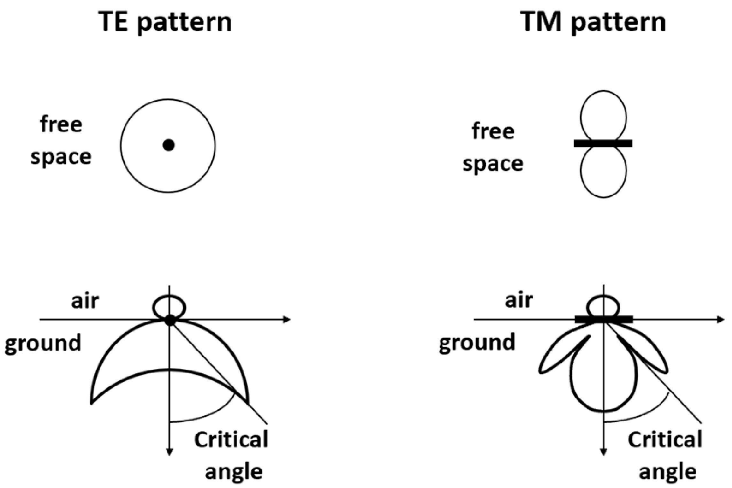
Advantage of Multi-frequency antennas

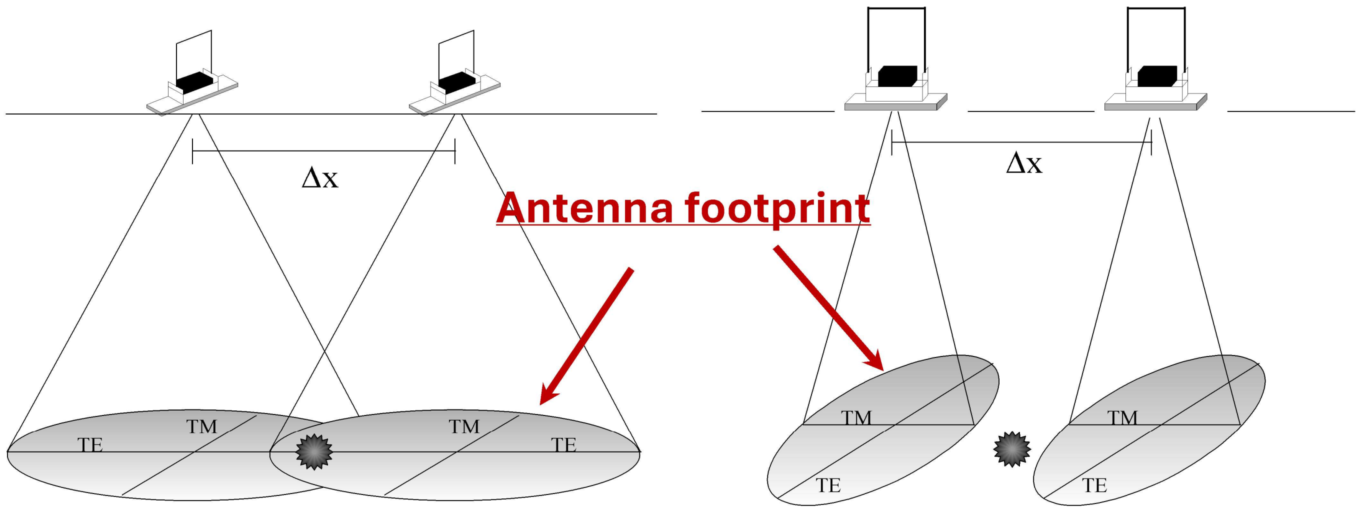


Detector DUO (IDS)

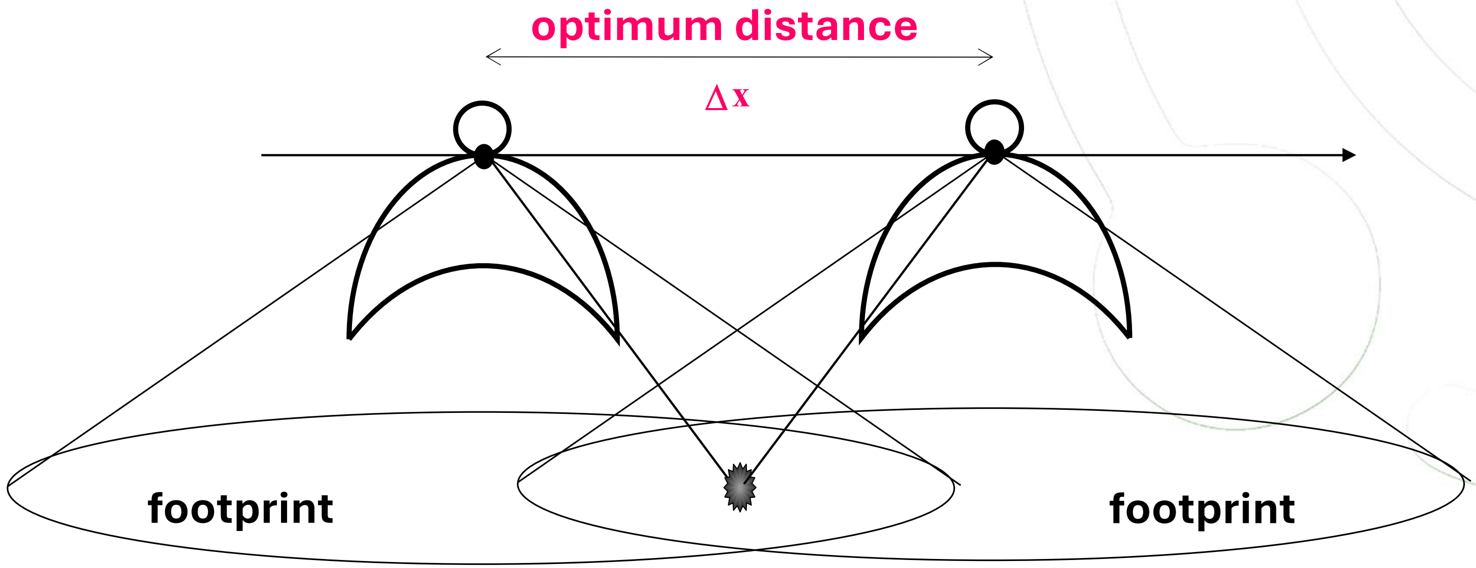
Antenna directivity

Directivity functions





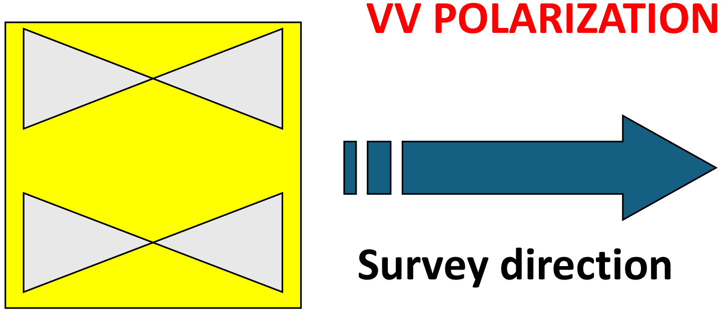
Antenna directivity



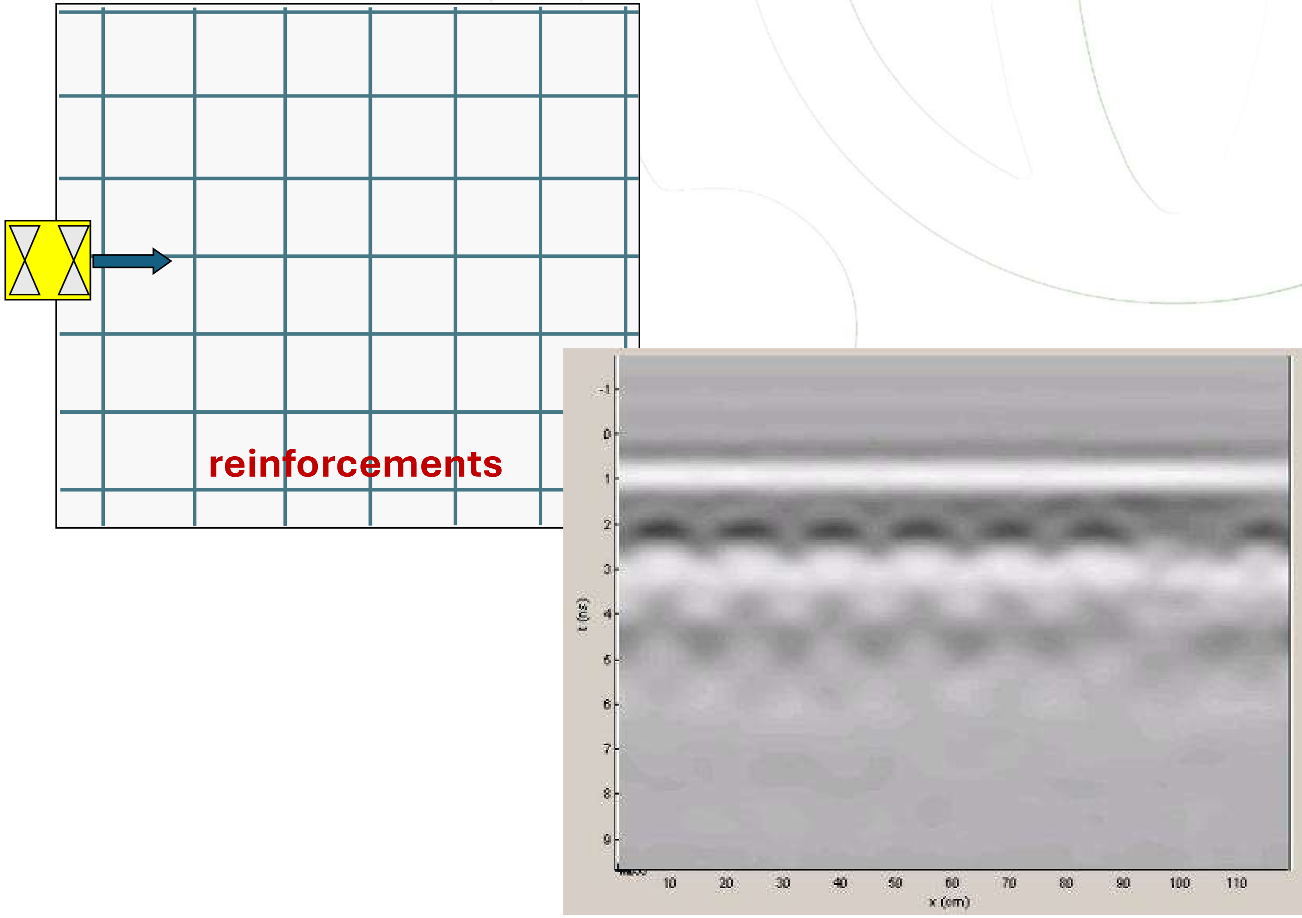
Polarization

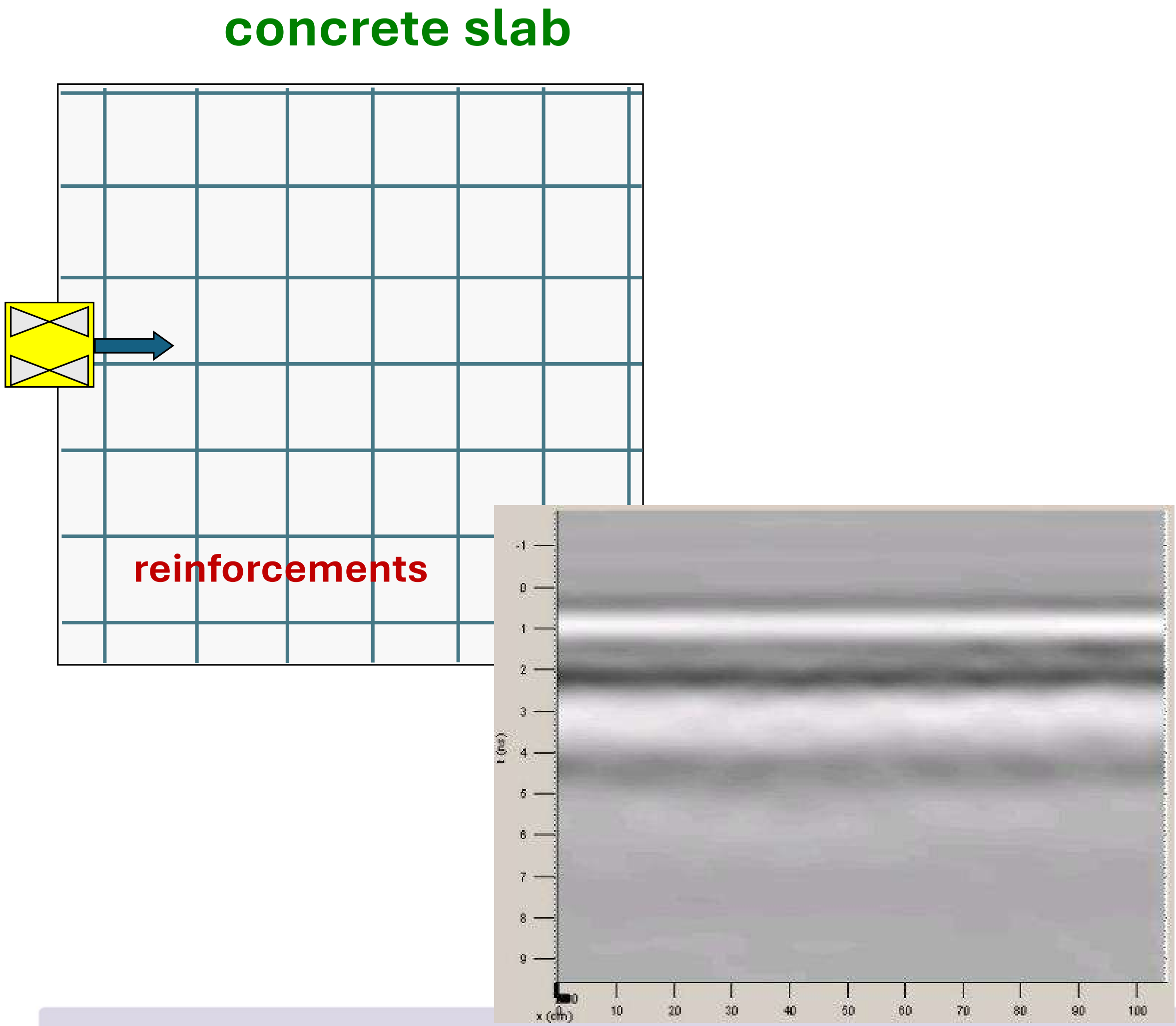
HH POLARIZATION

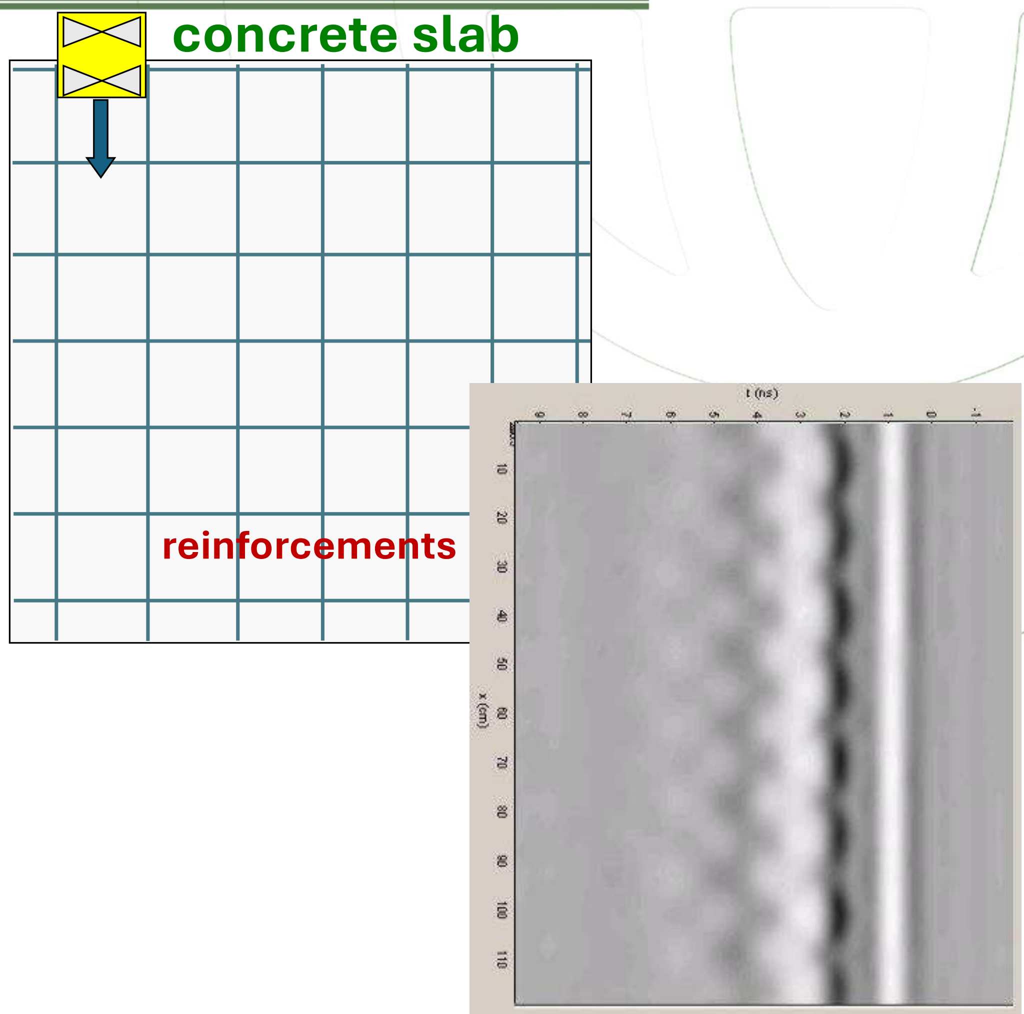
VV POLARIZATION



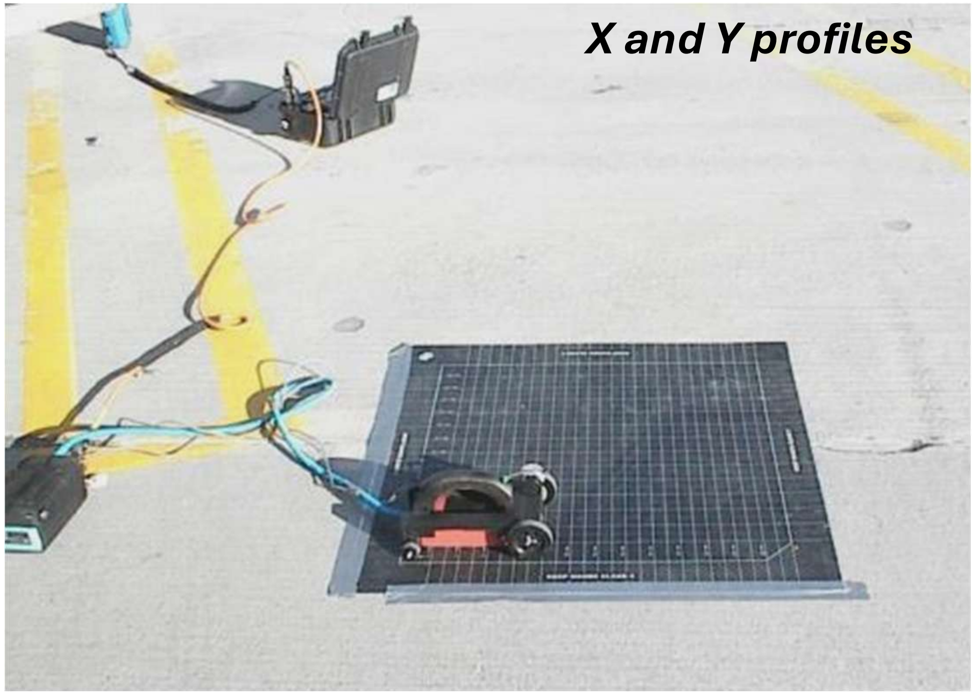
concrete slab



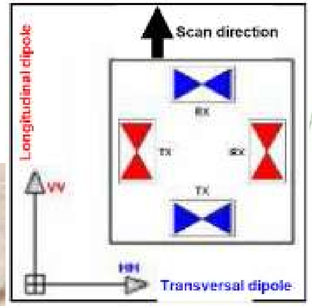

concrete slab
reinforcements
t (ns)
x (cm)

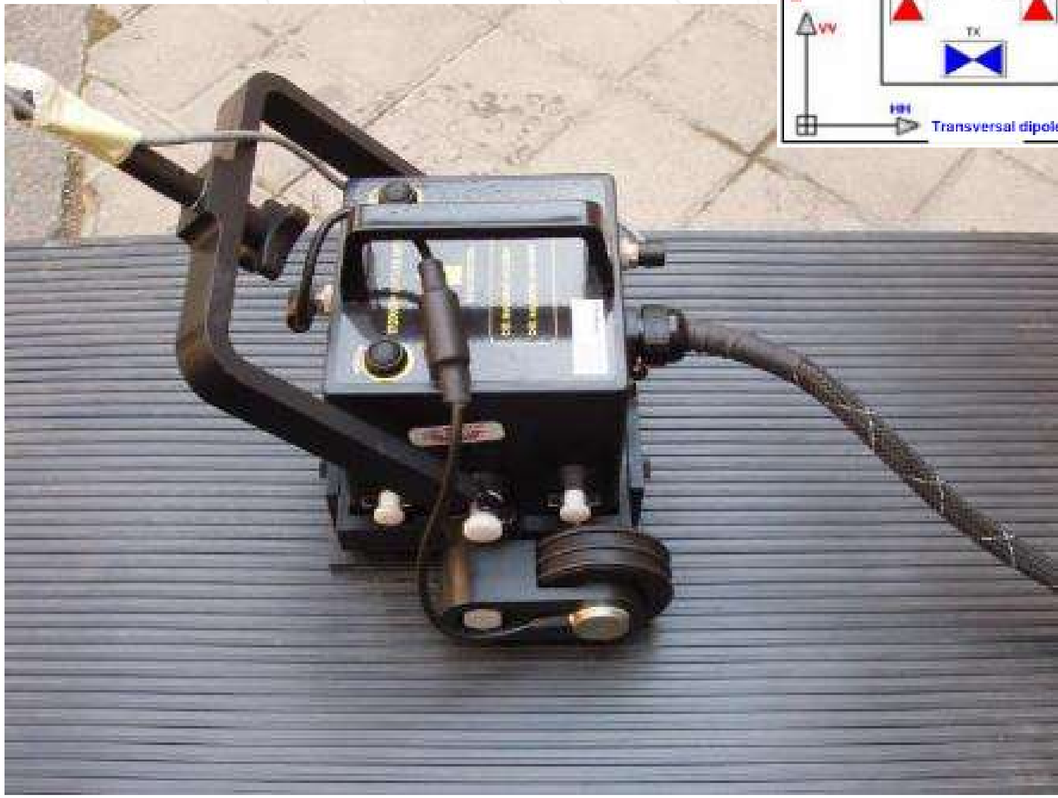

concrete slab
reinforcements
t (ns)
x (cm)

Polarization

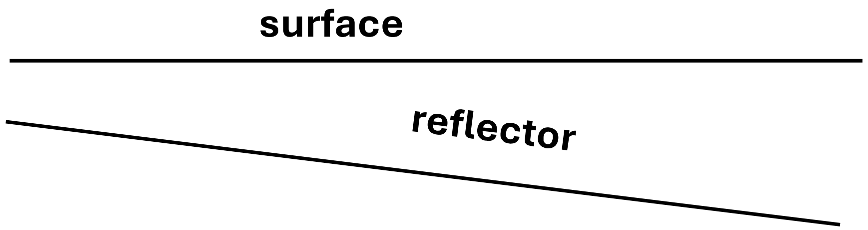


X profiles

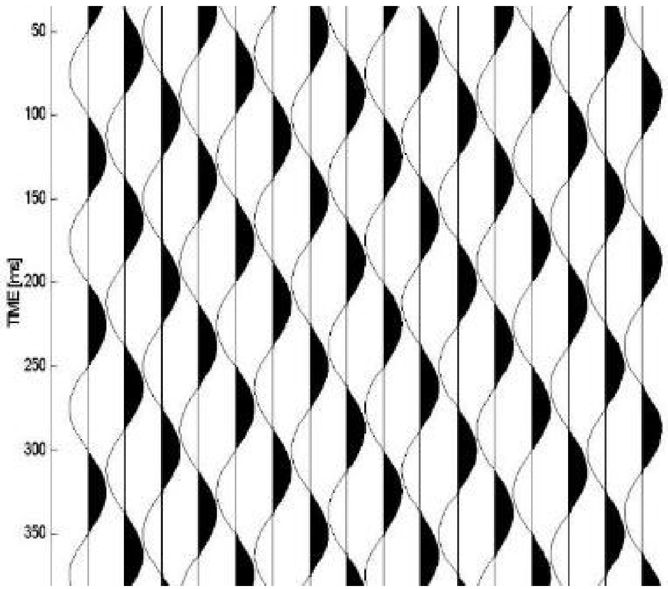


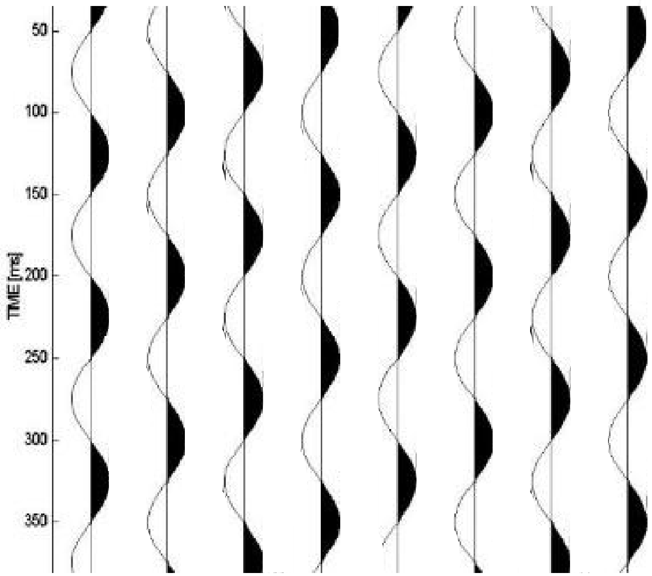


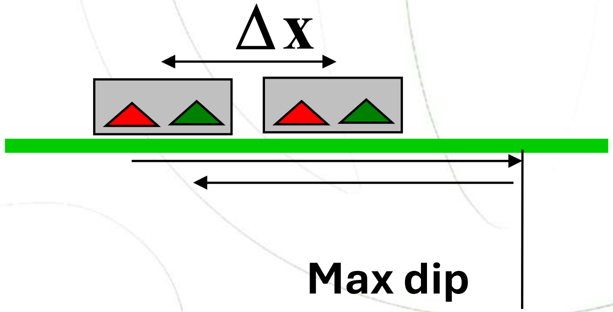
Spatial aliasing



no aliasing / *with aliasing*







$$\Delta x < \frac{1}{4}\lambda_{min}$$

$$\Delta x < \frac{1}{4} V/F_{max}$$

$$\Delta x < \frac{1}{6} V/F$$

Spatial positioning

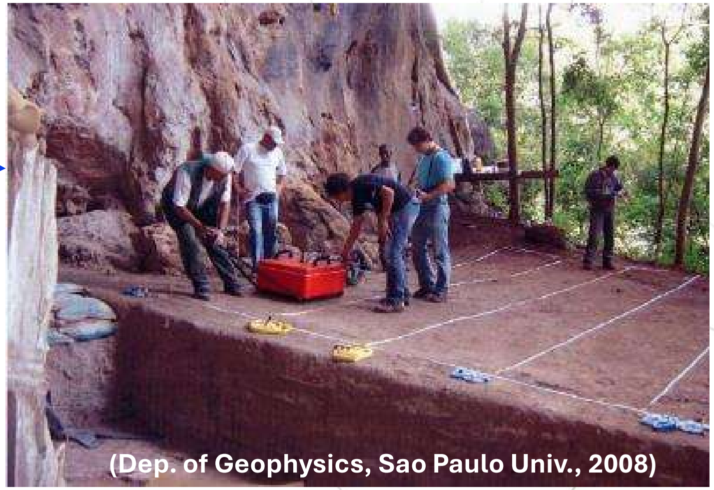
2D survey

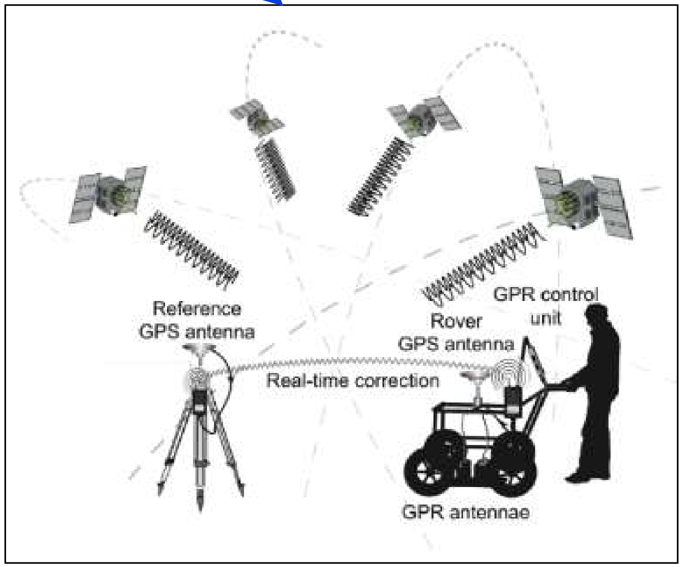
- fixed step positioning
- fiducial markers
- odometer

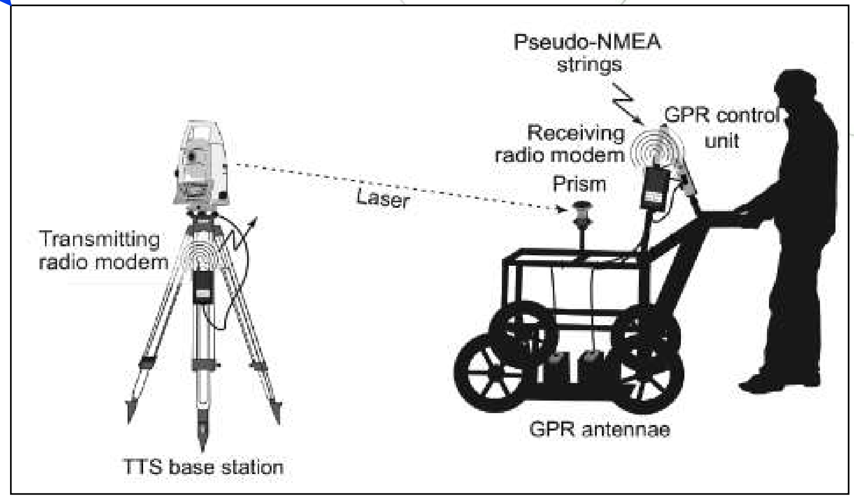
Spatial positioning

3D survey

- tapes or ropes
- advanced 3D systems
  (GPS, Self-Tracking Total Station)

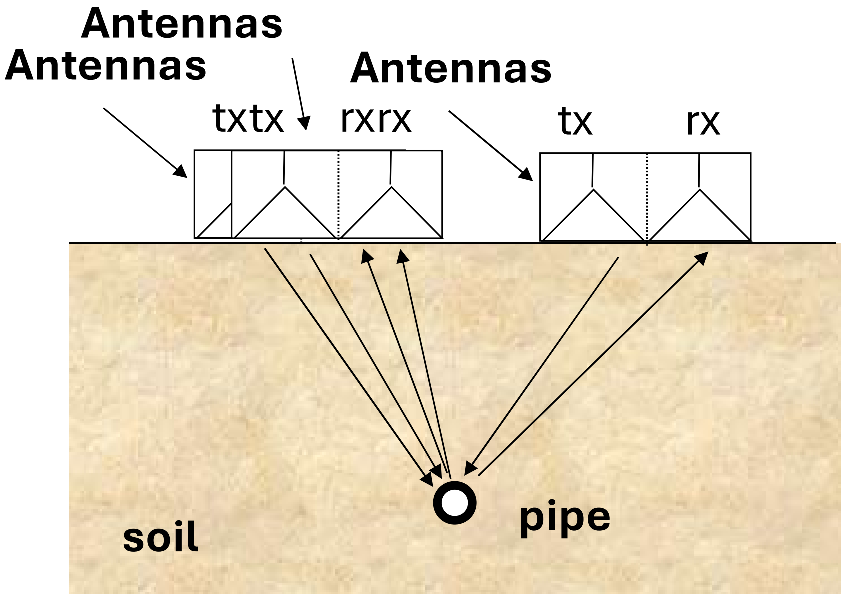




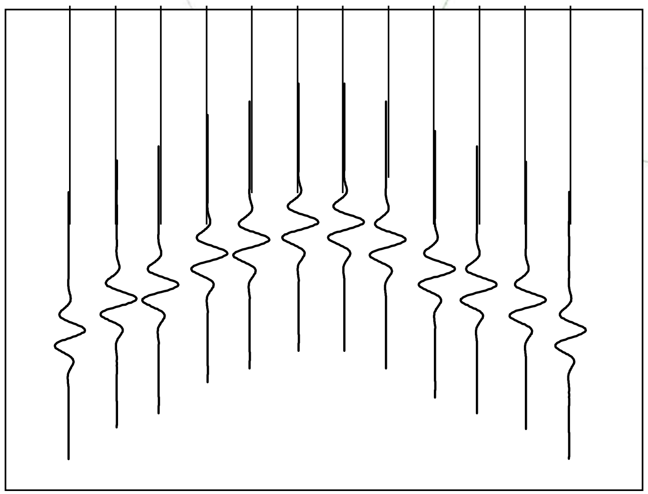


(Tronicke and Boniger, 2010, Potsdam Univ.)

Diffractions



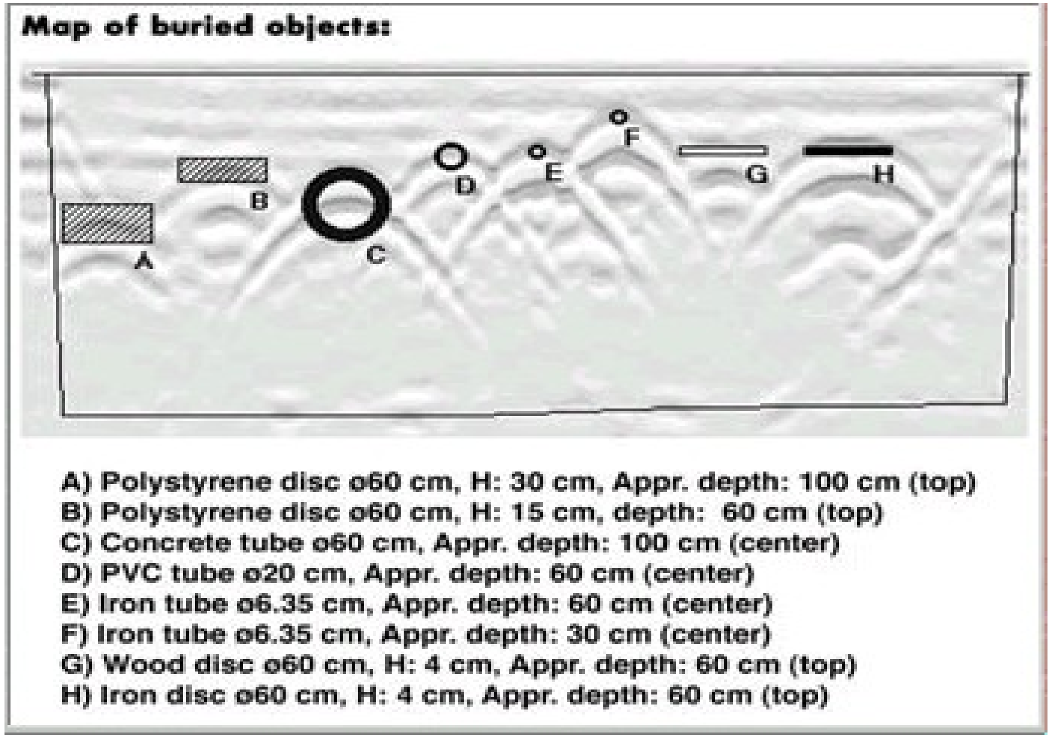
Diffraction generated by the pipe

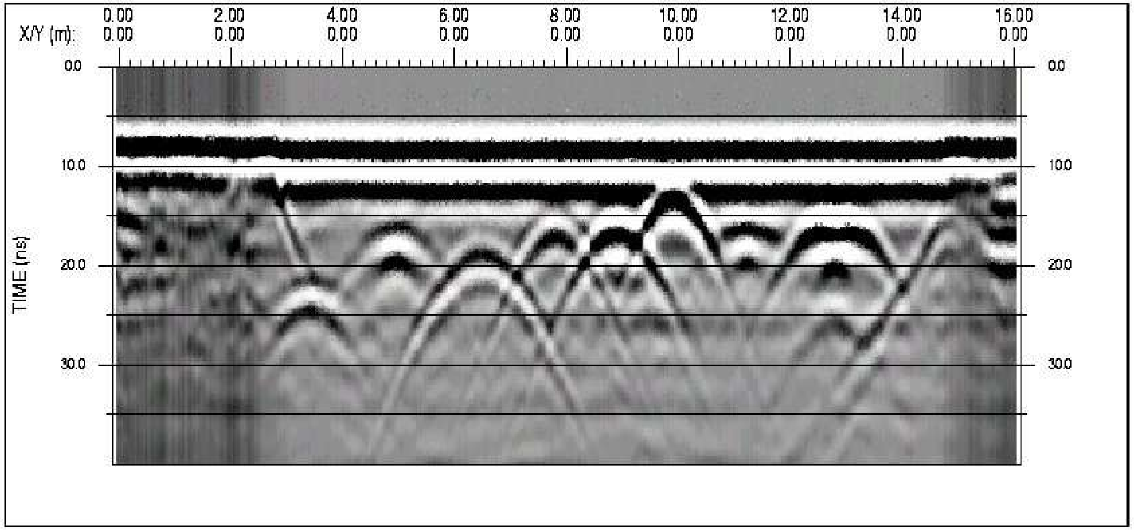


Data analysis and interpretation

ISMES test site

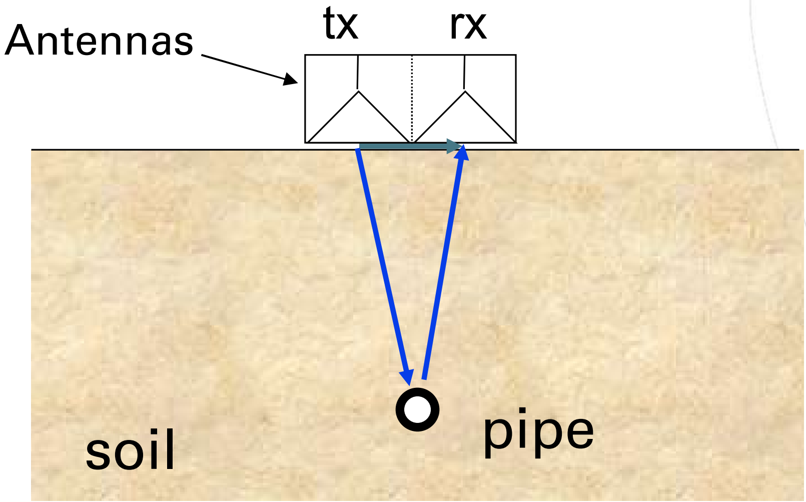
Raw data (RAMAC 400 MHz)

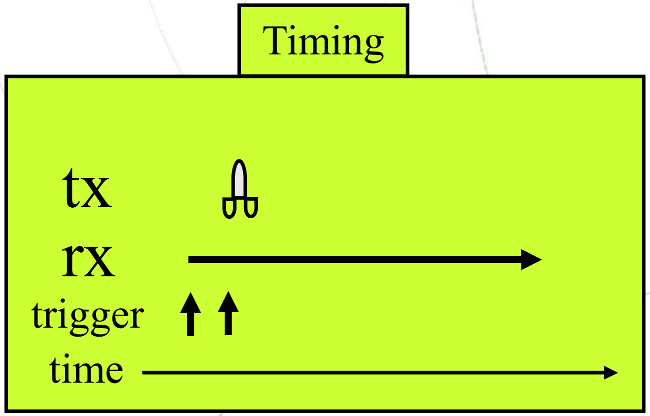


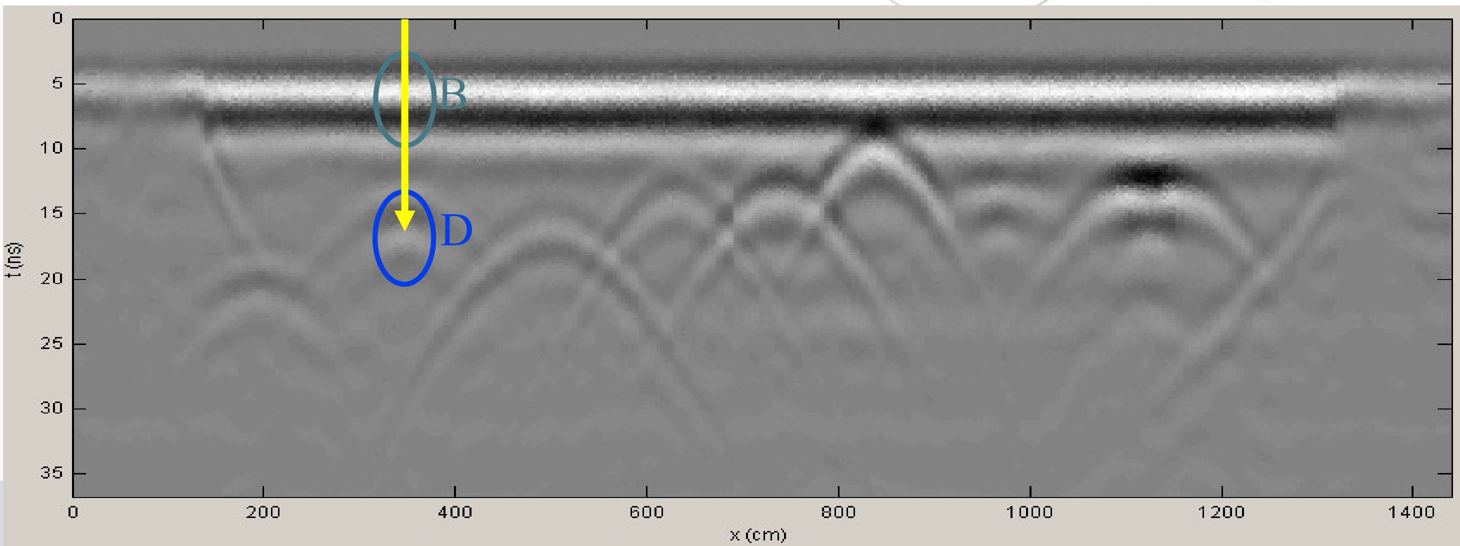


Data analysis and interpretation

Time calibration







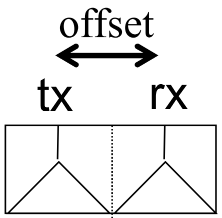
Data analysis and interpretation

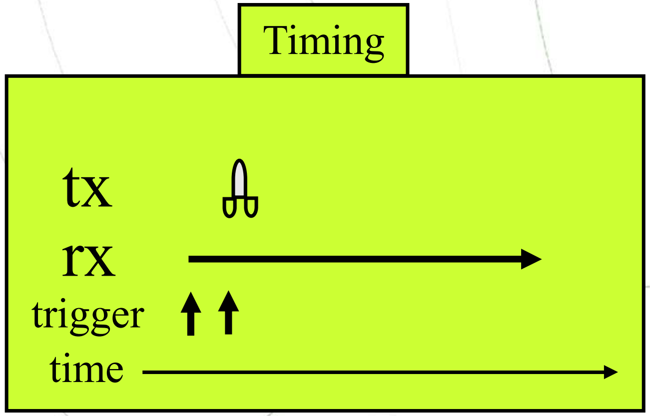
Time calibration

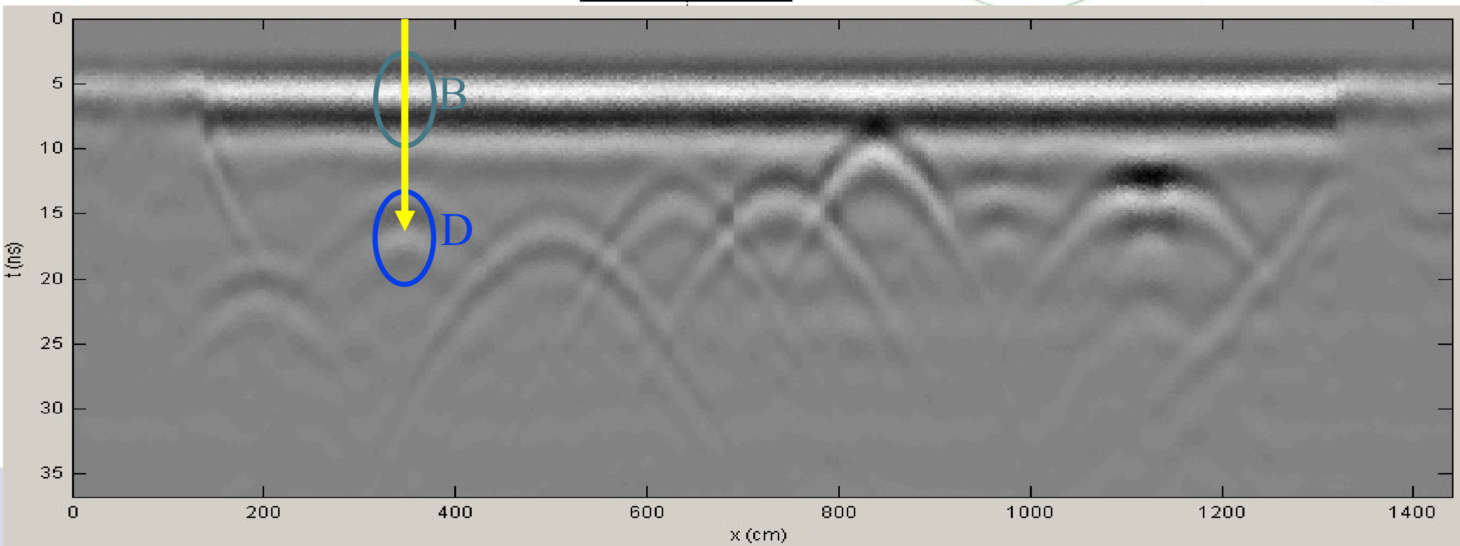
- Time calibration moves the time scale so that zero time occurs when the tx is triggered.
- This time is obtained from the data by picking event B and ....

$$t_0 = t_B - \frac{offset}{c}$$

with c = 30cm/ns

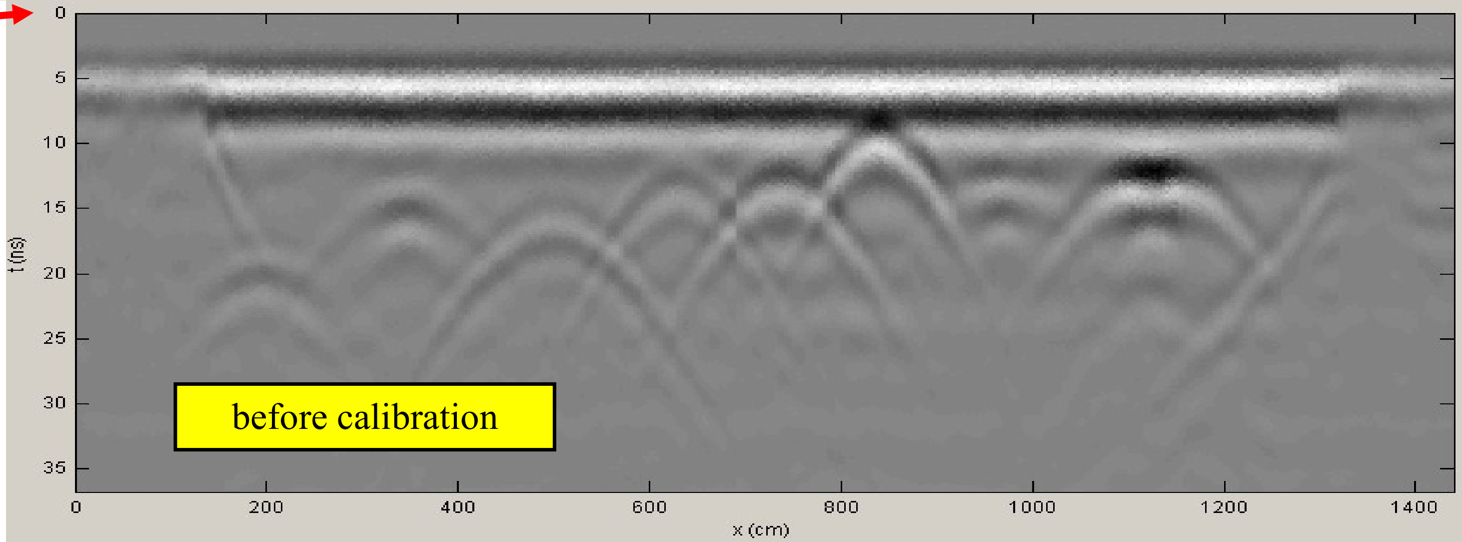




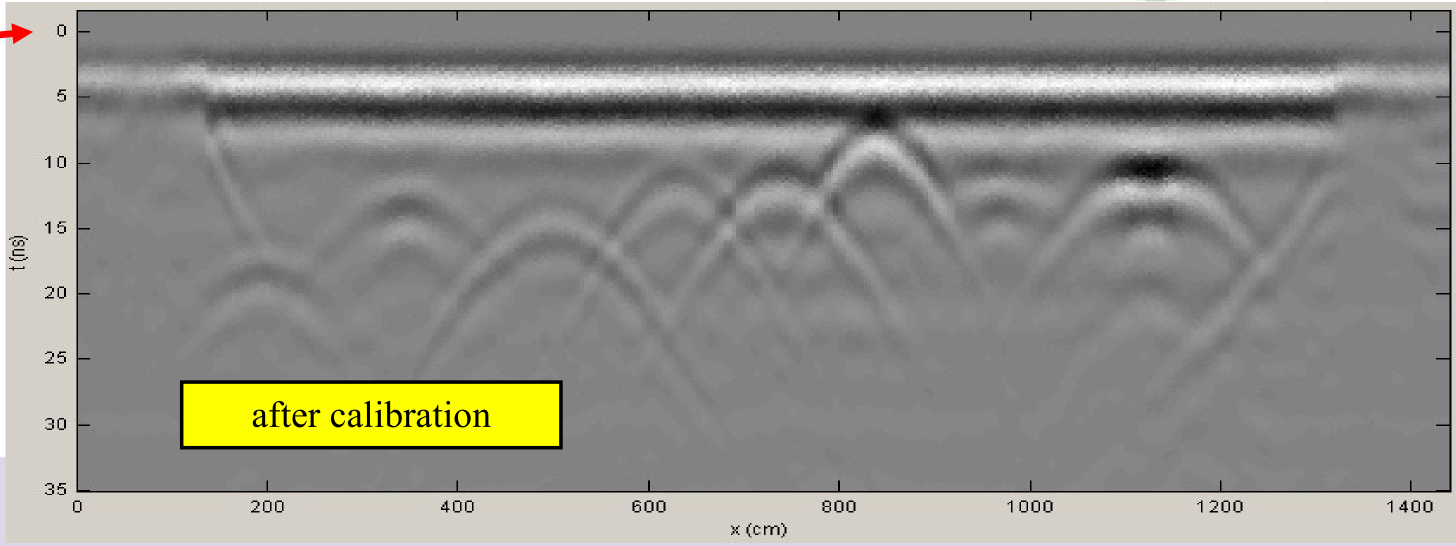


Data analysis and interpretation

time zero



time zero



Data analysis and interpretation

Spherical Exponential Compensation (SEC)

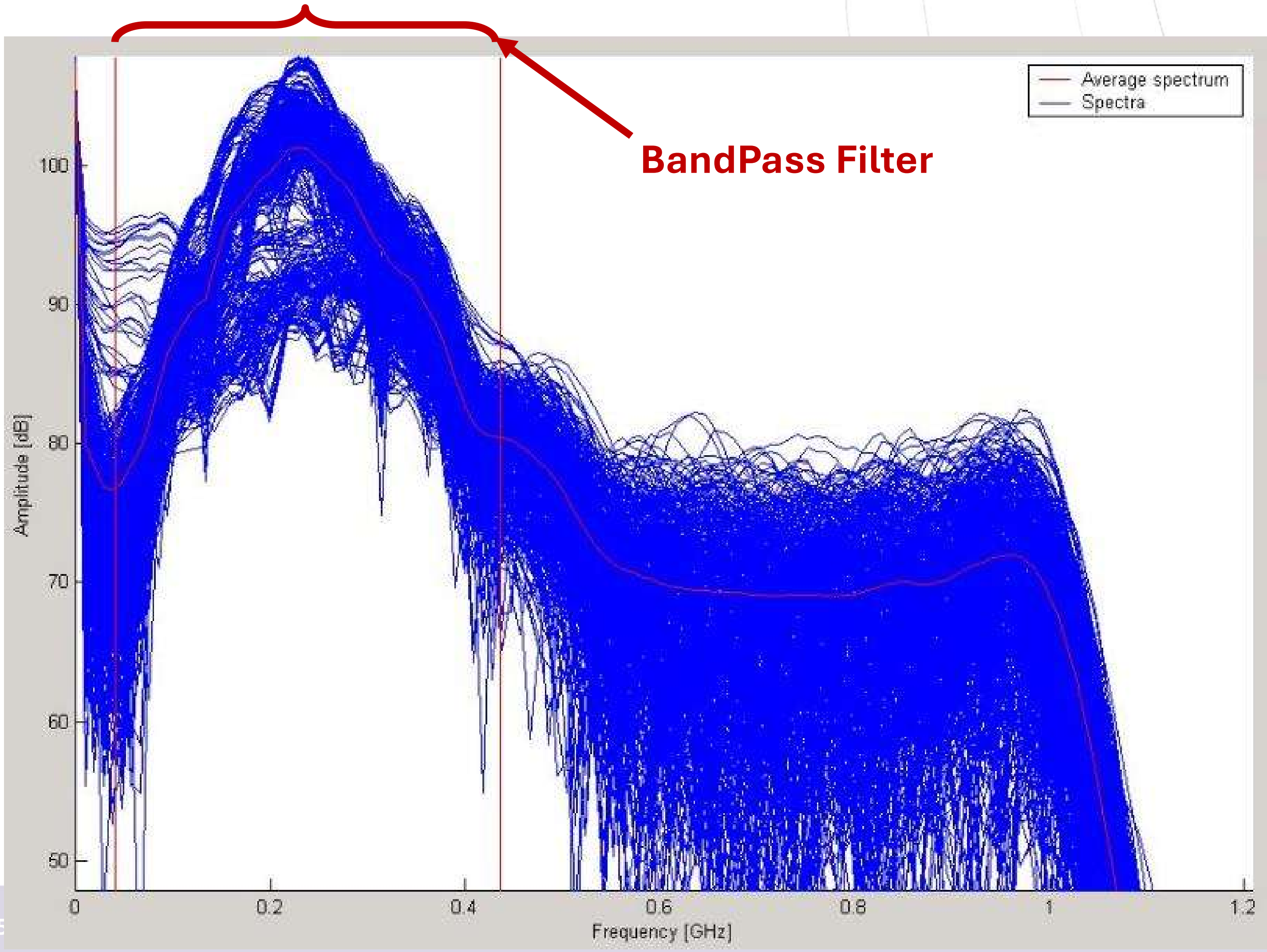
Because of spherical divergence ➡ $A(r) \propto \frac{1}{r}$

Because of absorption ➡ $A(r) \propto e^{-\alpha * r}$

SEC compensation:

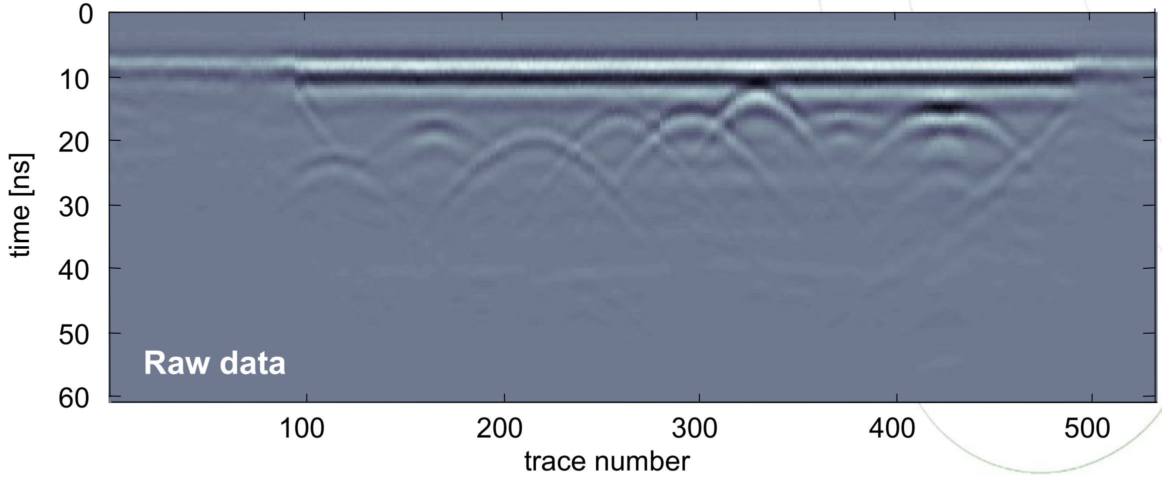
$$G(t) \propto r * e^{\alpha * r} \Rightarrow G(t) \propto v * t * e^{\alpha * v * t}$$

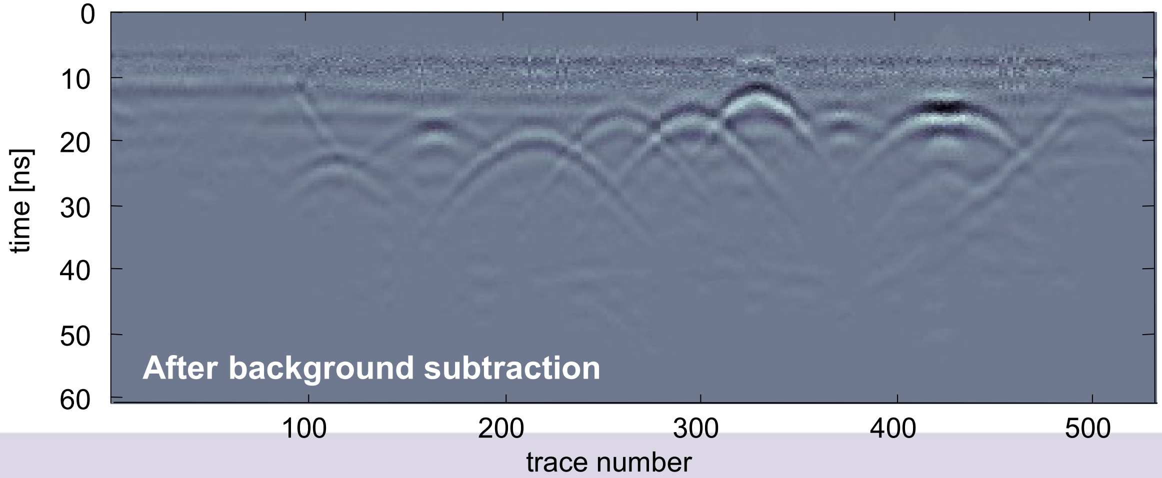
Data analysis and interpretation



Data analysis and interpretation

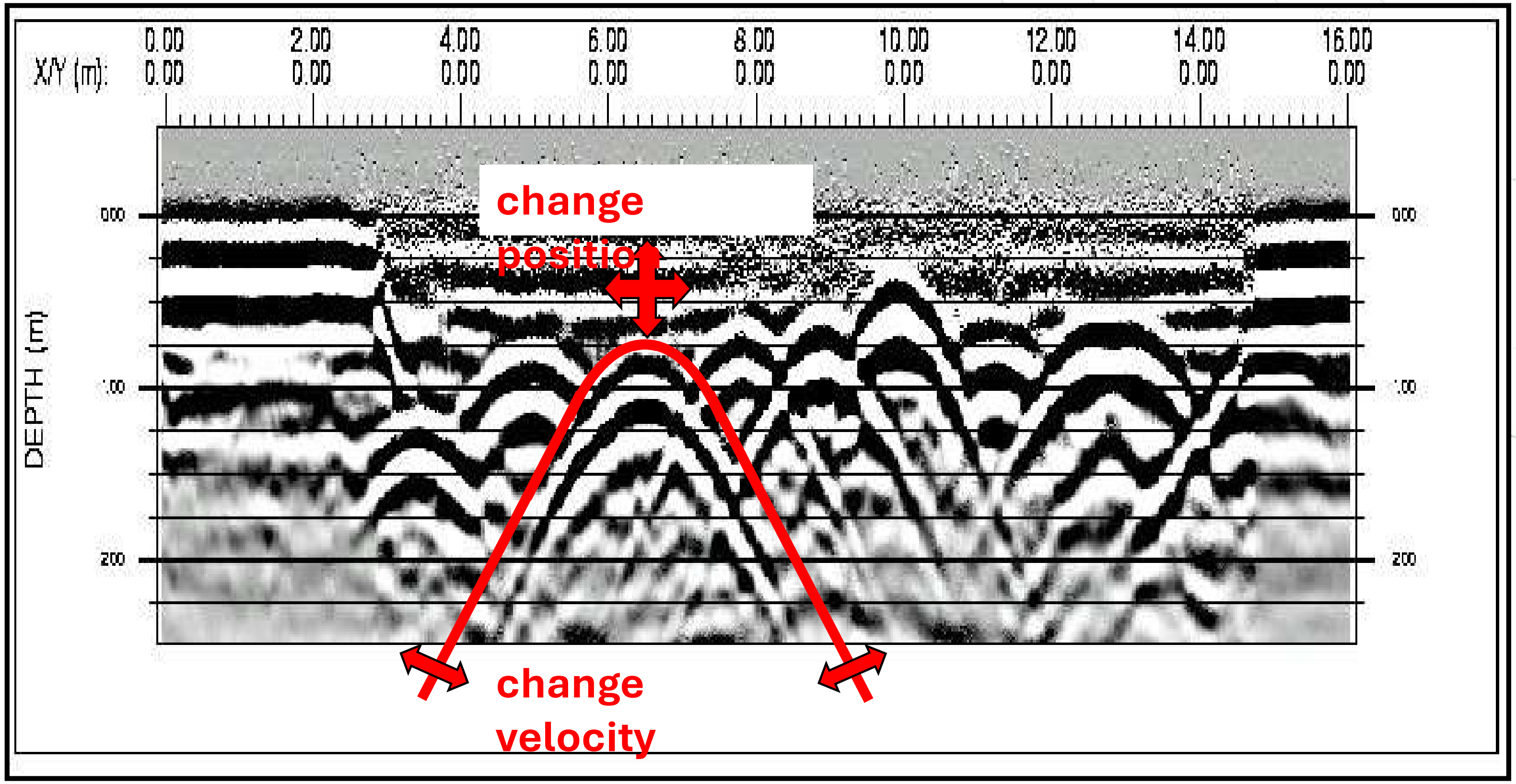
Background subtraction





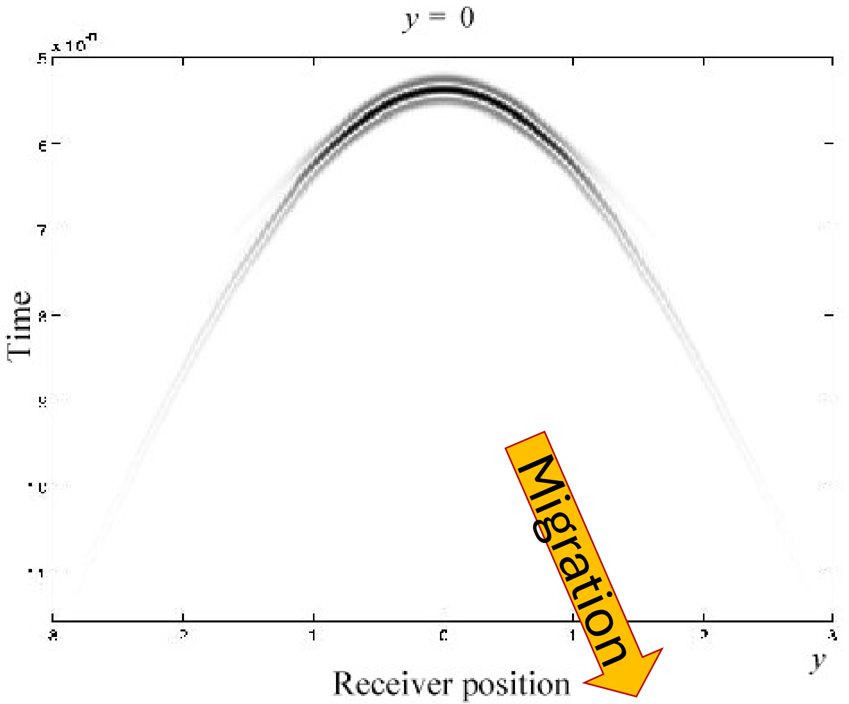
Data analysis and interpretation

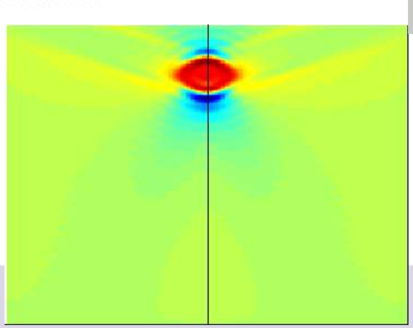
Velocity Analysis

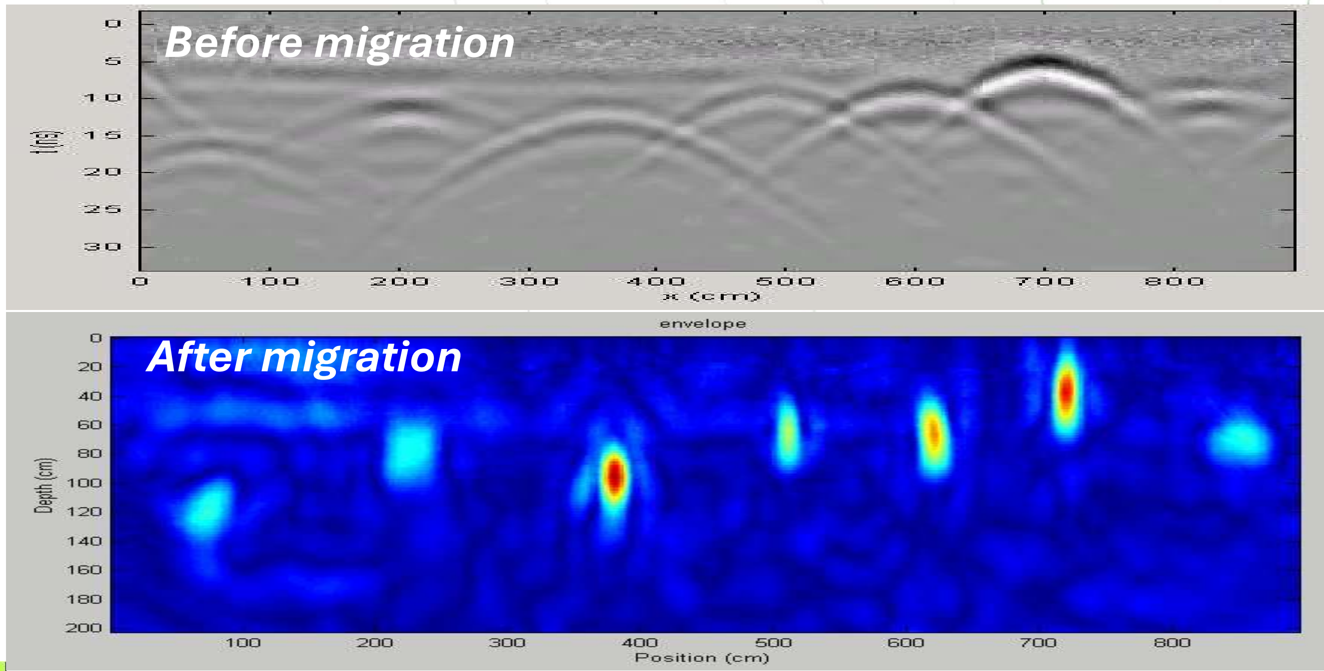


Data analysis and interpretation

Migration



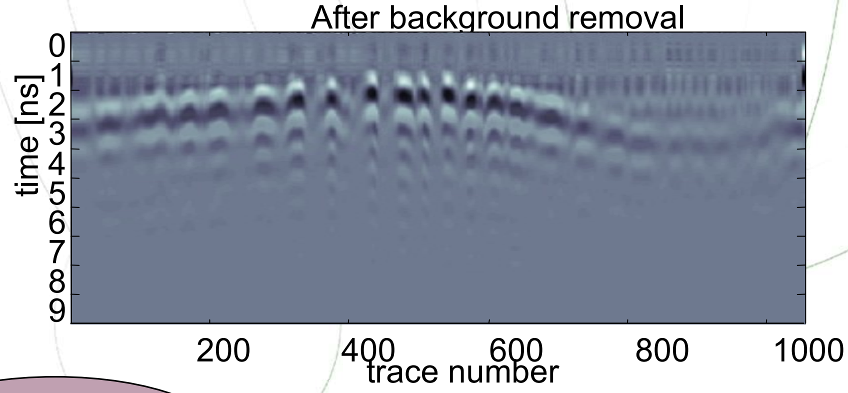


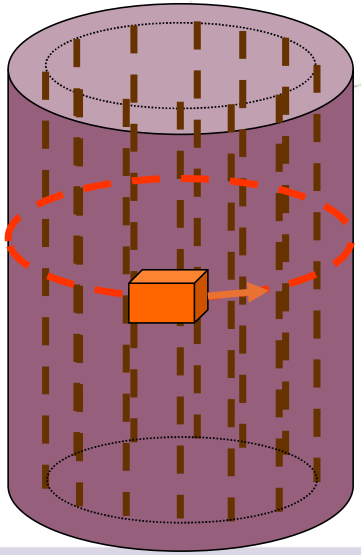


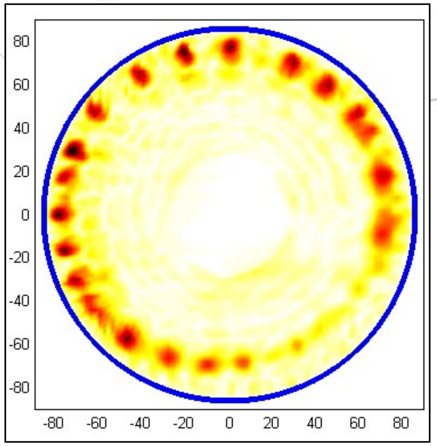
Applications

- **Bedrock depth**
- **Water table depth**
- **Rock fractures**
- **Detection of urban subsurface utilities for safe excavations**
- **Highway and bridge maintenance**
- **Non-Destructive testing on buildings**
- **Glaciology**
- **Lake bottom mapping**
- **Mining**
- **Archaeology**
- **Forensic**
- **Humanitarian demining**

Bar detection in reinforced concrete

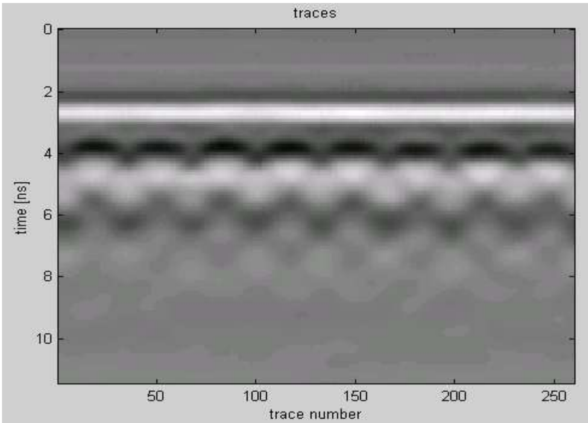




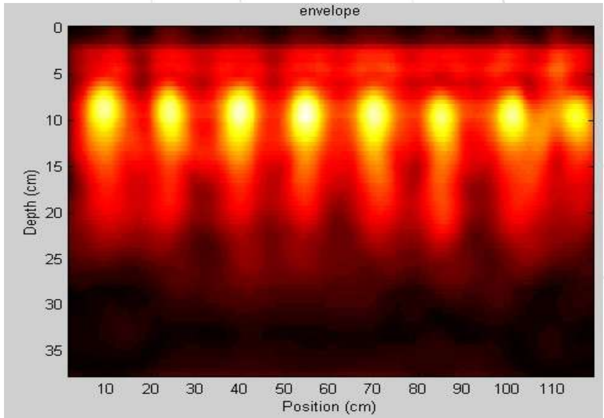


Example: bar detection in concrete

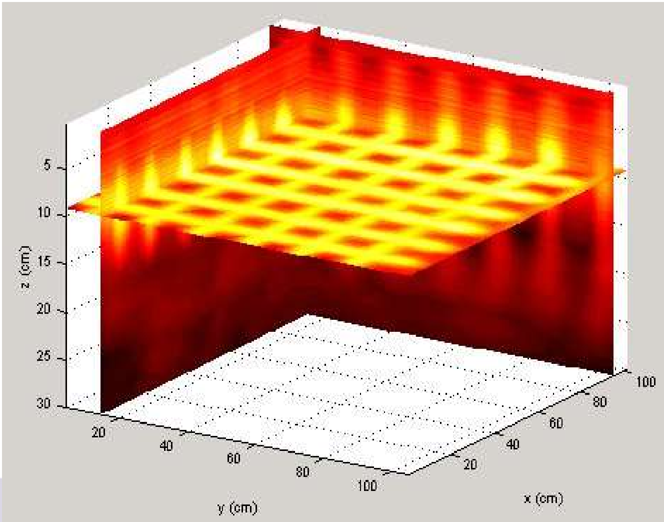
Raw data

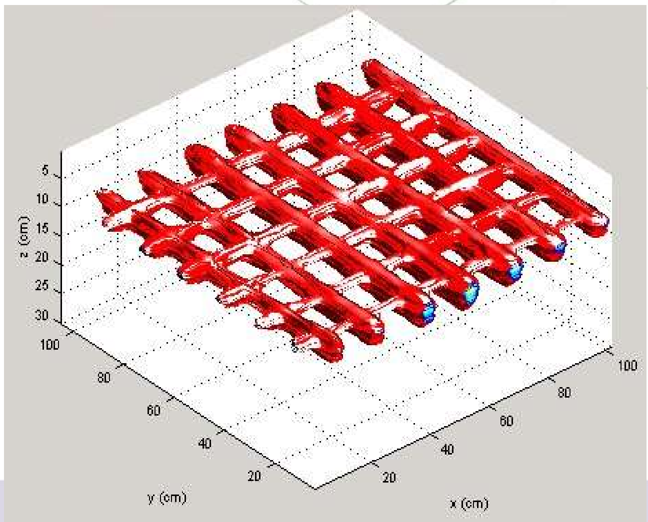


2D processed data

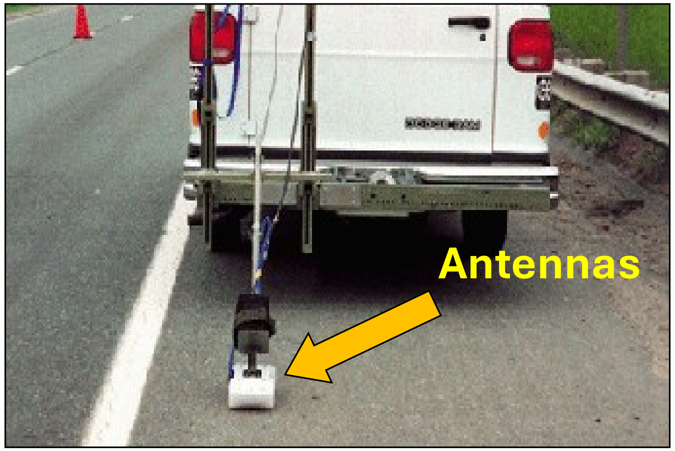


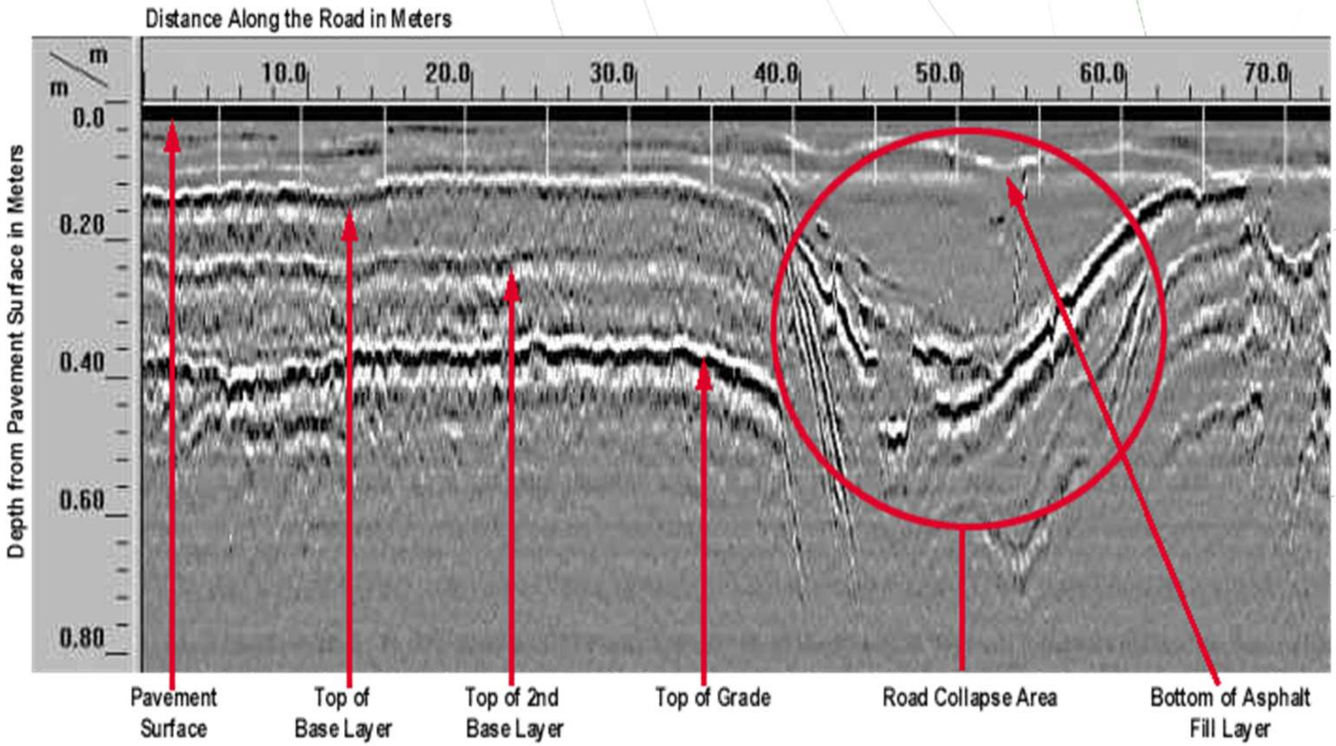
3D processed data





Example: bridge and highway inspections

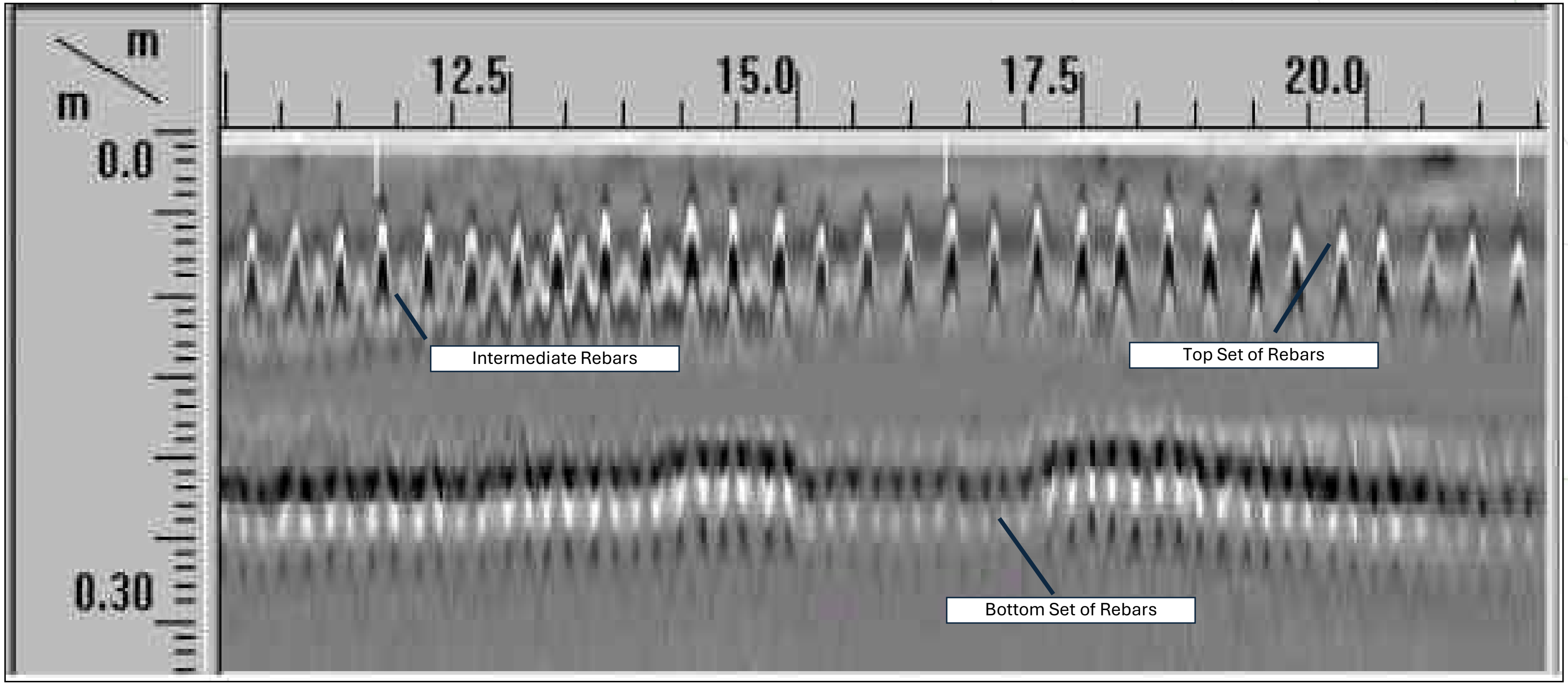




(courtesy GSSI)

Example: bridge and highway inspections

Location and depth of Rebars as part of a concrete slab investigation.



Note that the intermediate rebars were found to be missing on the right side of this section.

(courtesy GSSI)

Example: tunnel inspections

OYO's (Japan) highway tunnel inspection vehicle "RAPIDAS"

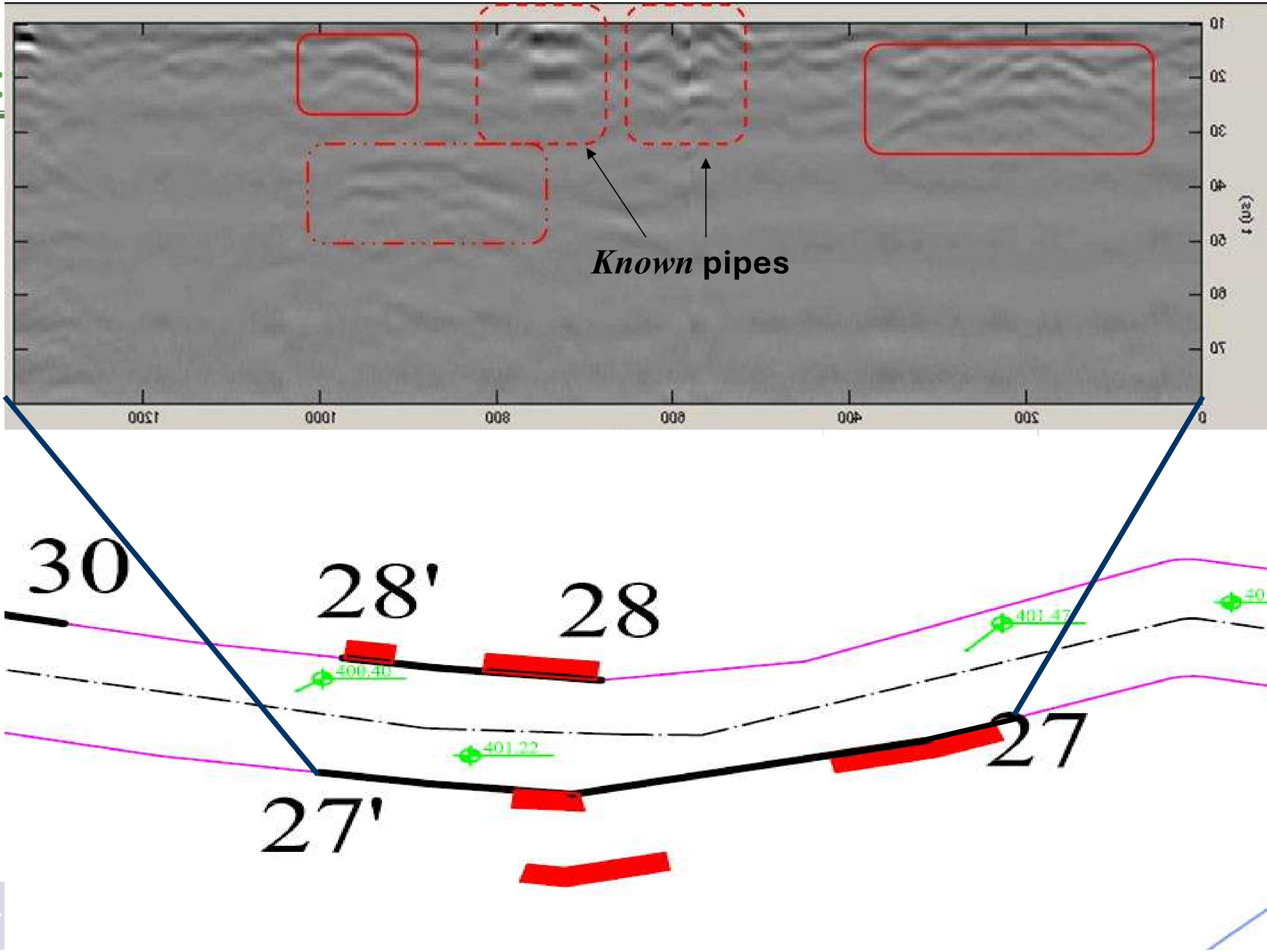
400 MHz or 900 MHz antenna

Example: tunnel inspections (a water tunnel)



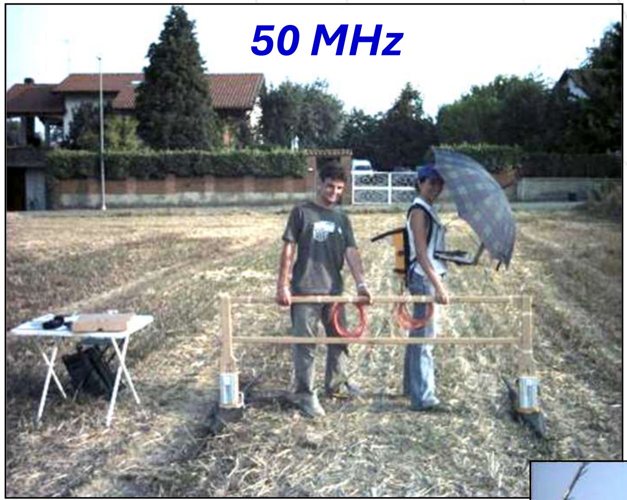



Example:



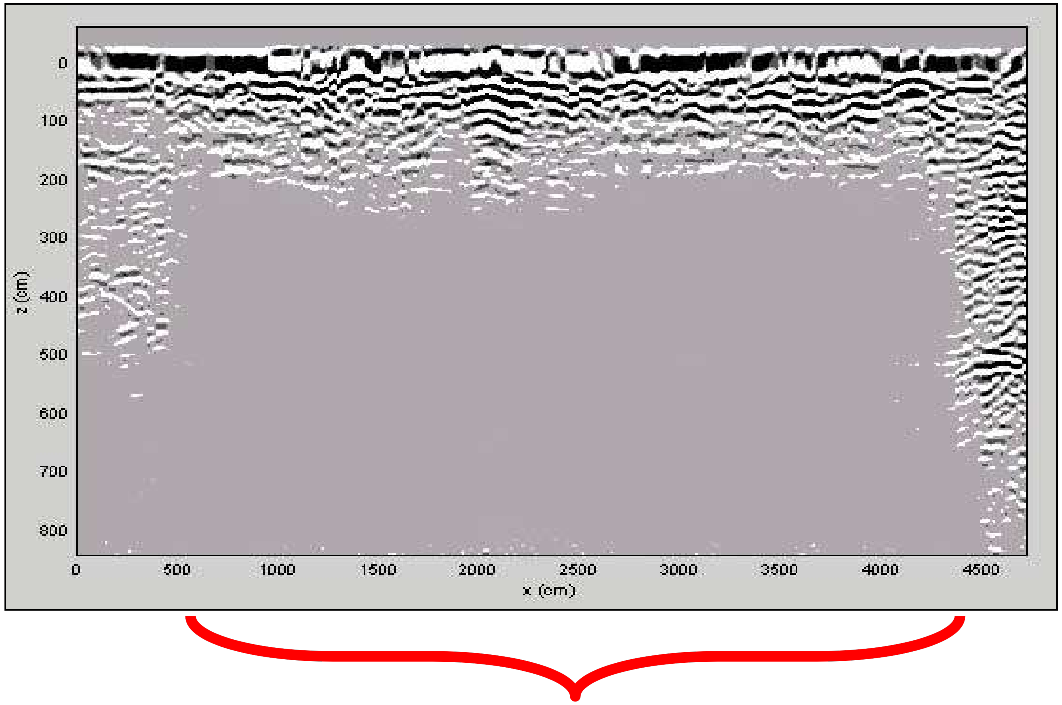
Example: landfills

Investigations on an industrial landfill (contaminations from metals and hydrocarbons)

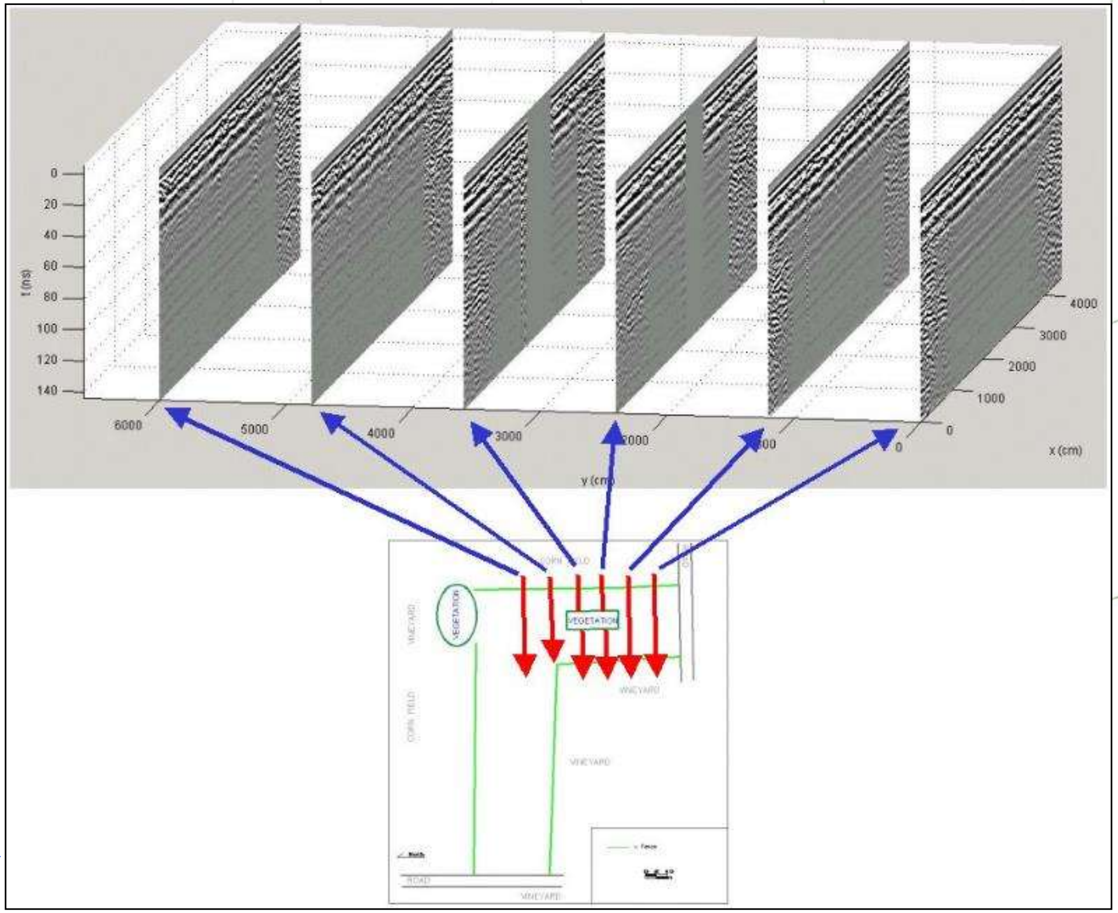


Example: landfills

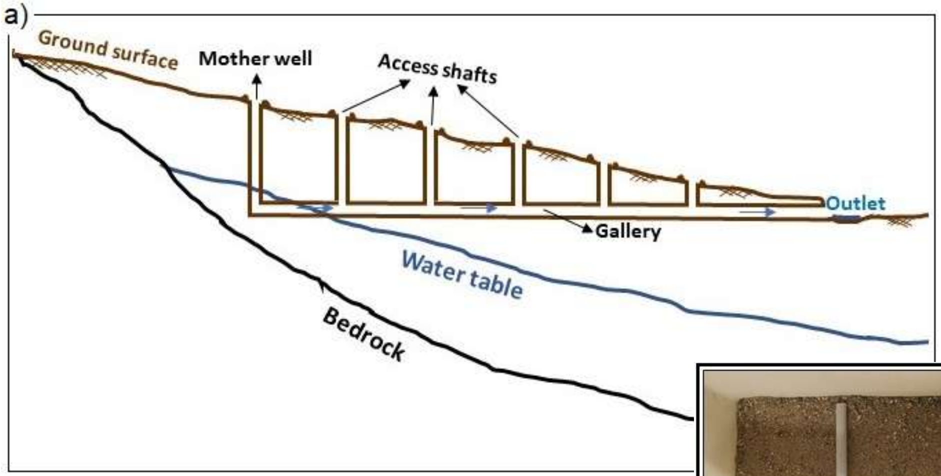
250 *MHz* data



High absorption due to the conductive landfill body



Example: qanat

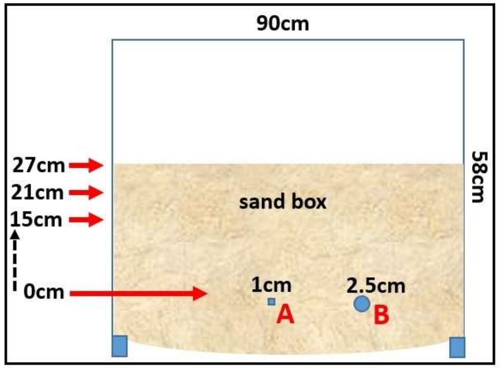


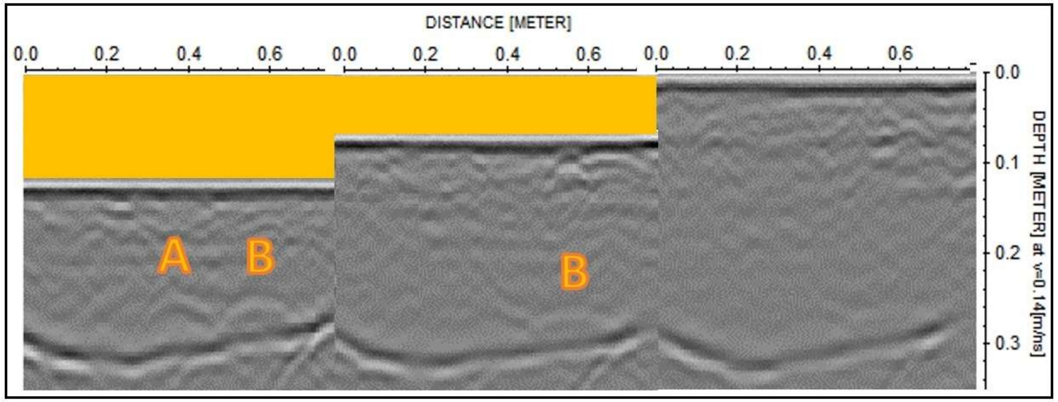
(a) (b)

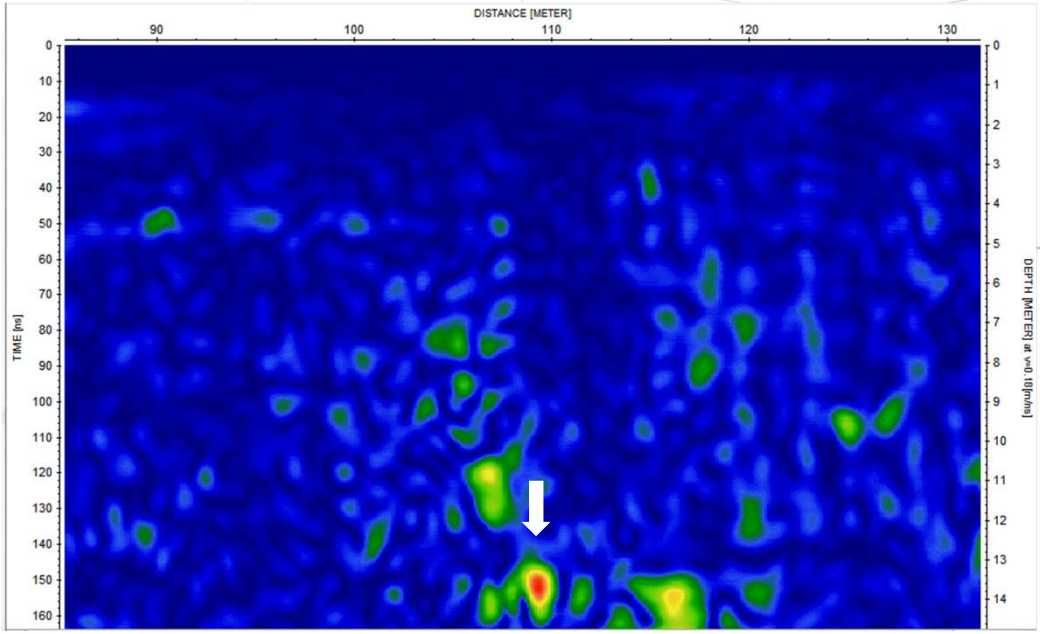
(Hojat et al., 2023)

Example: qanat

Targets buried in the sand with VWC=8%







(Hojat et al., 2023)

Example: quarries

GPR applications in stone production

Quarry

- ✓ **Detecting the depth to layers.**
- ✓ **Determining main discontinuities and defects (faults, fractures, voids, intrusions).**

Blocks

- ✓ **Exploring smaller defects (fractures, voids, intrusions).**
- ✓ **Monitoring the repair condition.**

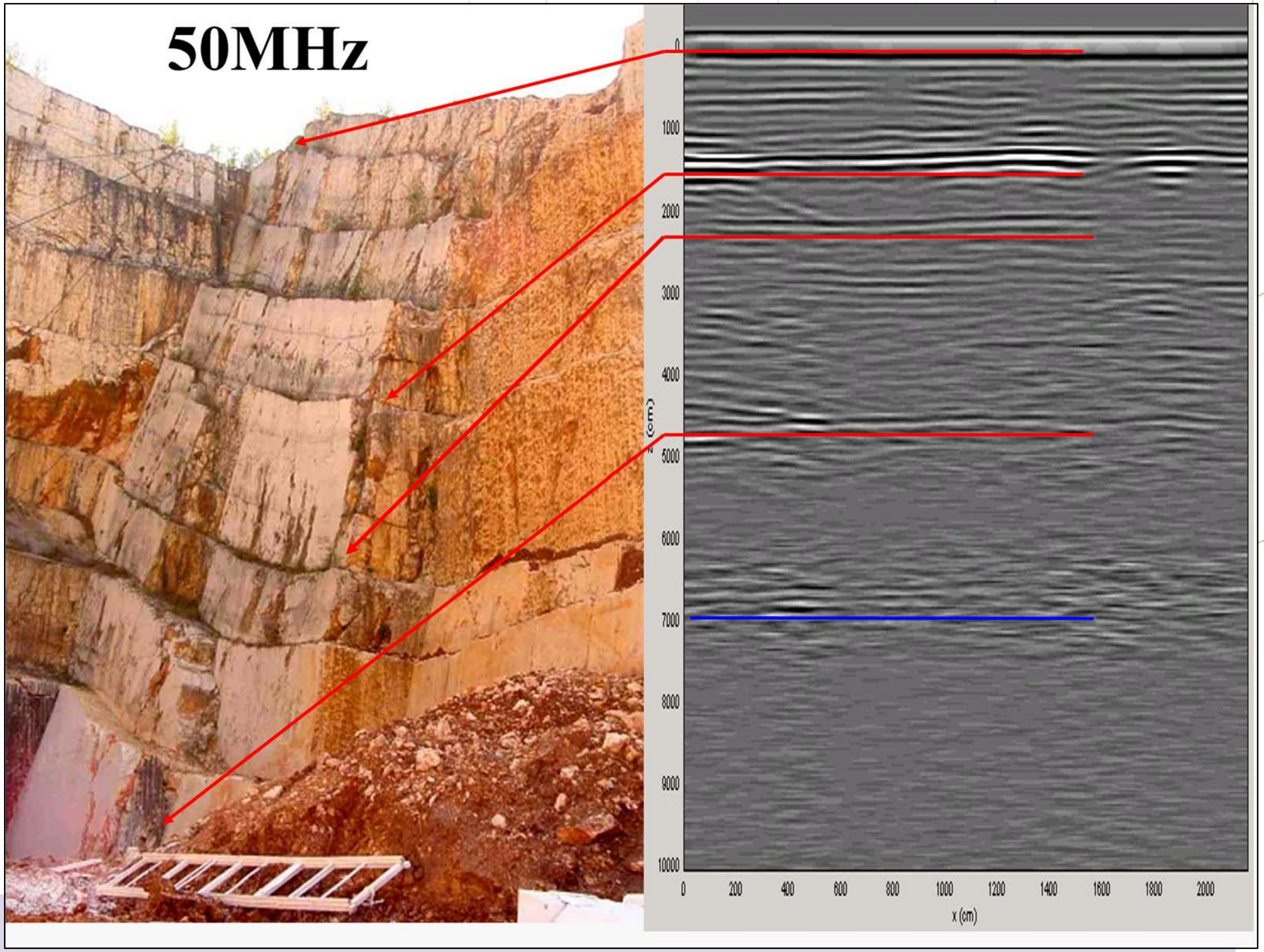
(Hojat, 2023)

Example: quarries

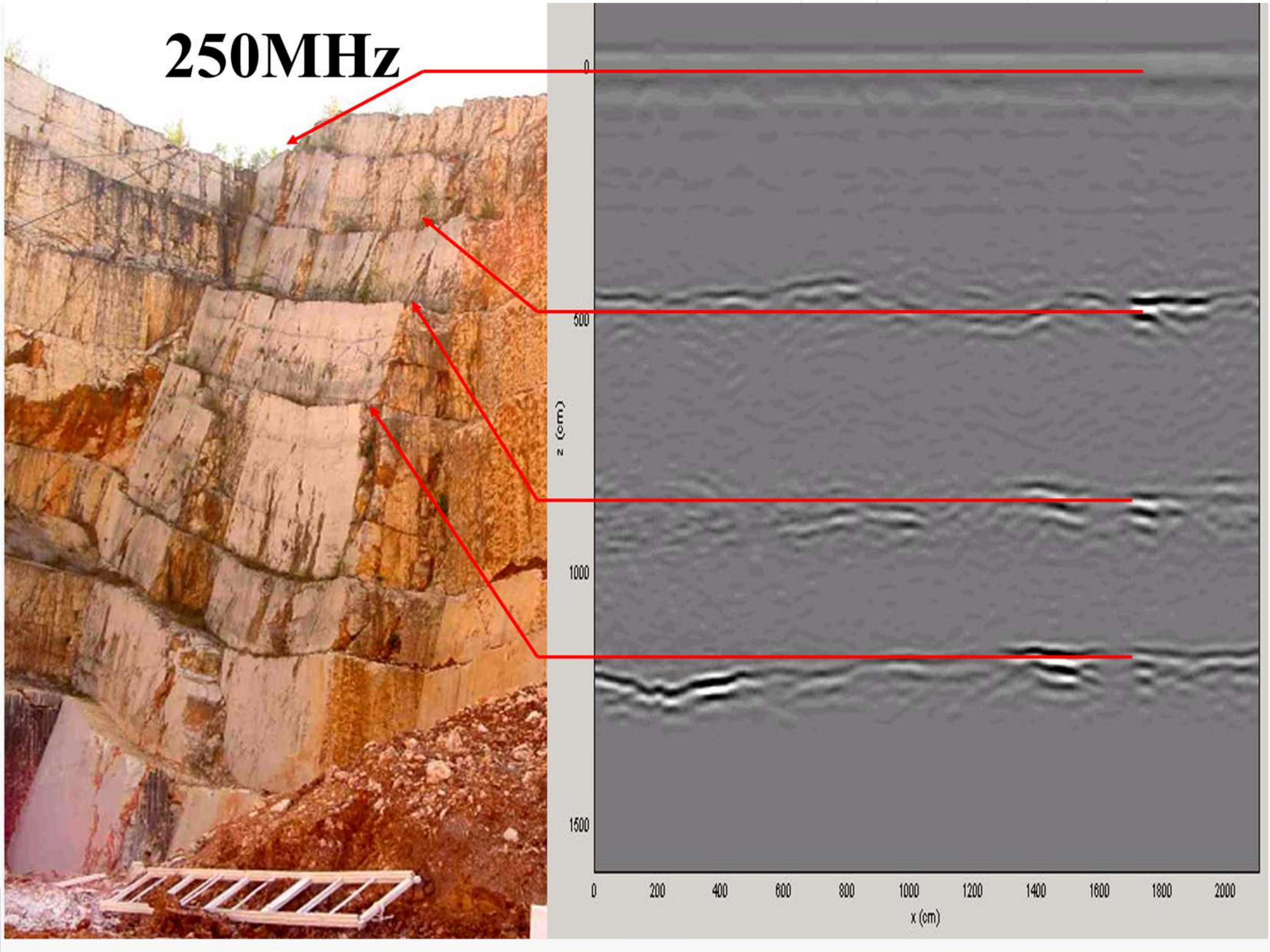
Investigations in a limestone quarry

Example: quarries

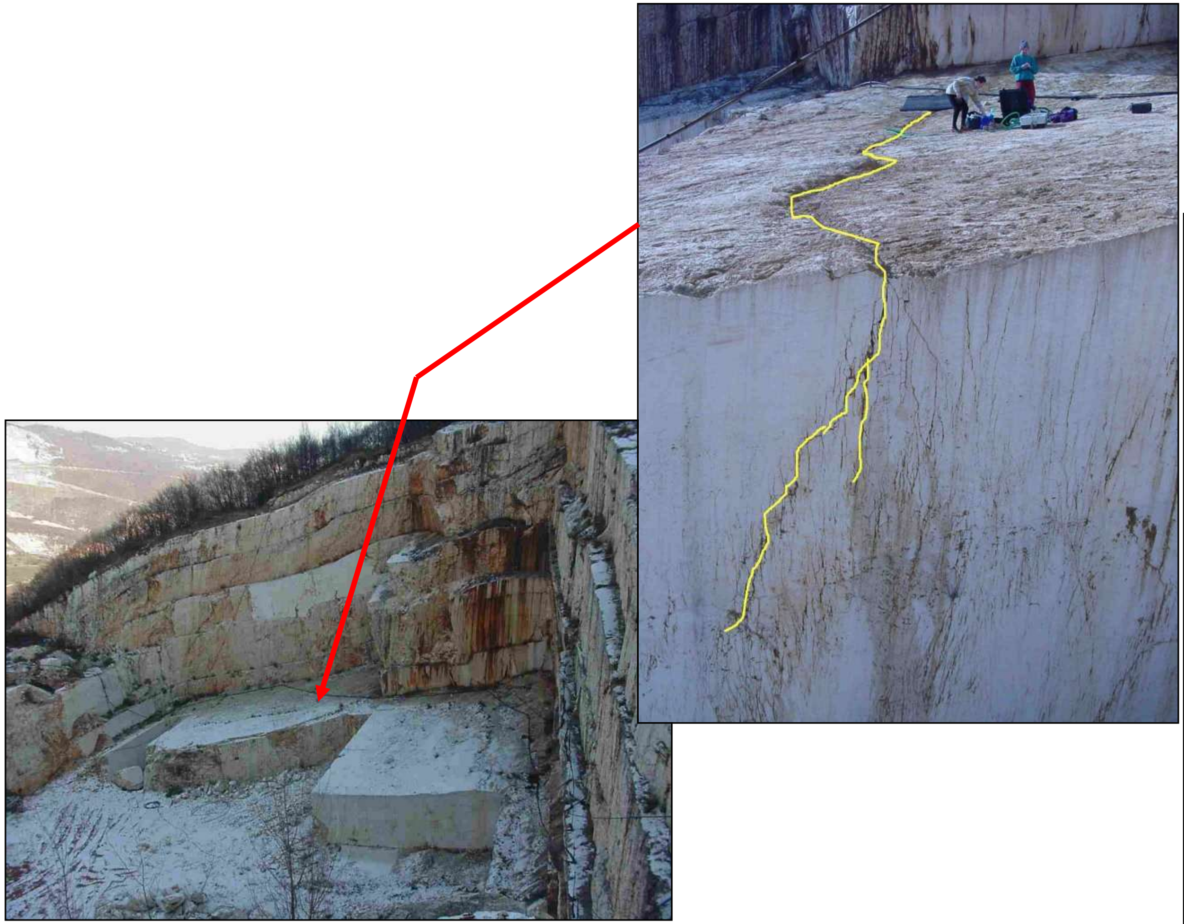
Acquisitions with the 50MHz antenna



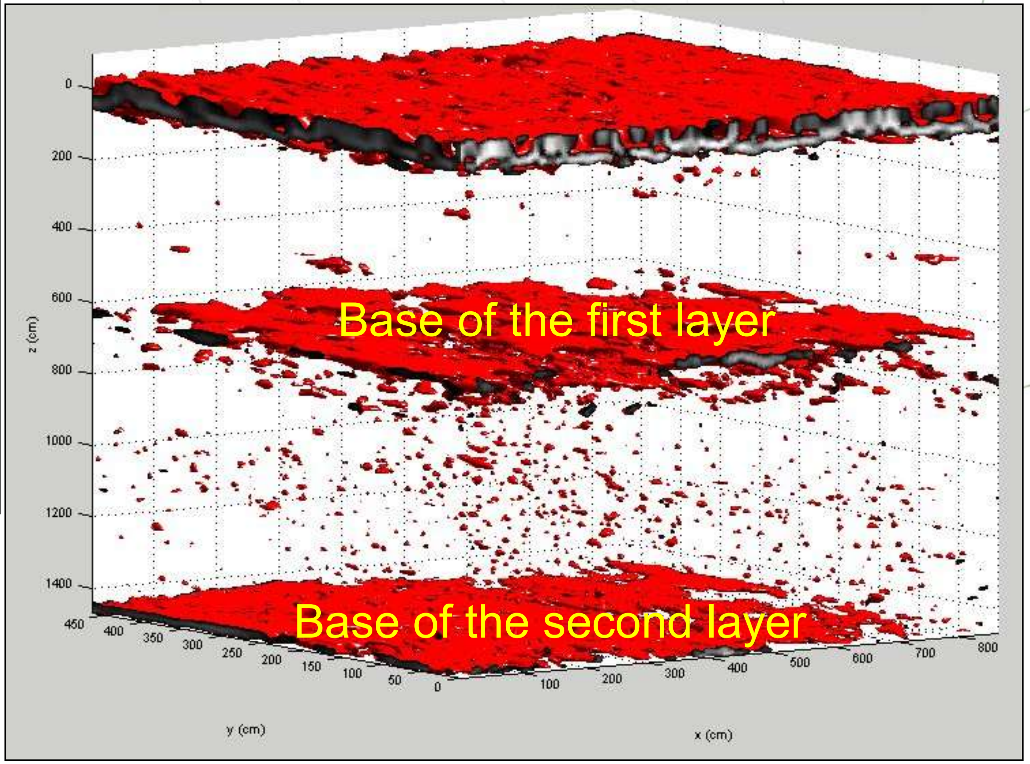
Example: quarries



Example: quarries

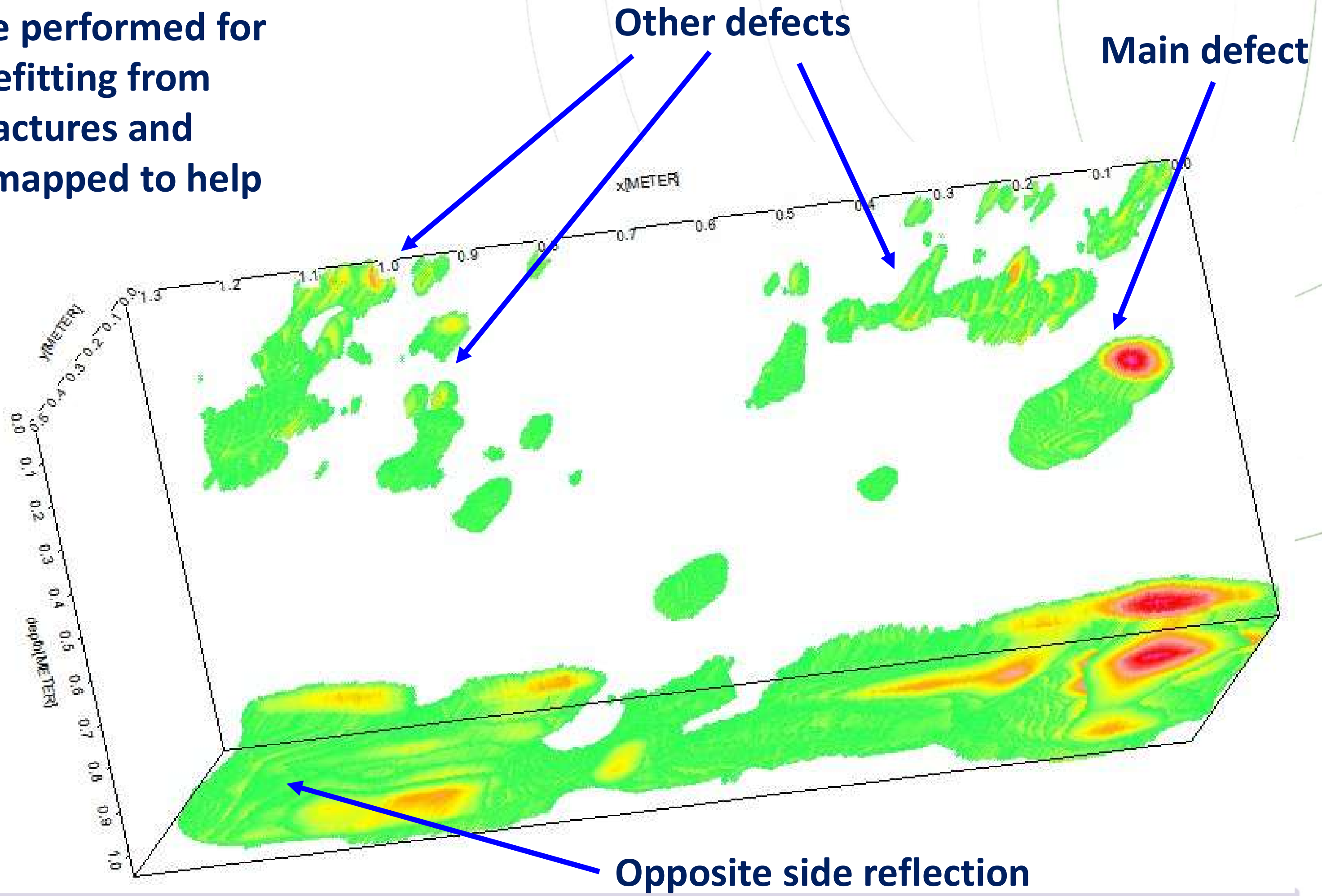


250 MHz data



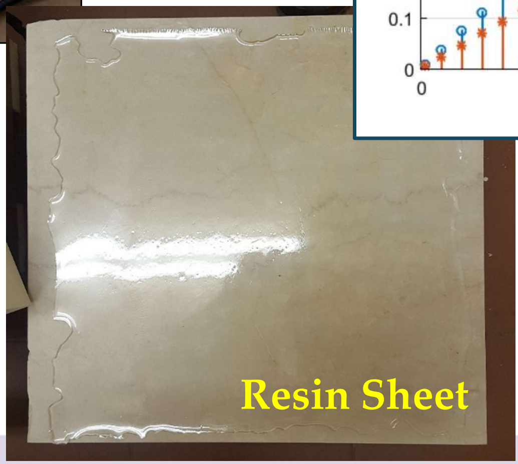
Example: quarries

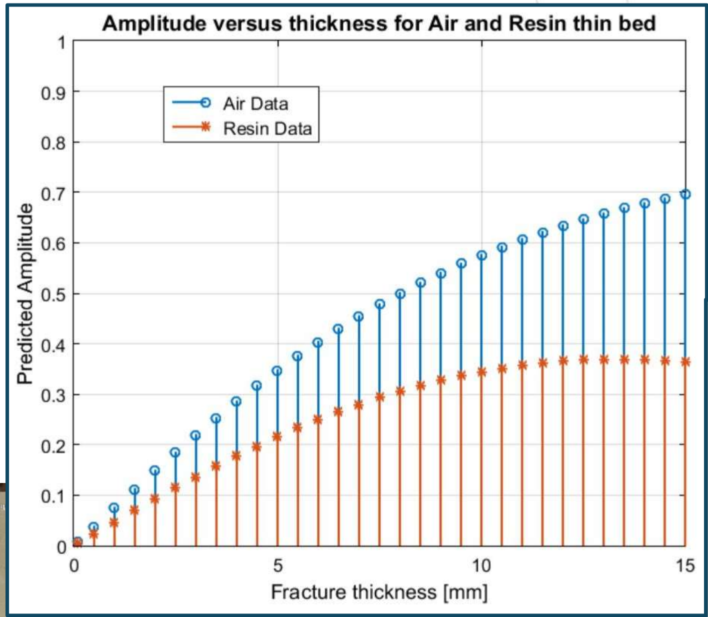
High-frequency measurements can be performed for the quality control of the blocks. Benefitting from better resolution at this stage, thin fractures and internal defects of the blocks can be mapped to help improving the slab production.



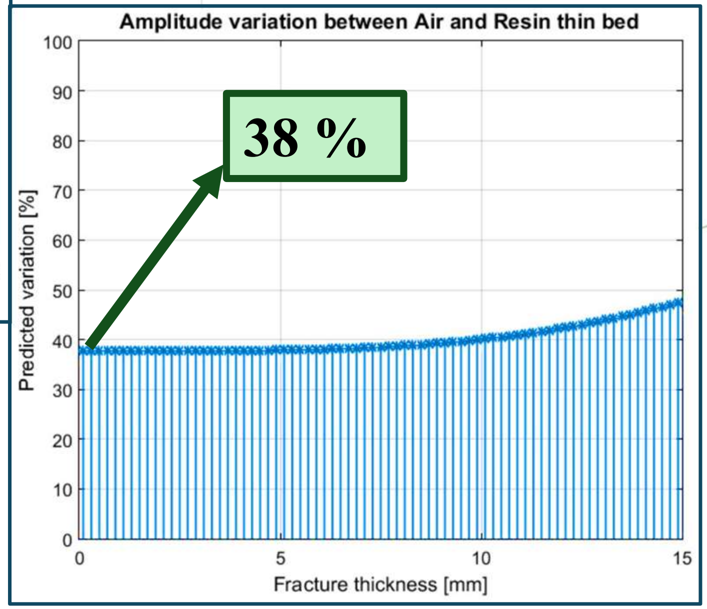
Example: quarries

Time-lapse GPR to check the repair condition of fractures



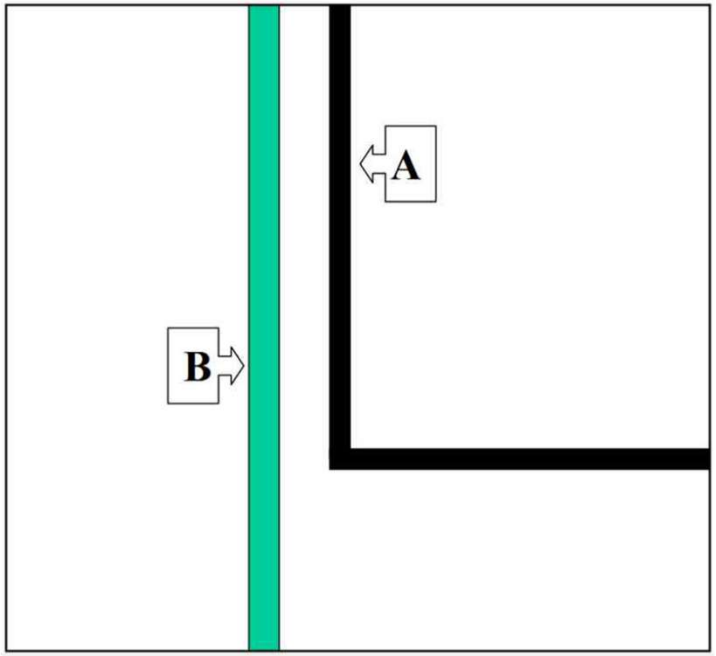


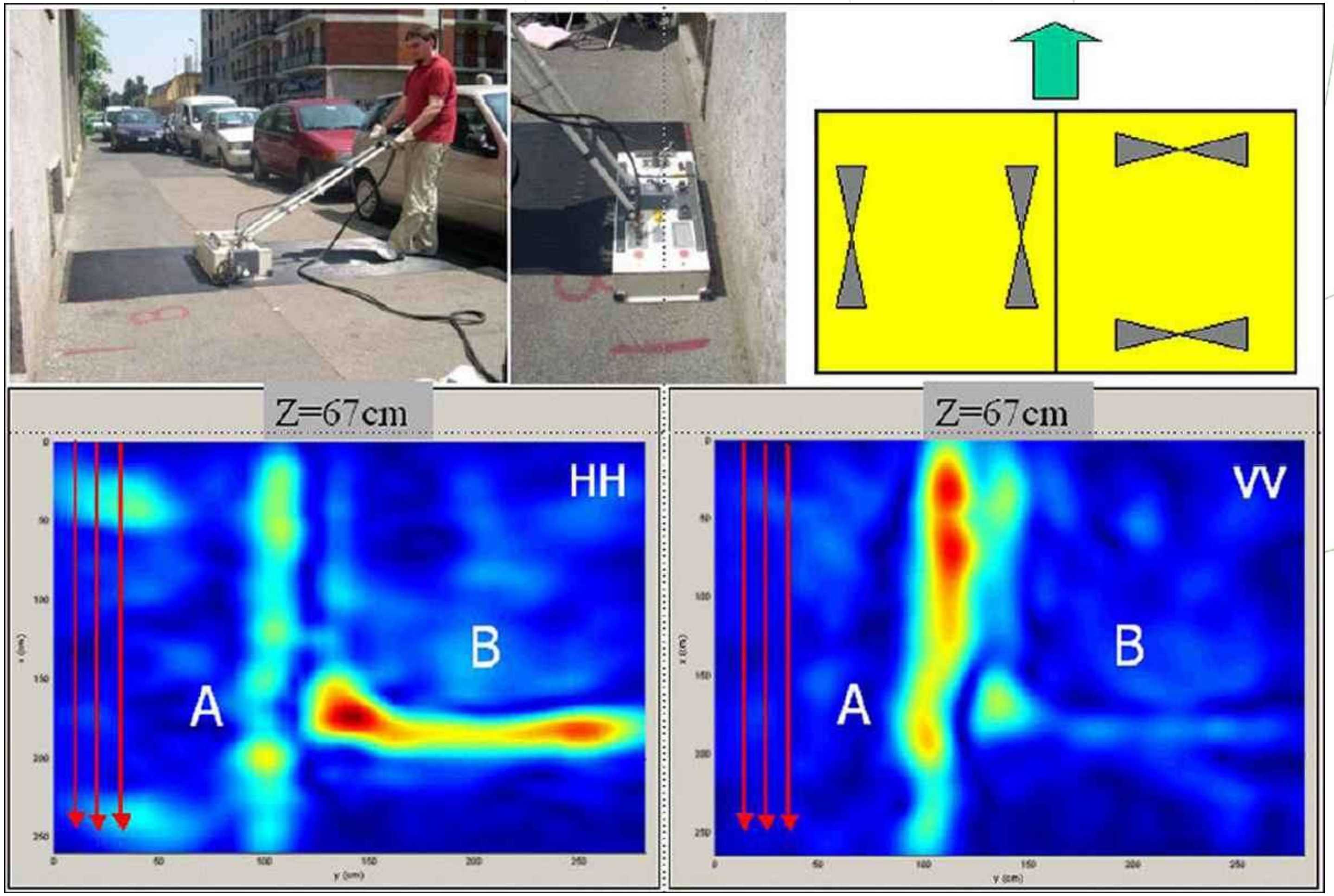
Analytical model



(Izadi et al., 2020)

Example: utility detection

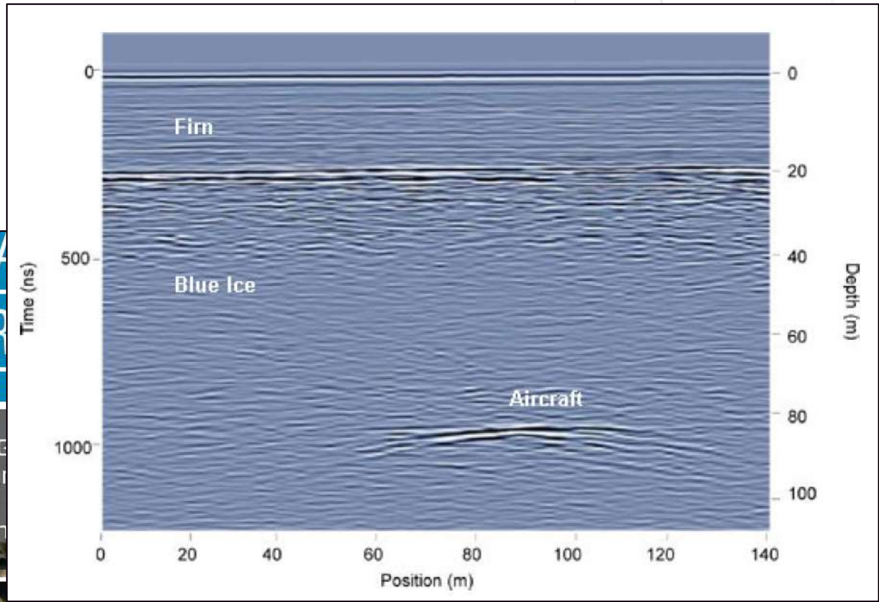


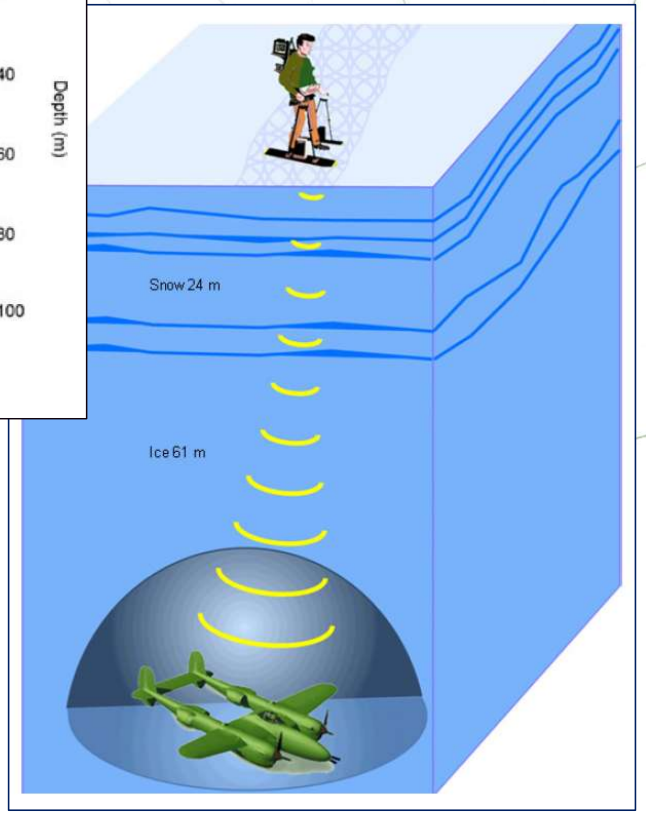


Example: ice and snow

Mt. Everest summit expedition (IDS, 2004)

Example: ice and snow





Example: ice and snow

ITINERIS

Geophysical methods in geoscience and near surface geophysics - Ground Penetrating Radar

Pisa, 22 January 2025

THANKS!

Azadeh Hojat (azadeh.hojat@polimi.it)

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