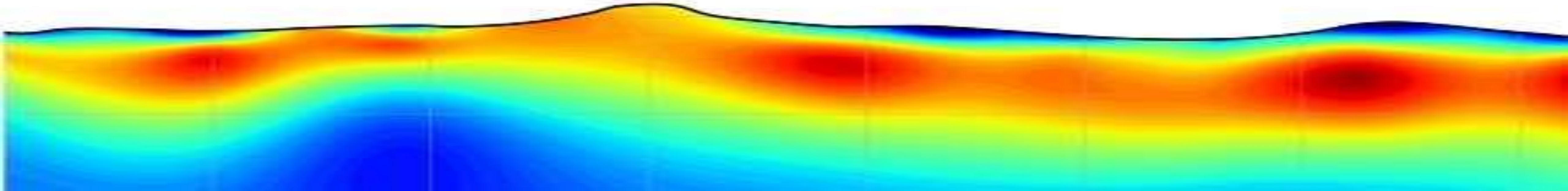
ESS302 Applied Geophysics II

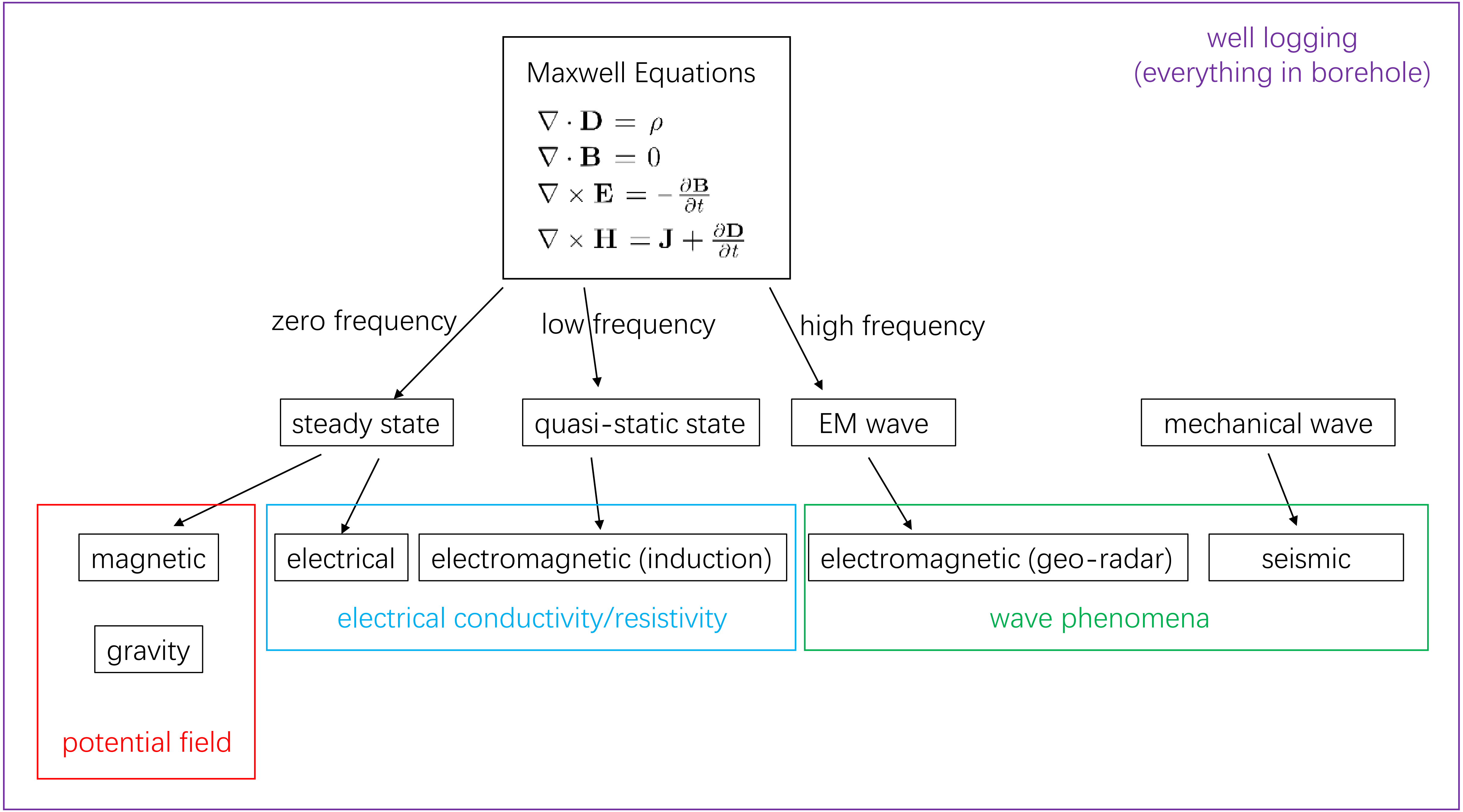
Gravity, Magnetic, Electrical, Electromagnetic and Well Logging

GPR

Instructor: Dikun Yang

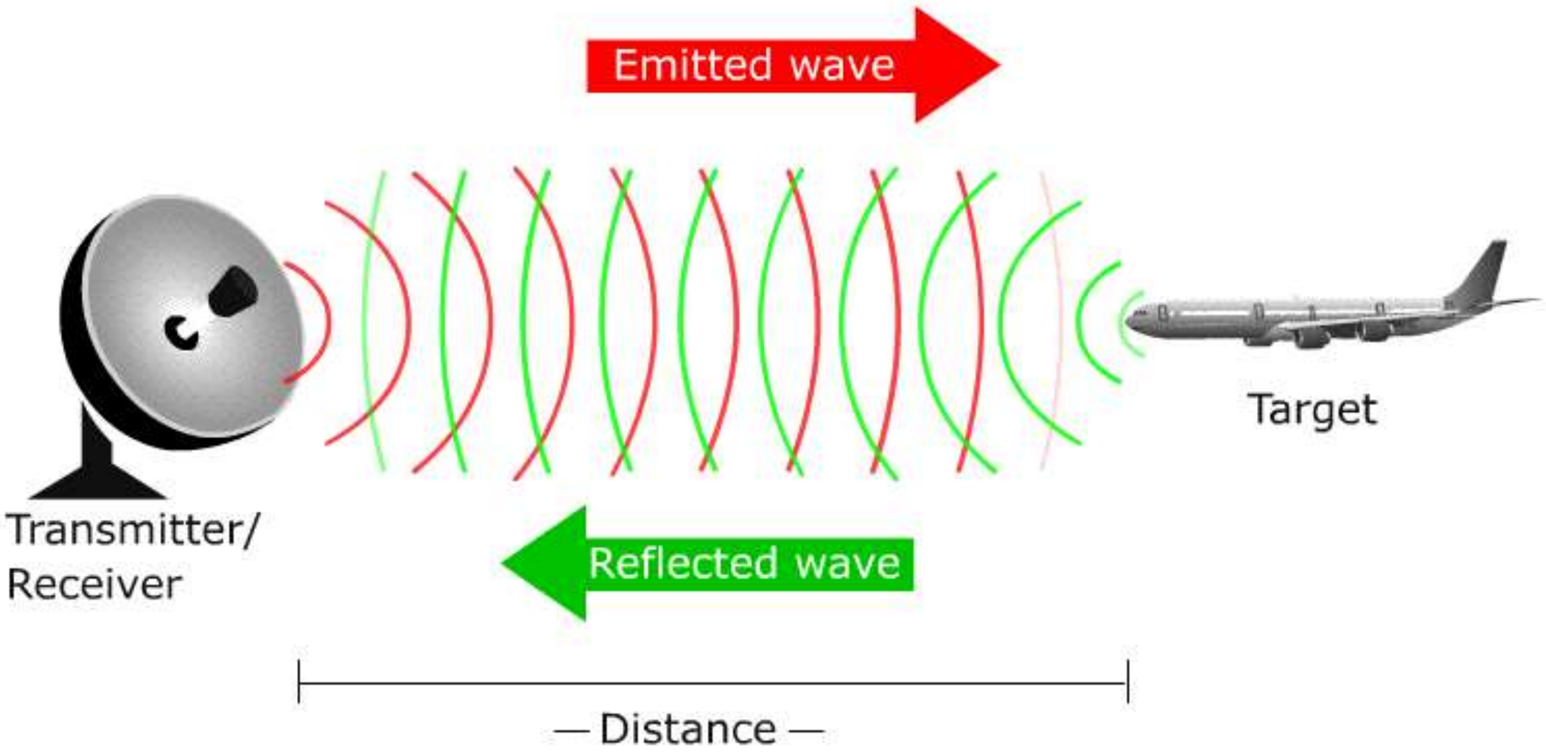
Feb – May, 2020





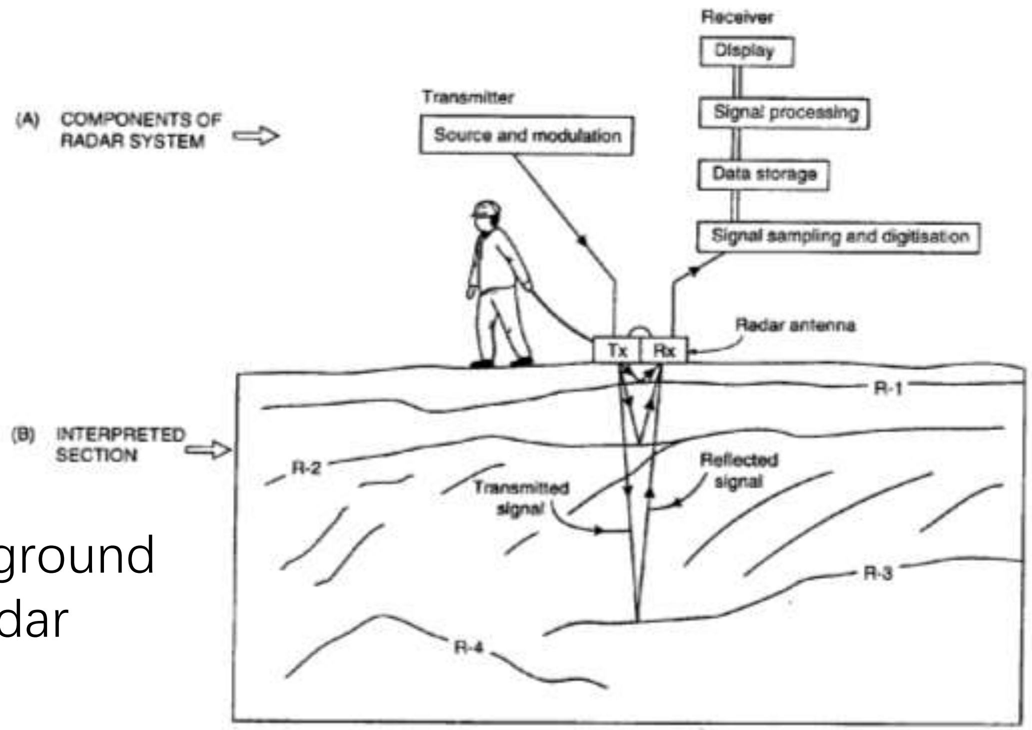
well logging
(everything in borehole)
Maxwell Equations
$\nabla \cdot \mathbf{D} = \rho$
$\nabla \cdot \mathbf{B} = 0$
$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$
$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$
zero frequency
low frequency
high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

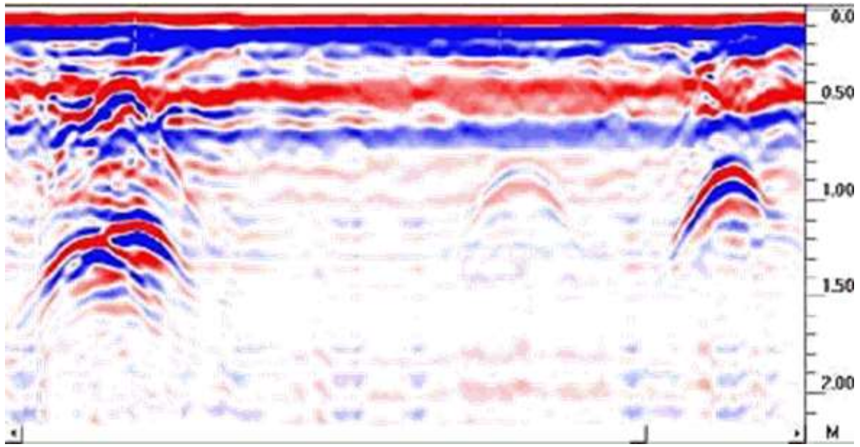
Radar



- Can we do the same thing to the subsurface?
- What are the differences between finding an object in the air and underground using EM waves?

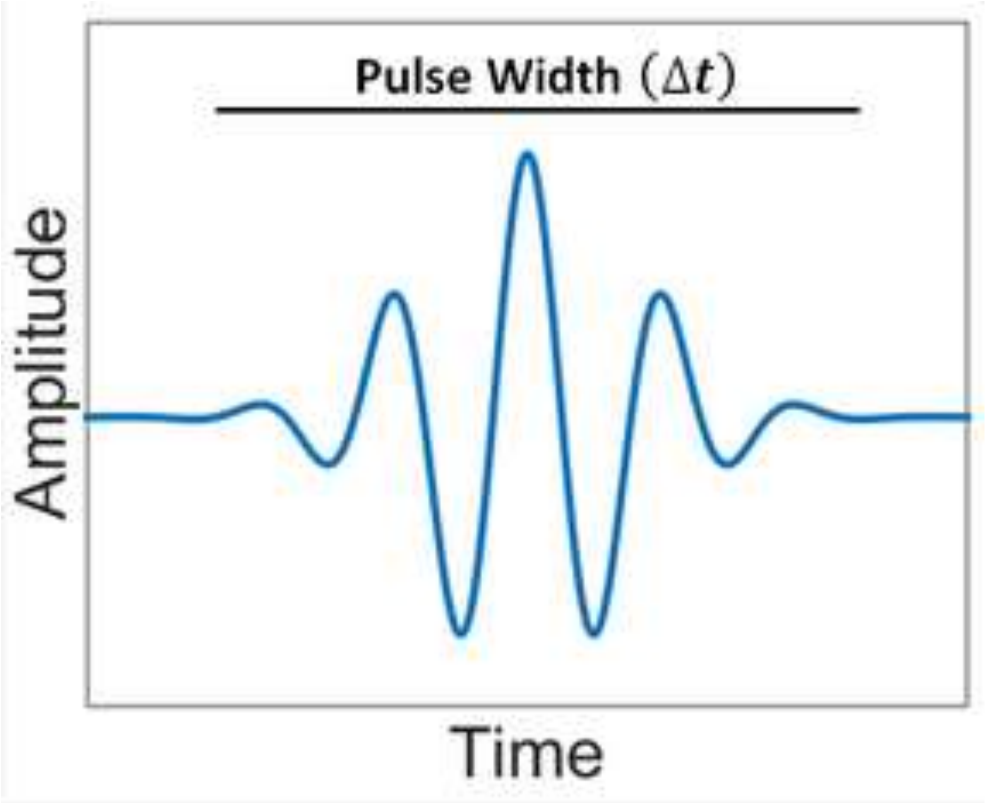
Geo-radar or ground penetrating radar (GPR)

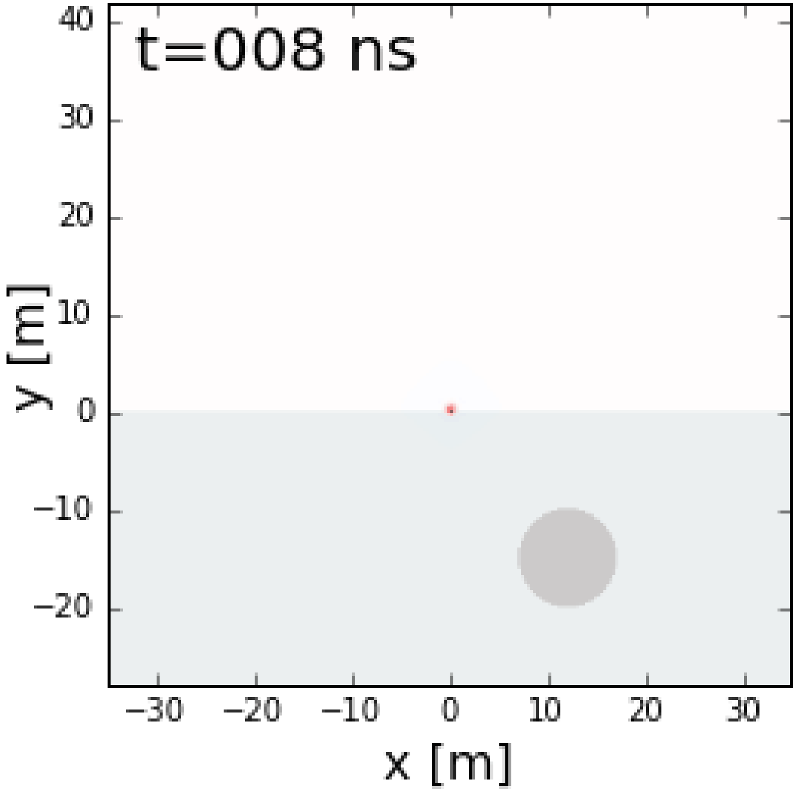




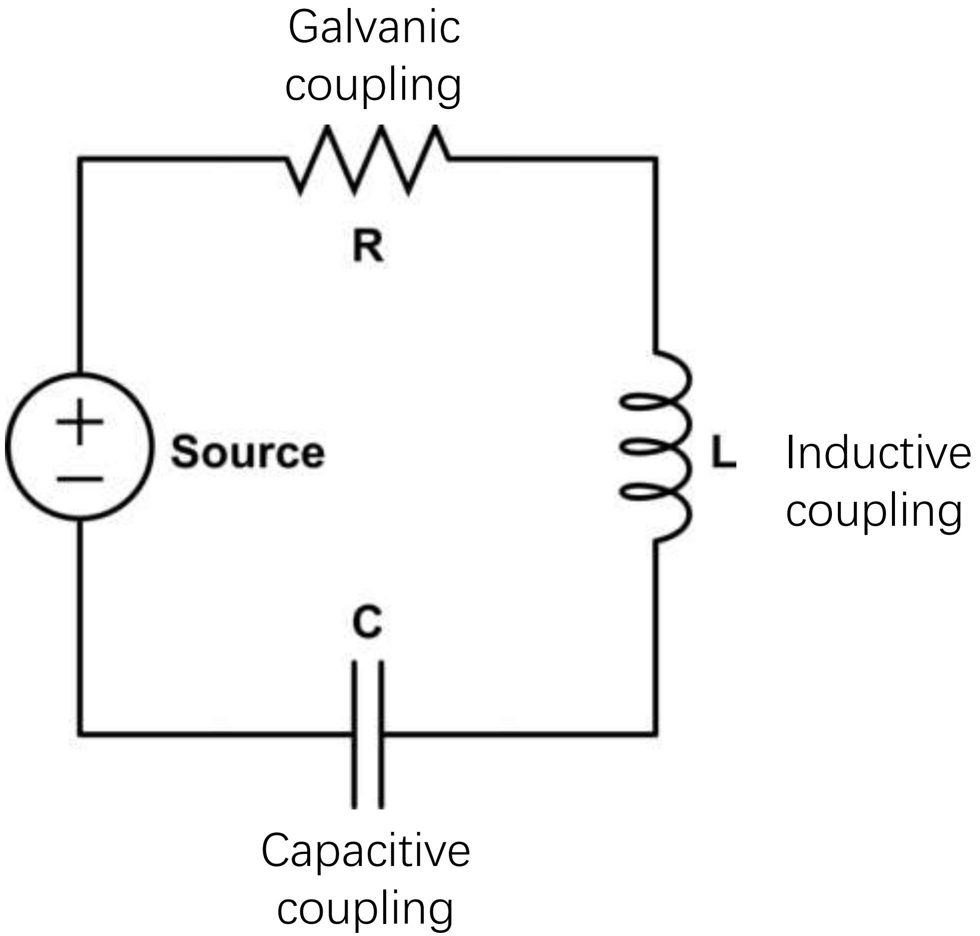
Radargram

EM Field at High Frequencies – Wave

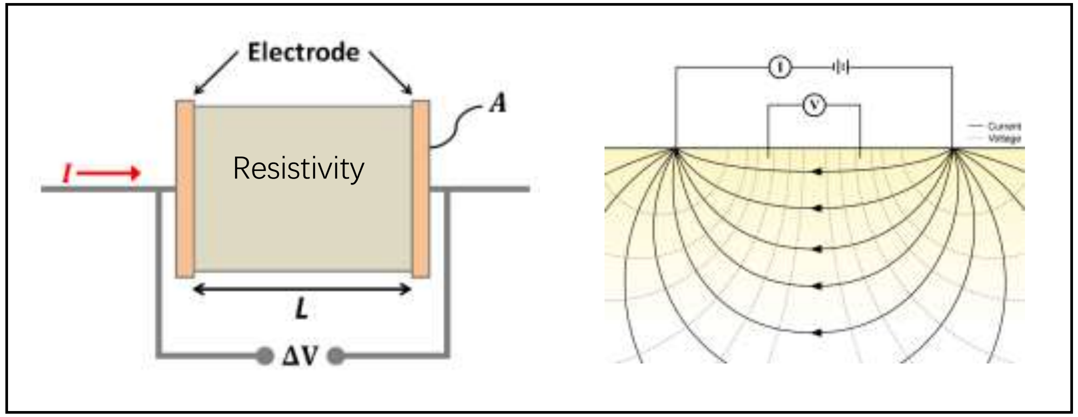


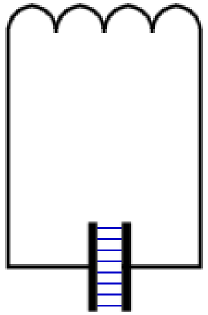


Ground Penetrating Radar (GPR)



Recall…



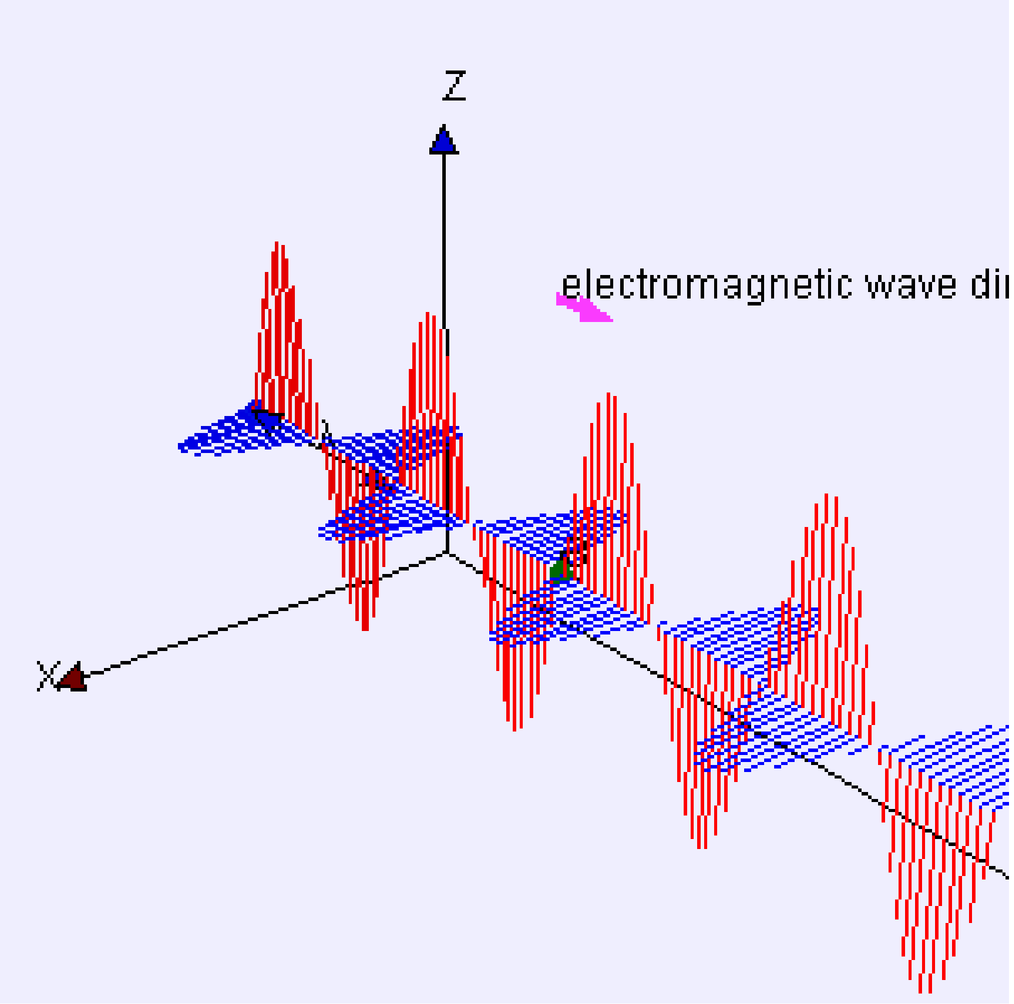


Capacitive coupling

- High frequency EM field
- Dielectric constant (ε_r)
- Wave phenomenon

Wave Propagation

Medium characterized by three physical properties:
σ (electrical conductivity), ε (electrical permittivity), μ (magnetic permeability)



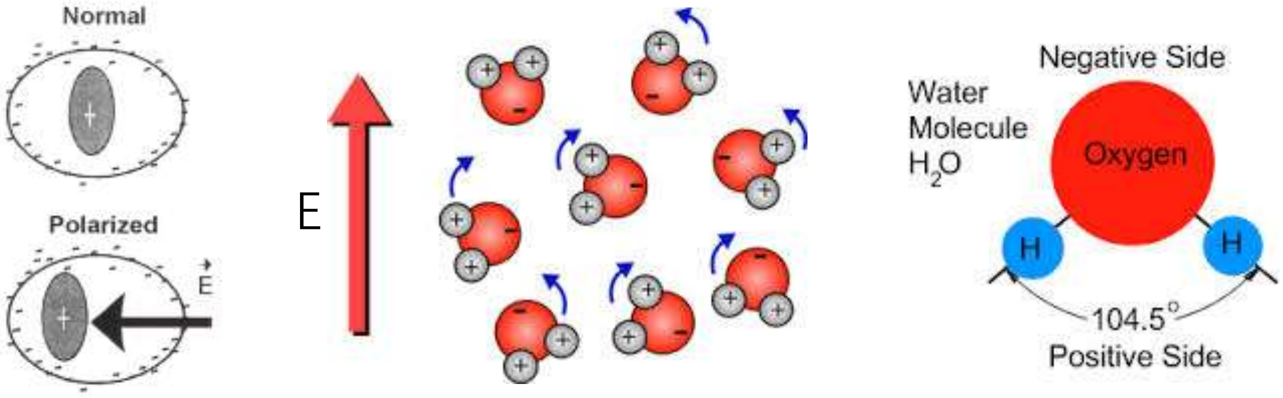
In general: $$V = \sqrt{\frac{2}{\mu\varepsilon}}\left[\left(1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2\right)^{1/2}+1\right]^{-1/2}$$

Wave regime ($\sigma \ll \omega\varepsilon$): $$V = \frac{1}{\sqrt{\mu\varepsilon}} = \frac{c}{\sqrt{\mu_r\varepsilon_r}}$$

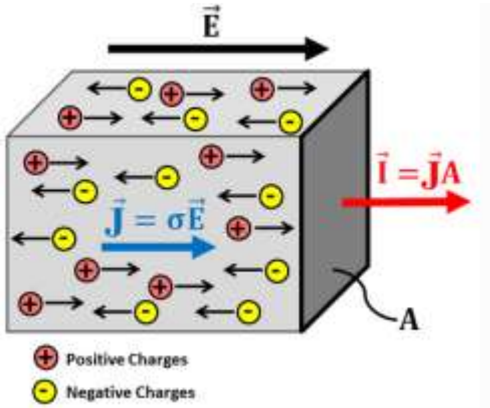
Non-magnetic approximation ($\mathbf{\mu_r = 1}$): $$\boxed{V = \frac{c}{\sqrt{\varepsilon_r}}}$$

Question: How does EM wave propagate in perfect conductors?

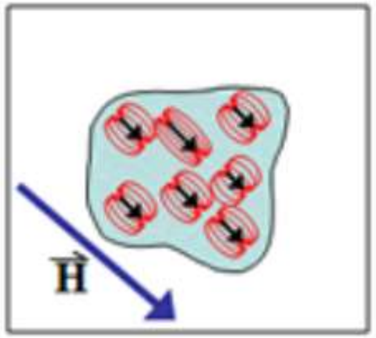
Dielectric Permittivity (ε):
How easily a material is electrically polarized



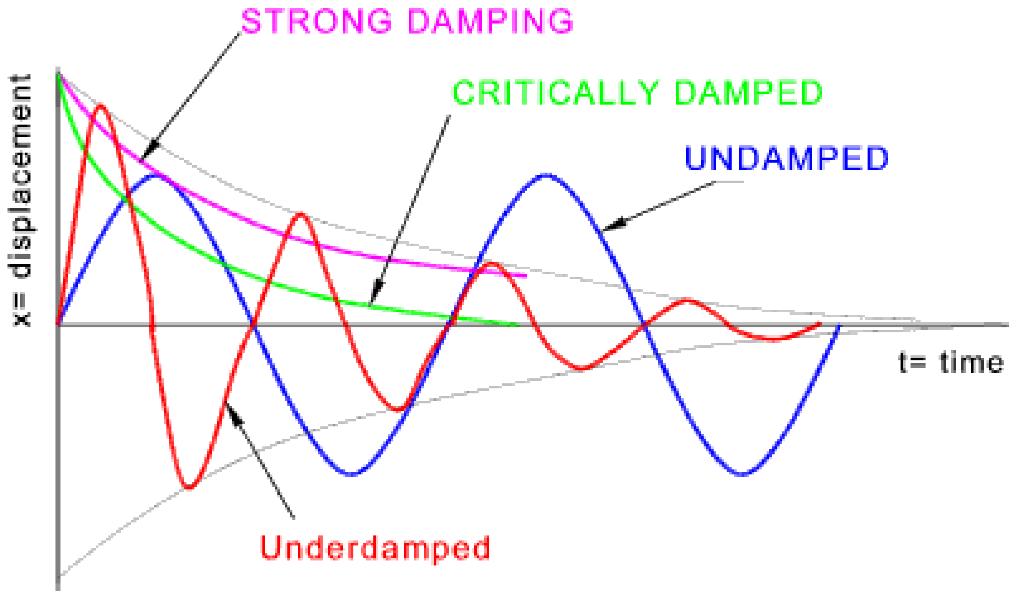
Electrical Conductivity (σ):
How easily electrical charges flow through a material

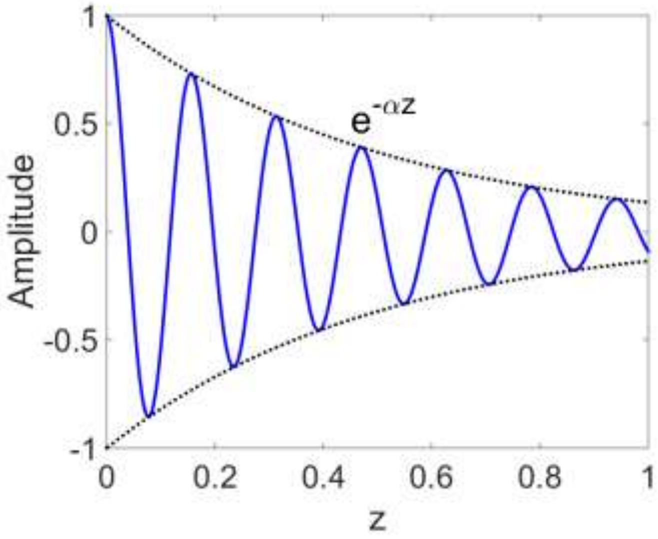


Magnetic Permeability (μ):
How strongly a material supports magnetism



Wave Attenuation



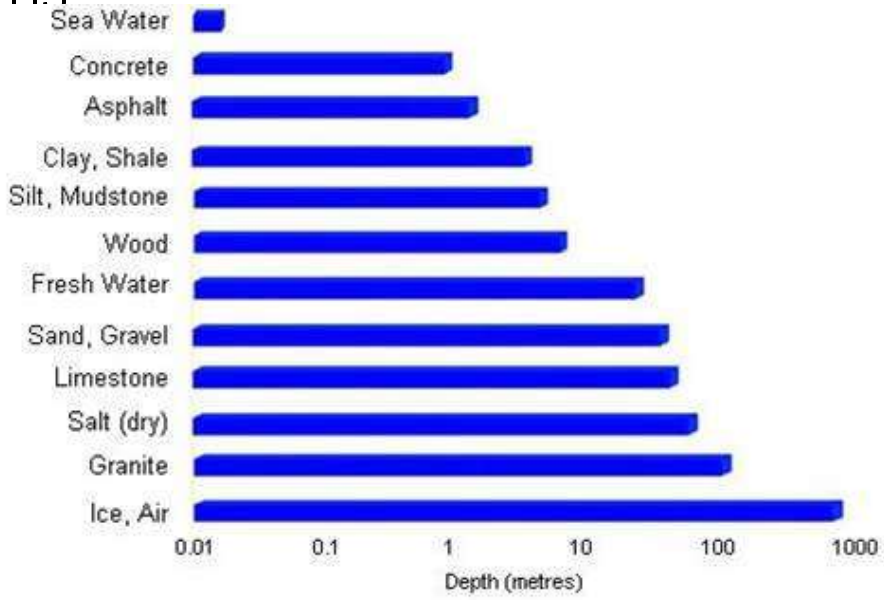


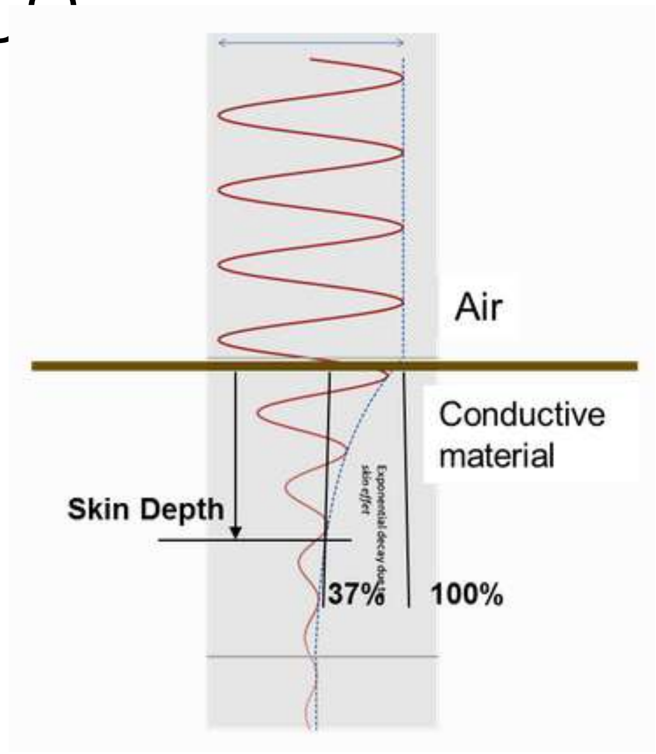
$$\alpha = \omega\sqrt{\frac{\mu\varepsilon}{2}}\left[\left(1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2\right)^{1/2} - 1\right]^{1/2} \approx \begin{cases} \sqrt{\dfrac{\omega\mu\sigma}{2}} & \text{for } \omega\varepsilon \ll \sigma \\ \dfrac{\sigma}{2}\sqrt{\dfrac{\mu}{\varepsilon}} & \text{for } \sigma \ll \omega\varepsilon \end{cases}$$

- Quasi-Static ($\omega\varepsilon << \sigma$): Conductive/Low-frequency
- Wave Regime ($\sigma << \omega\varepsilon$): Resistive/High-frequency

Skin Depth and Probing Distance

- Skin Depth: Distance at which a wave is reduced to 37% (1/e) of its original amplitude
- The probing distance is approximated 3 skin depths





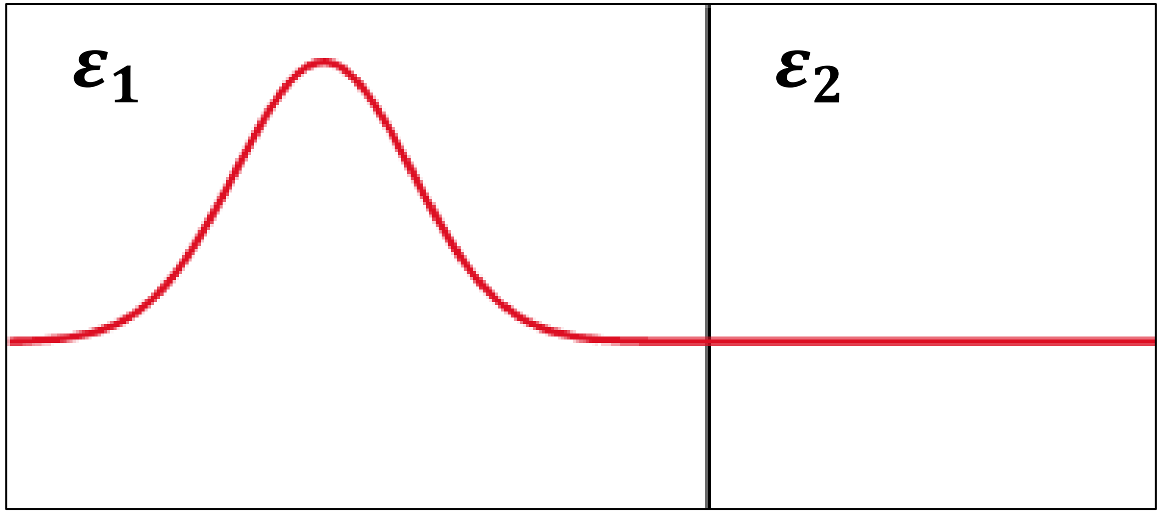
$$\delta \approx \begin{cases} 503\sqrt{\dfrac{1}{\sigma f}} & \text{for } \omega\varepsilon \ll \sigma \\ 0.0053\dfrac{\sqrt{\varepsilon_r}}{\sigma} & \text{for } \sigma \ll \omega\varepsilon \end{cases}$$

Table of relative dielectric permittivity (e_R), electrical conductivity (σ), and velocity.			
Material	**e_R**	**σ (mSeimens/m)**	**V avg (m/ns)**
Air	1	0	.3
Distilled water	**80**	**0.01**	0.033
Fresh water	80	0.5	0.033
Sea water	80	**3000**	**0.01**
Dry sand	**3**- 5	0.01	0.15
Saturated sand	20-30	0.1-1.0	0.06
Limestone	4-8	0.5-2.0	0.12
Shales	5-15	1-100	0.09
Silts	5-30	1-100	0.07
Clays	5-40	2- 1000	0.06
Granite	4-6	0.01-1.0	0.13
Dry salt	5-6	0.01-1.0	0.13
Ice	3-4	0.01	**0.16**

Reflection and Transmission

$$R = \frac{\text{Reflected Amplitude}}{\text{Incident Amplitude}} = \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}}$$

$$T = \frac{\text{Transmitted Amplitude}}{\text{Incident Amplitude}} = \frac{2\sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}}$$



- If $\varepsilon_1 \approx \varepsilon_2$, most of the wave is transmitted
- If $\varepsilon_1 \ll \varepsilon_2$ or $\varepsilon_1 \gg \varepsilon_2$, most of the wave is reflected

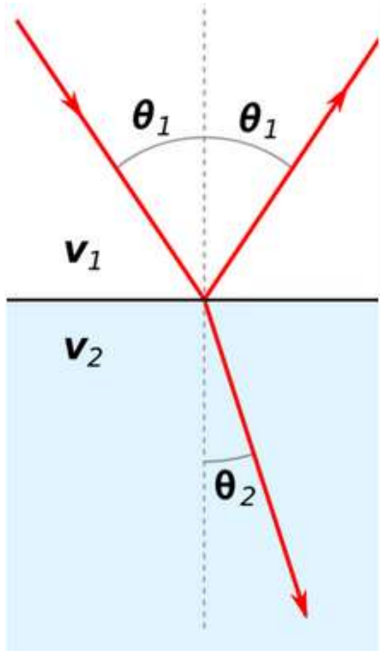
Refraction

- Snell's Law:

$$\frac{\sin\theta_1}{V_1} = \frac{\sin\theta_2}{V_2}$$

$$V = c/\sqrt{\varepsilon_r}$$

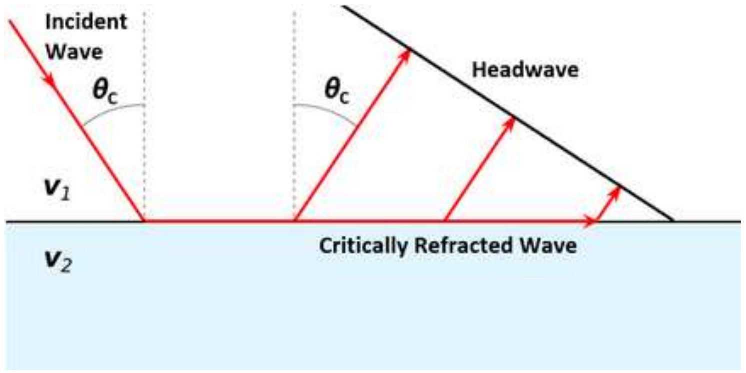
$$\sqrt{\varepsilon_1}\sin\theta_1 = \sqrt{\varepsilon_2}\sin\theta_2$$



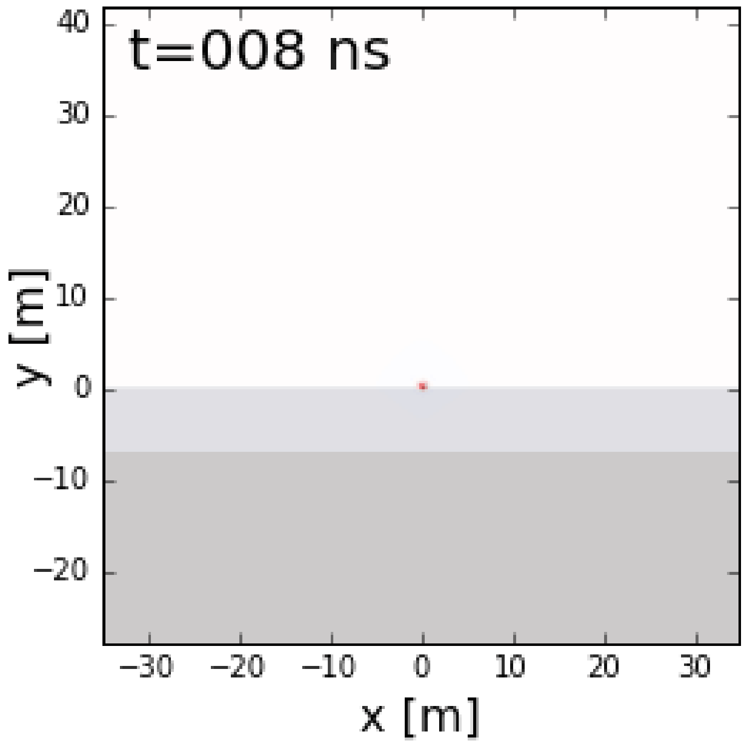
- Critical refraction

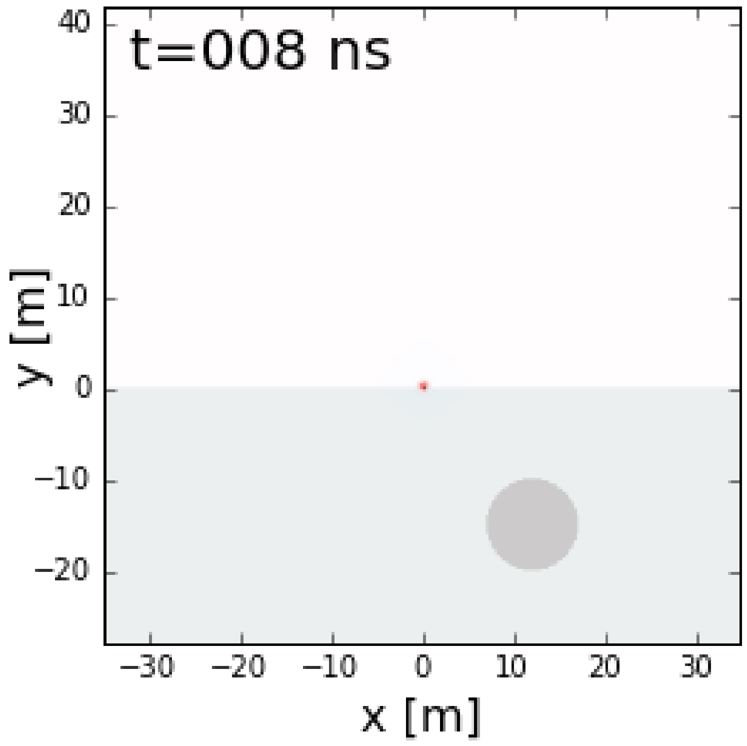
$$\sin\theta_c = \frac{V_1}{V_2}$$

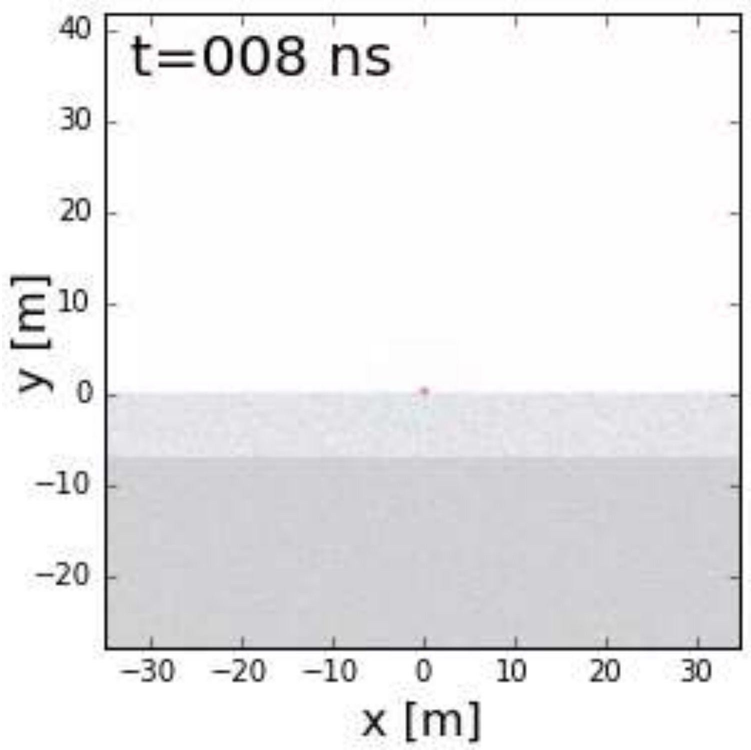
Requires $V_1 < V_2$



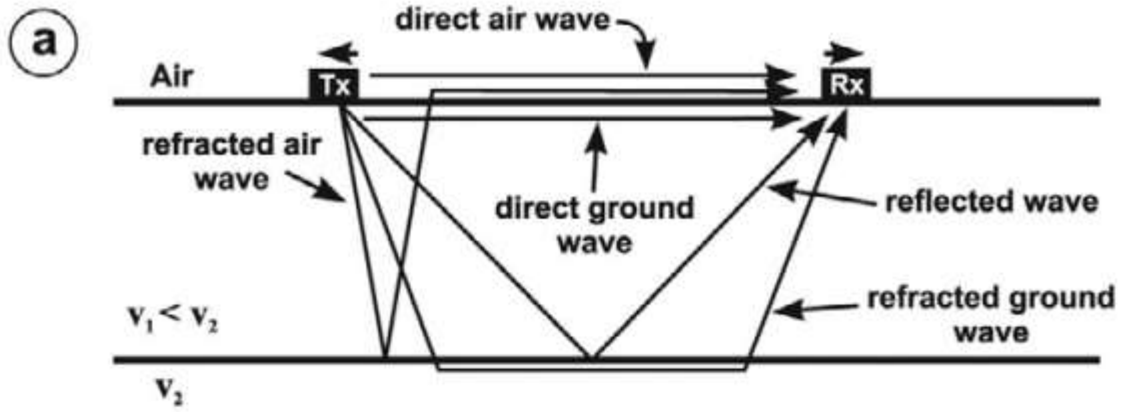
Reflection, Transmission, Refraction, Scattering

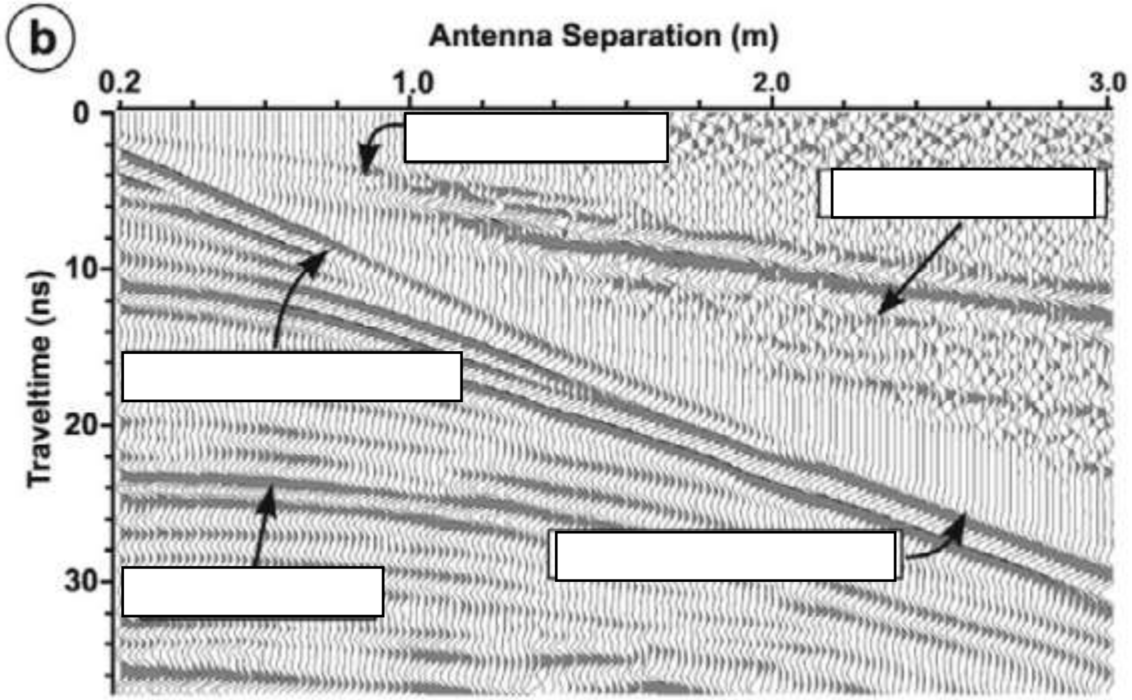






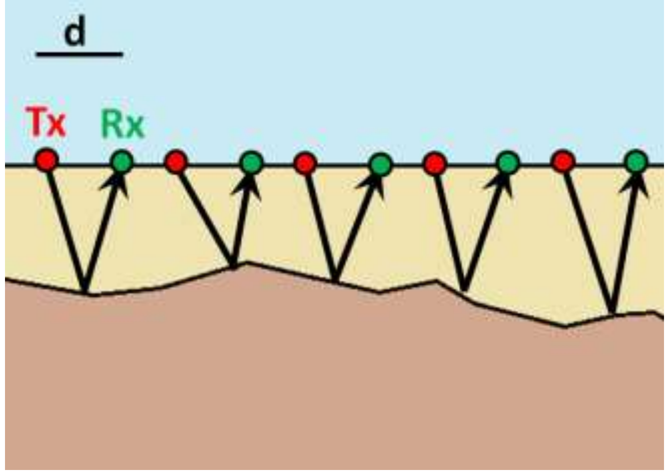
EM Wave Propagation in a Two-layer Earth

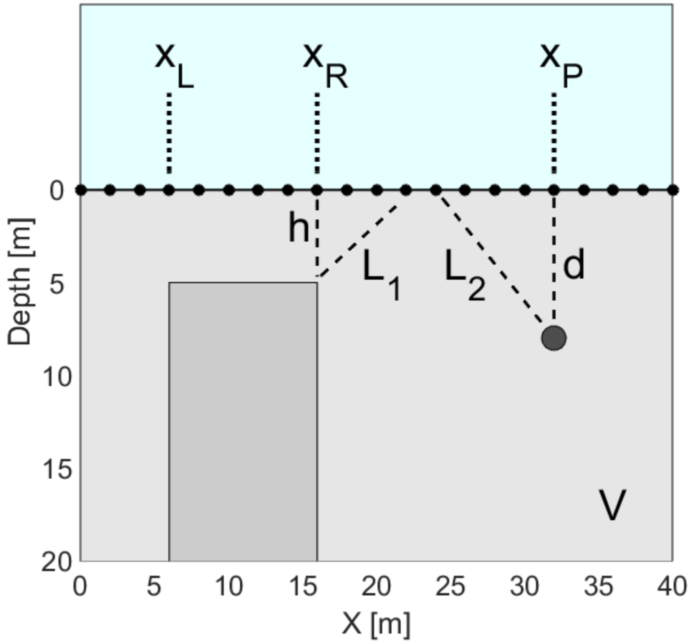


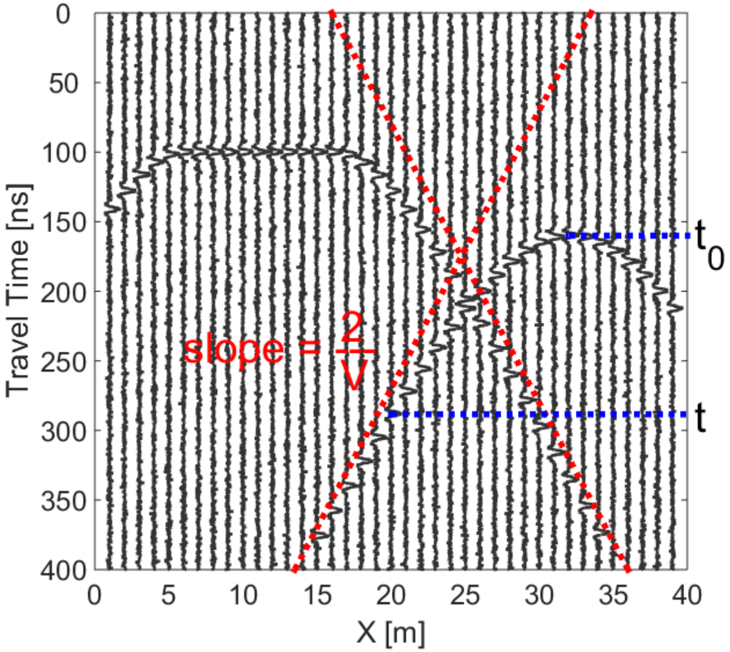


GPR Anomaly on Radargram

$$t_p = \frac{2L_2}{V} = \frac{2\sqrt{(x-x_p)^2+d^2}}{V}$$







- Determine background medium velocity
- Determine the depth of burial
- Determine the size of extended objects

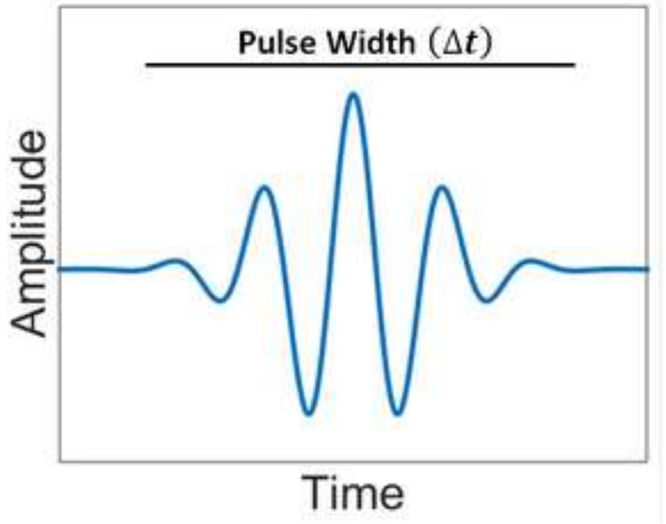
GPR Source Signal

- Wavelet: A wave-like oscillation of short duration
- Bandwidth: Range of frequencies in the wavelet
- Pulse Width: Time-duration of wavelet
- Spatial Length: Wavelength of the wavelet
- Central Frequency: Operating frequency of GPR survey

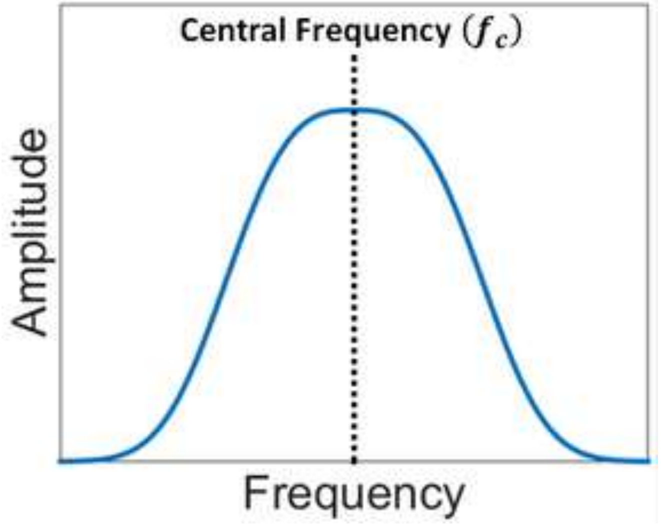
$$f_c = \frac{1}{\Delta t}$$

Typically 50 MHz to 1 GHz

Wavelet



Frequencies in Wavelet



GPR Source Signal: Spatial Length

- The spatial length (wavelength) of the GPR pulse is dependent on the central frequency and velocity

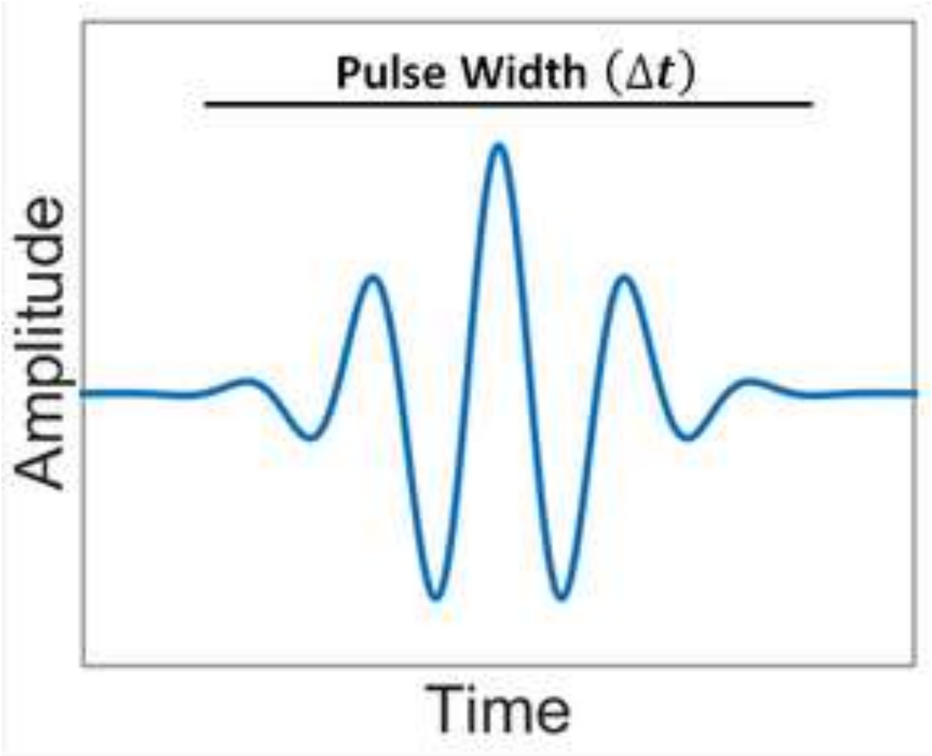
$$\lambda = \frac{V}{f_c} = \frac{c}{f_c\sqrt{\varepsilon_r}} = \frac{c\,\Delta t}{\sqrt{\varepsilon_r}}$$

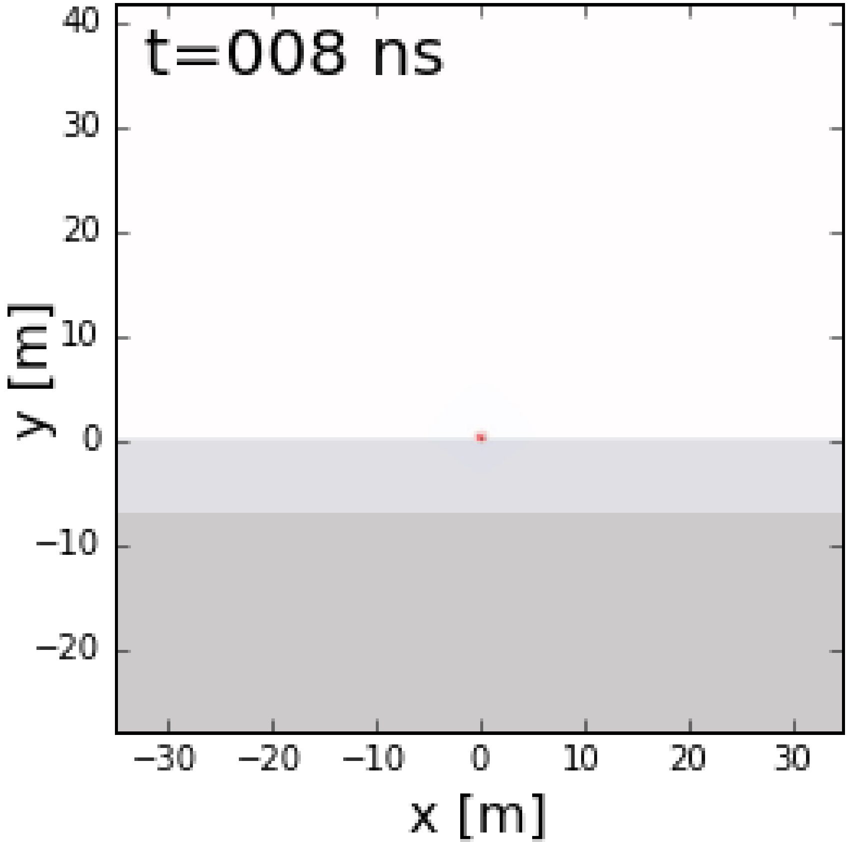
- When the GPR signal at some frequency is transmitted across an interface, it can be stretched or contracted

- Lower velocity → Shorter spatial length

- Lower frequency → Larger spatial length

Signal Stretched or Contracted?





Resolution of GPR

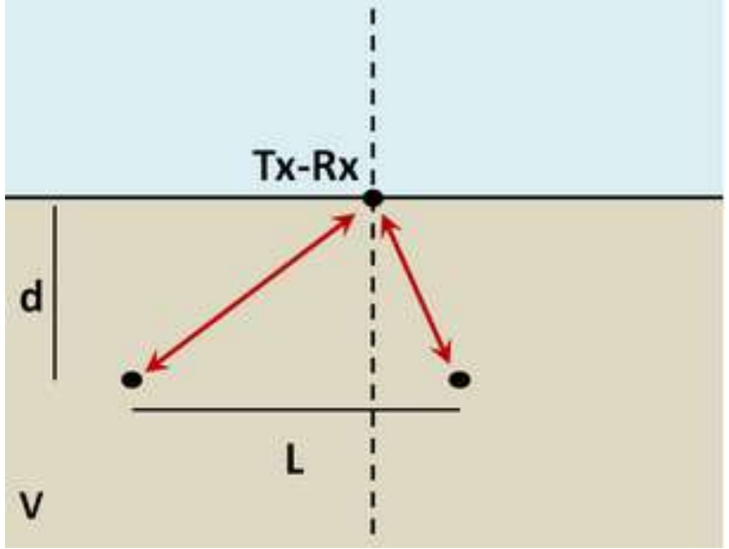
- ¼ wavelength rule:

  The thickness of a layer must be at least ¼ the wavelength of the GPR signal.

$$L > \frac{c}{4 f_c \sqrt{\varepsilon_r}} = \frac{c\Delta t}{4\sqrt{\varepsilon_r}}$$

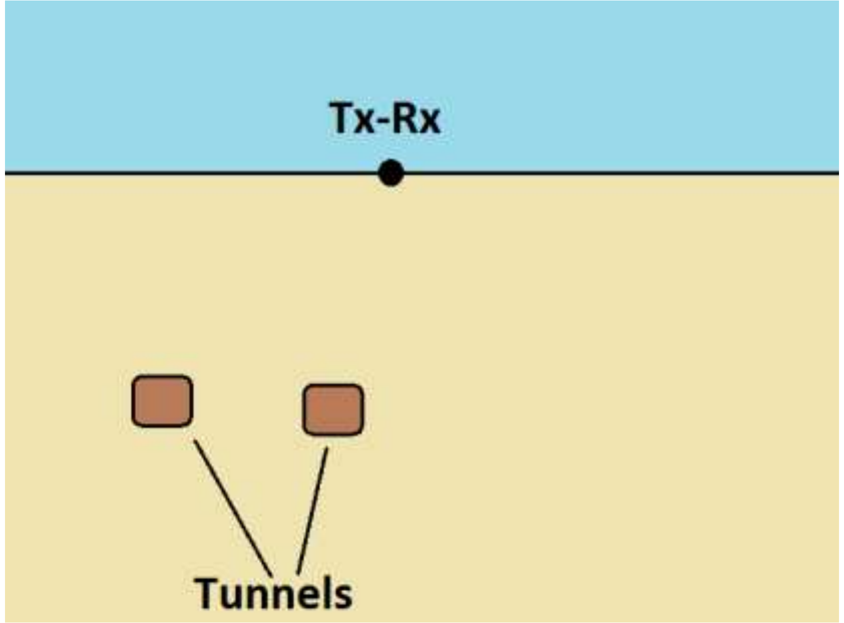
- For zero offset survey

$$L > \sqrt{\frac{V\, d}{2 f_c}}$$



Probing Distance vs. Resolution

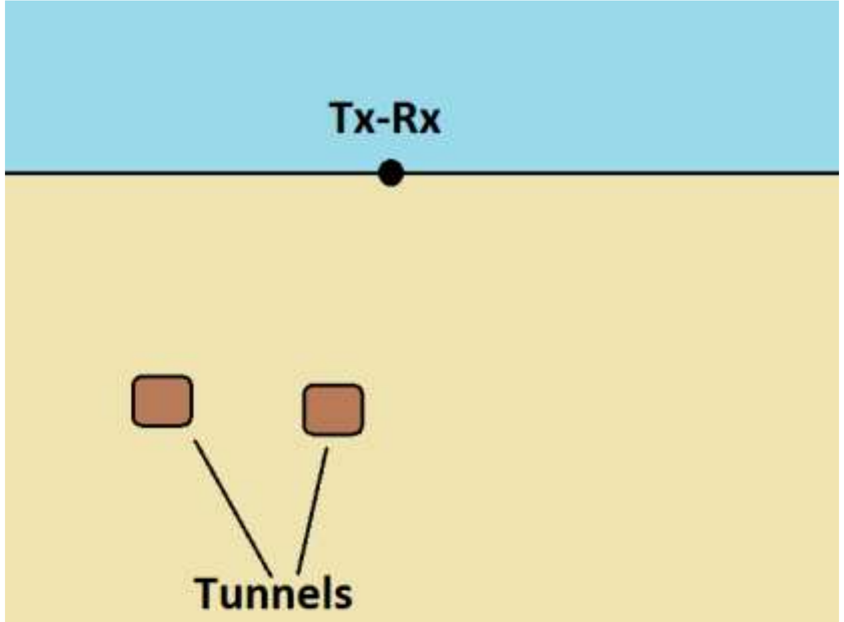
- Want to find two buried tunnels.
- Using a zero offset survey configuration.
- Higher frequencies give better resolution
- Lower frequencies give larger probing distance

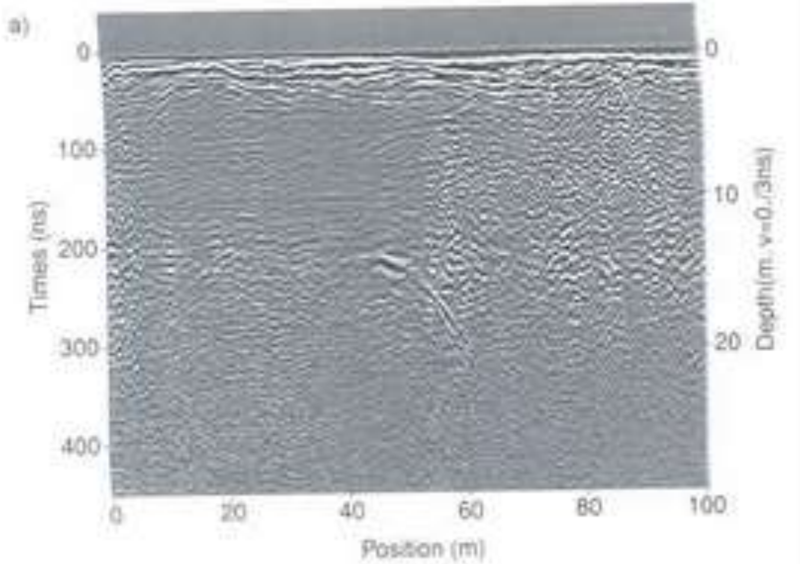


Radargram 200 MHz

- Little to no useful signal after 200 ns
- Can't see features from the tunnels

- Too much attenuation of signal
- Probing distance insufficient



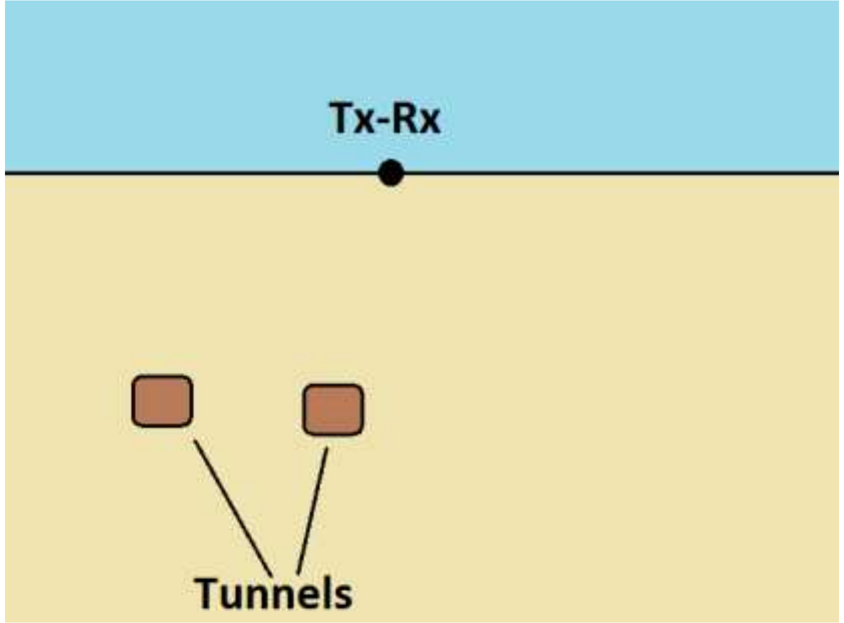


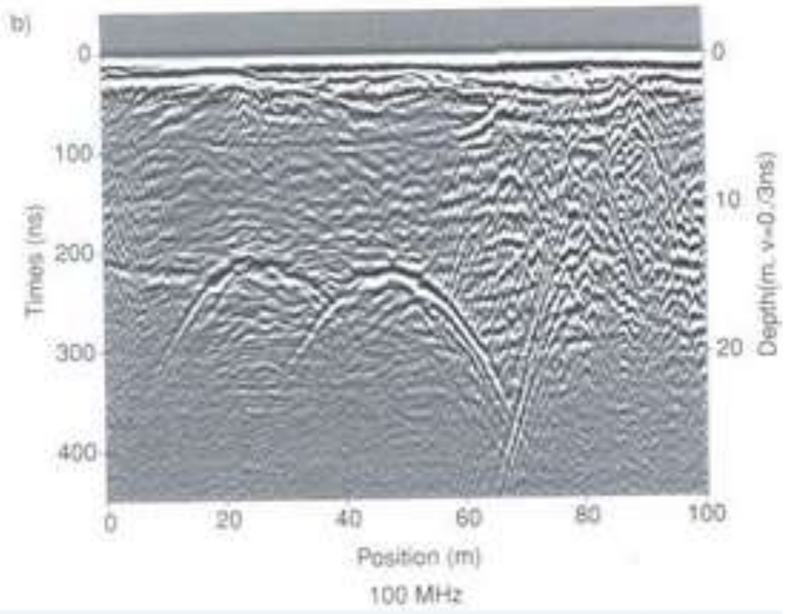
200 MHz

Radargram 100 MHz

- Useful signals up to 300 ns
- See top of hyperbolas from tunnels

- Lower resolution
- Can see tunnels

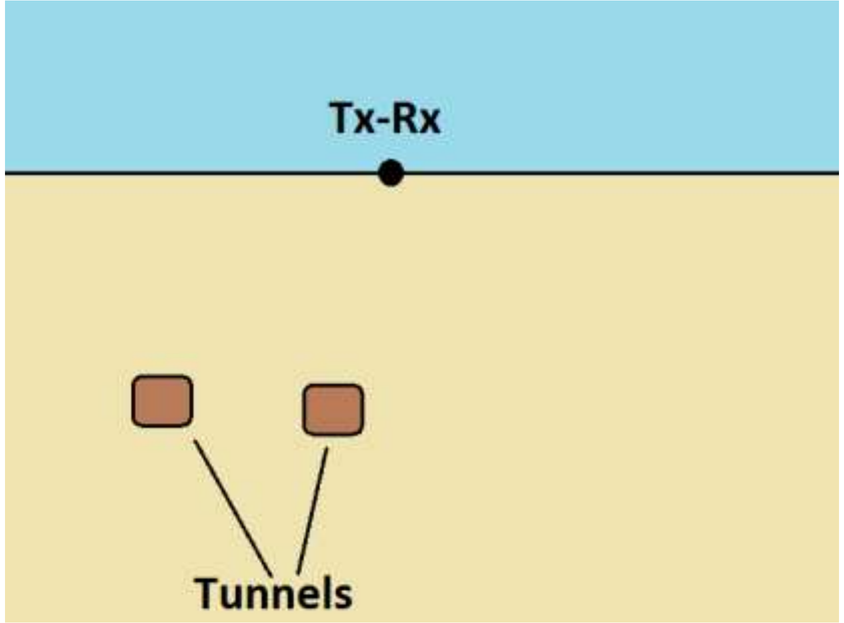


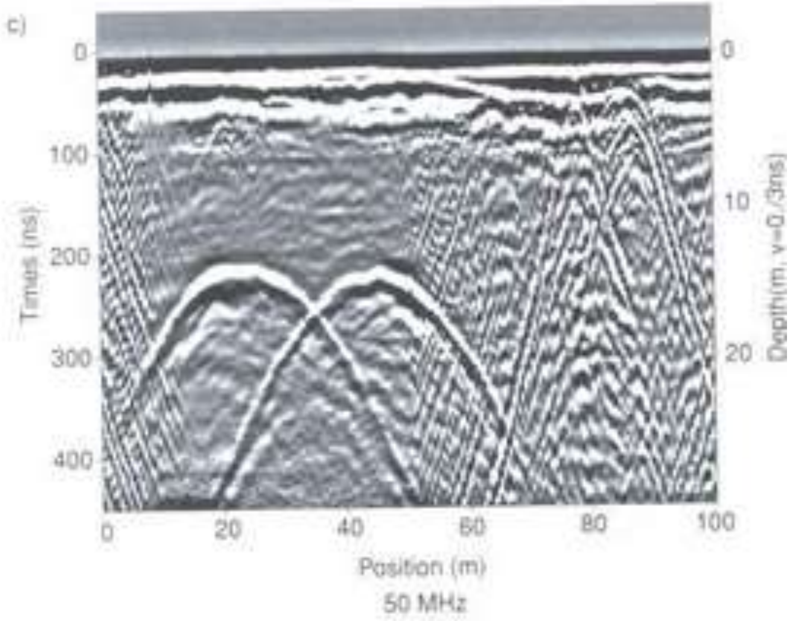


Radargram 50 MHz

- Useful signals through 400 ns
- Well-defined hyperbolas from tunnels

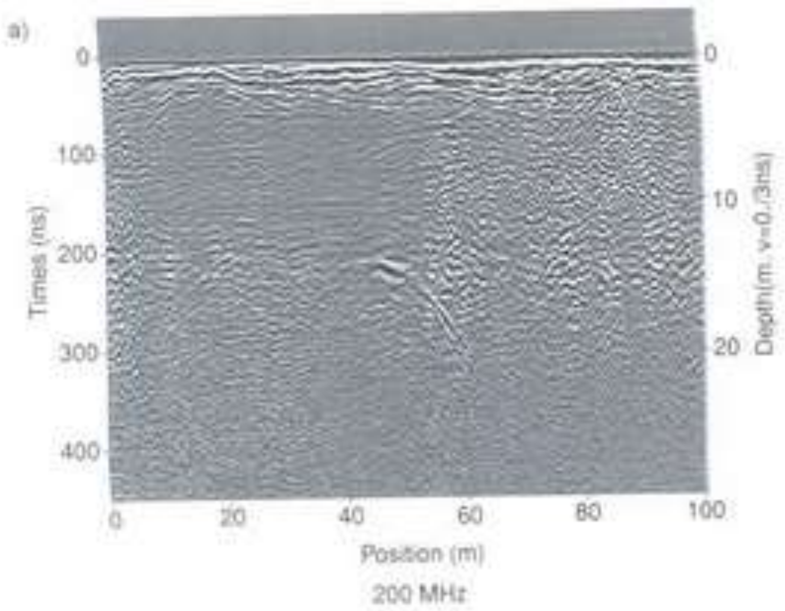
- Lower resolution image
- Best frequency for what we want to observe



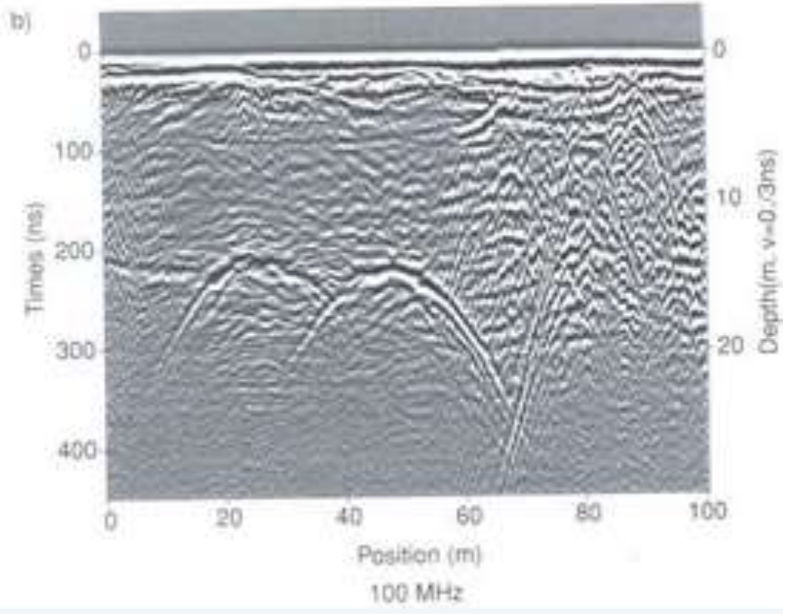


Depth vs. Resolution

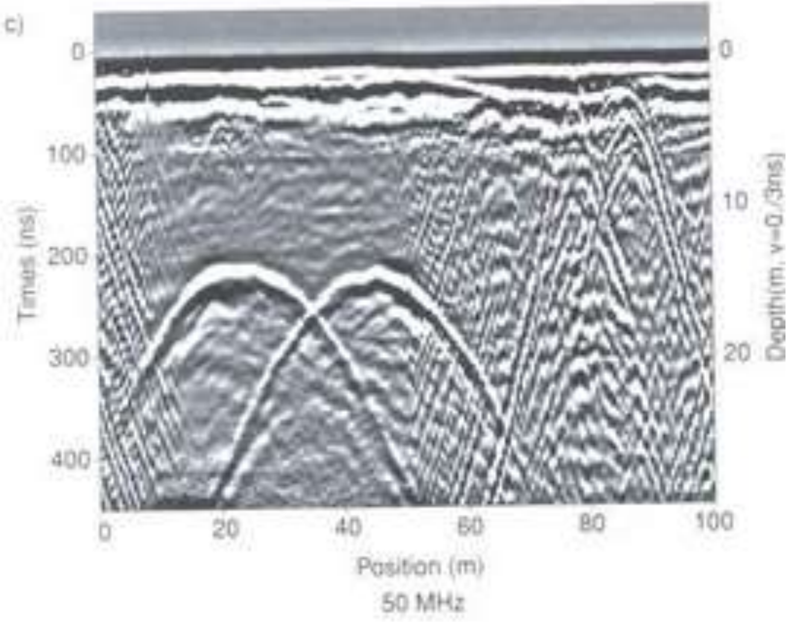
200 MHz



100 MHz



50 MHz

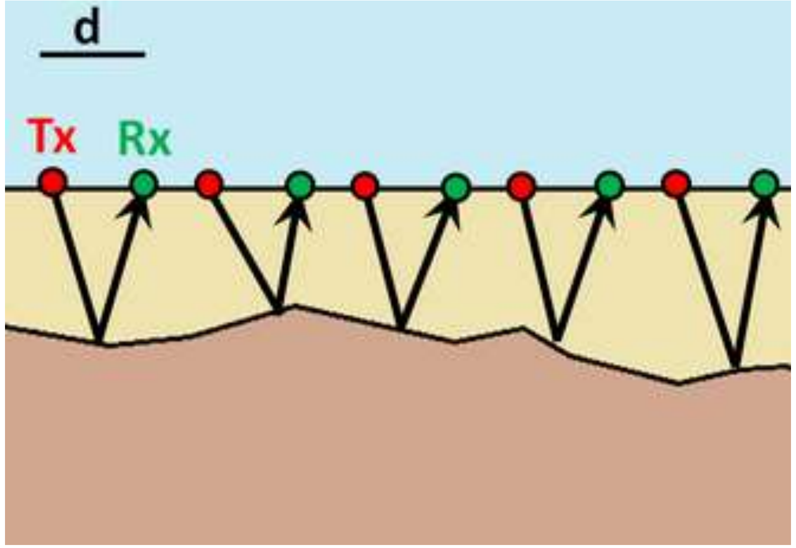


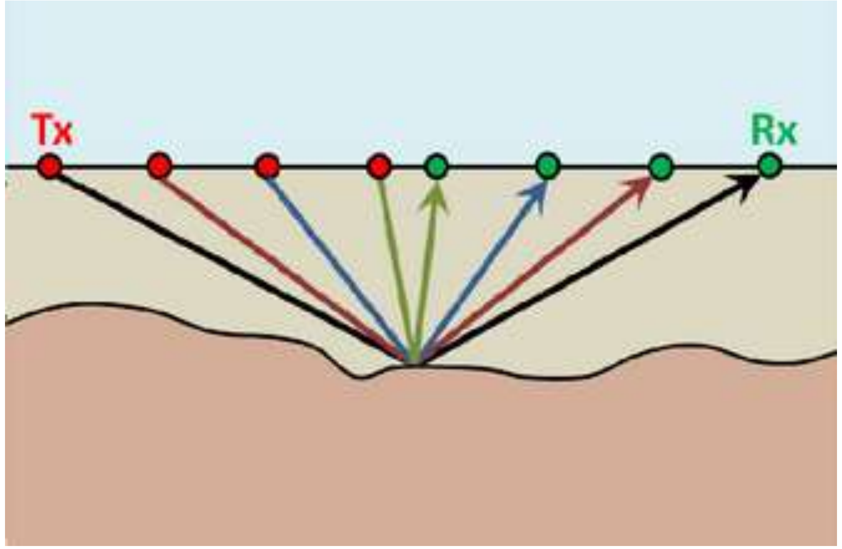
Quiz

- True or false and why: While dc resistivity is only sensitive to the electrical resistivity, GPR data only response to the variation of electrical permittivity.
- Both dc resistivity and GPR can use electrical dipole sources. In a dc survey the dipole electrodes need to be in contact with the earth, but the GPR dipole source can be suspended in the air. Why?
- Which survey parameters determine the depth of investigation (DOI) in dc resistivity and GPR?

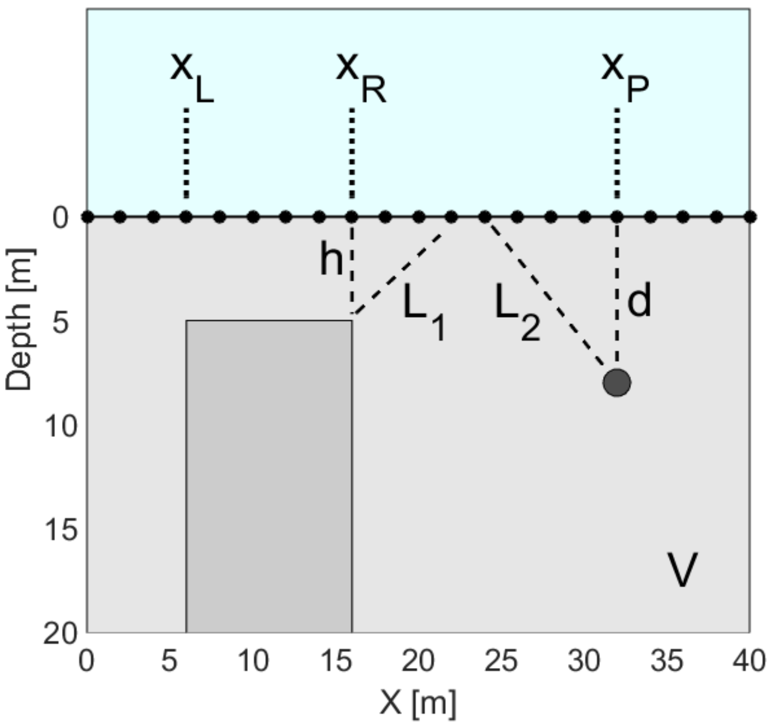
Common Offset

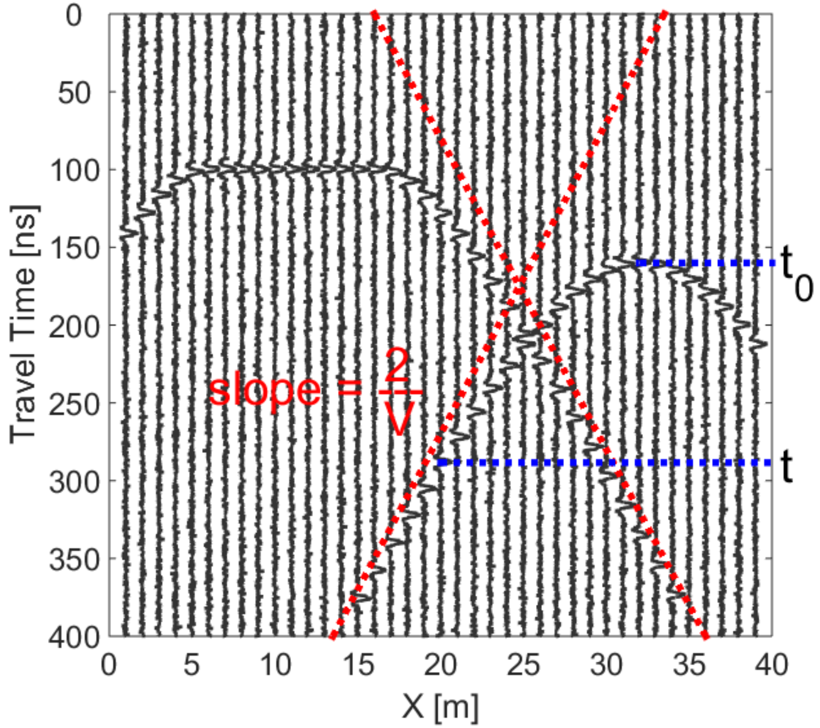
Common Midpoint





Zero Offset: Finding Buried Objects





Two-way travel time for a point scatter

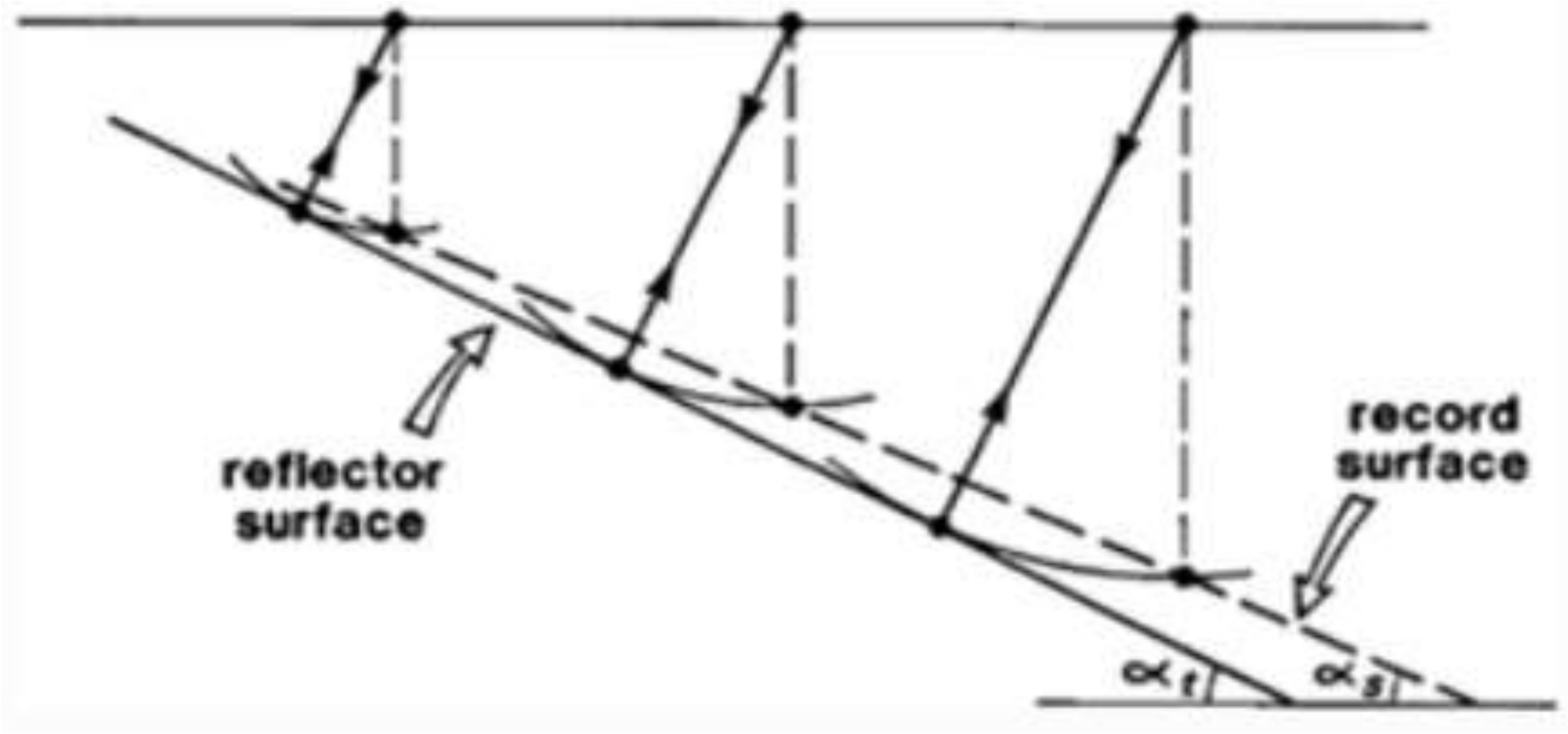
$$t_p = \frac{2L_2}{V} = \frac{2\sqrt{(x - x_p)^2 + d^2}}{V}$$

(1) Estimate the velocity *V*. Can you think of two methods?

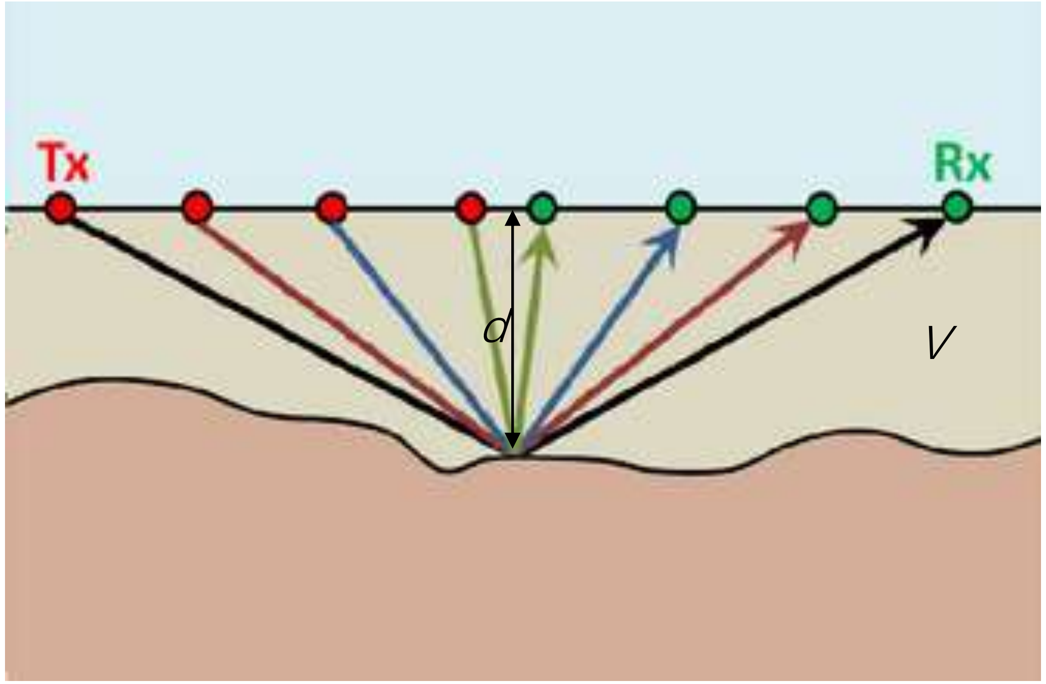
(2) Calculate the depth of burial *d* or *h*

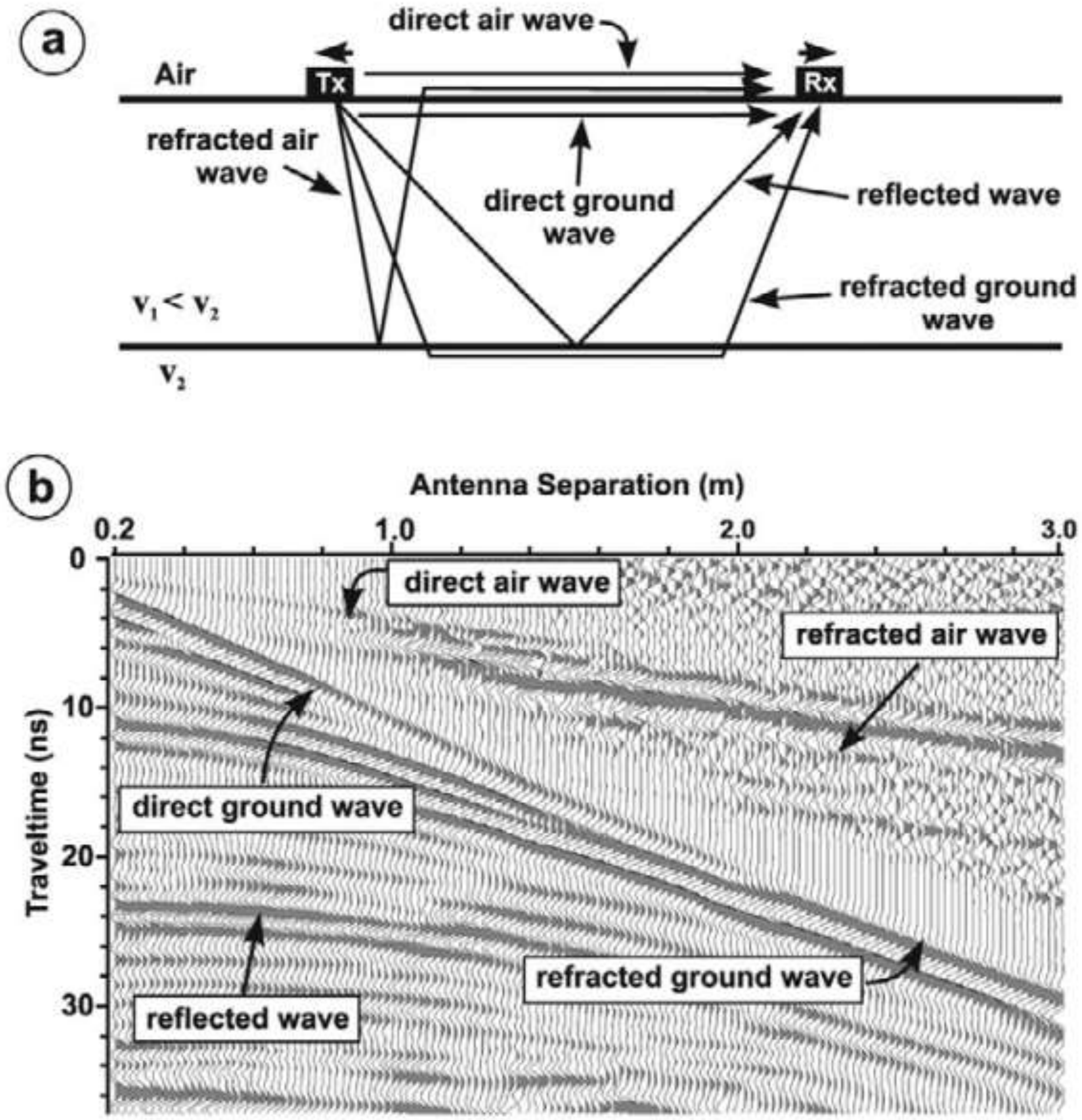
Migration

Zero offset survey along lines



Common Midpoint



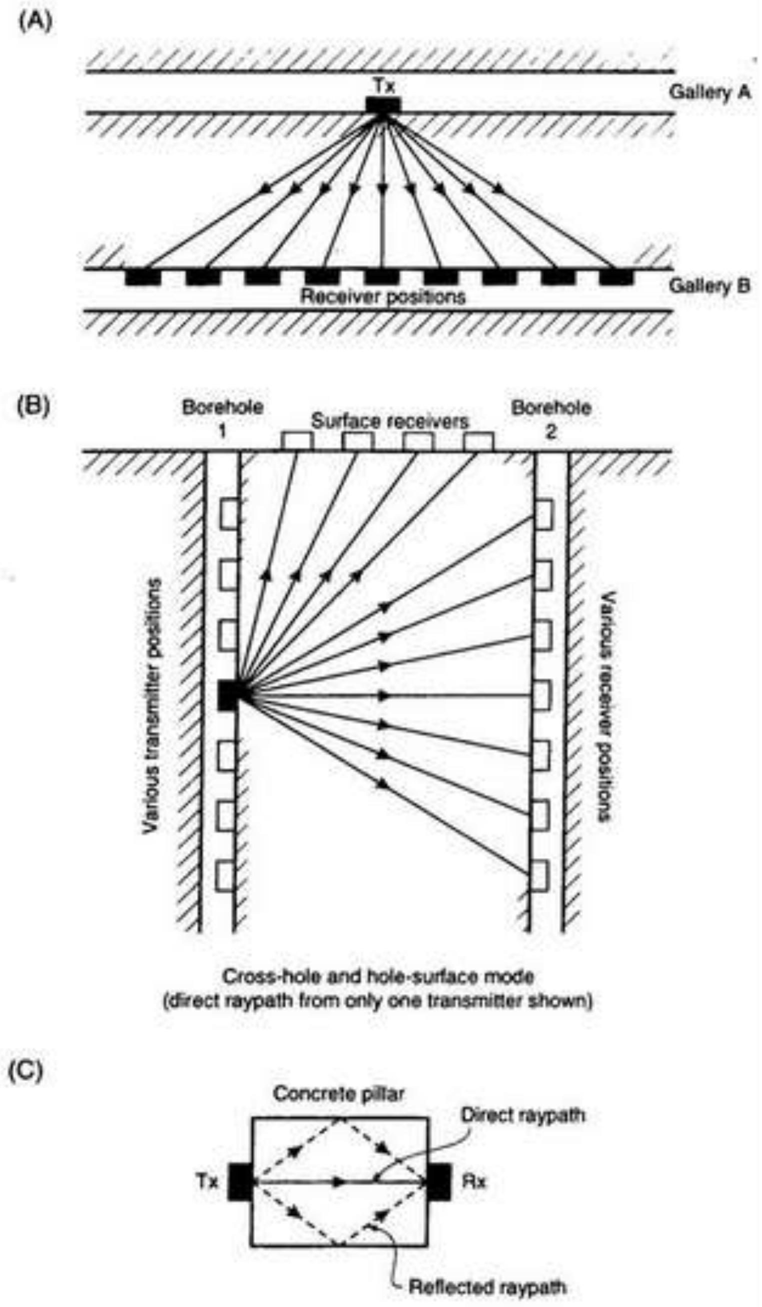


$$t = \frac{2\sqrt{x^2 + d^2}}{V}$$

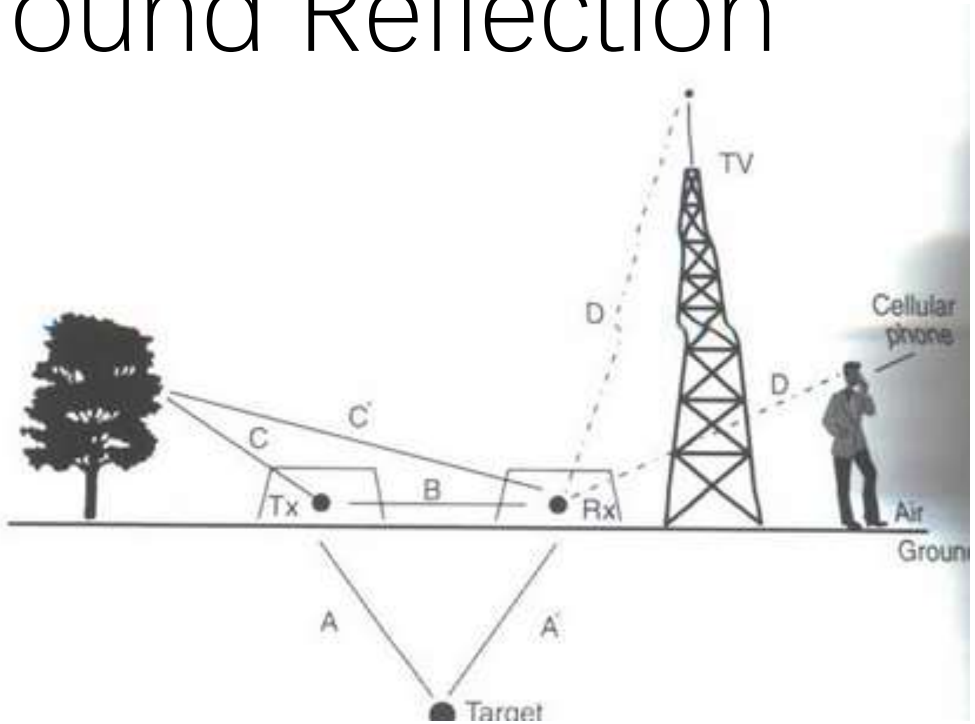
Solve for V and d

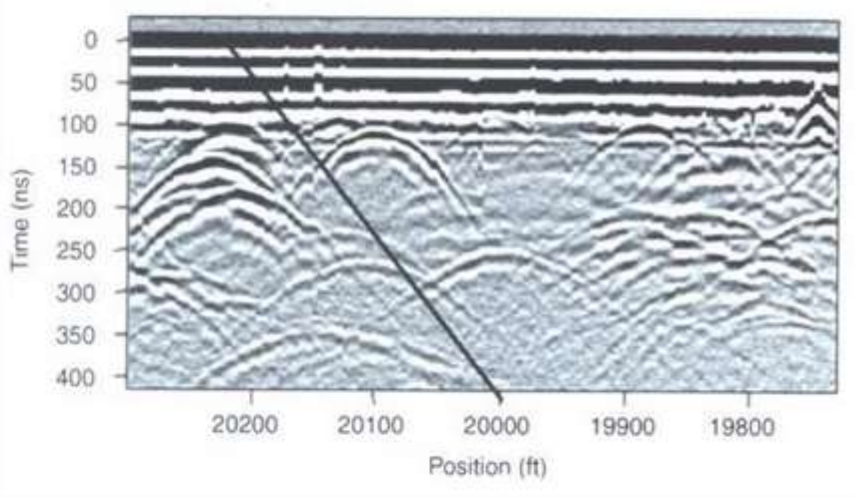
Transillumination Surveys

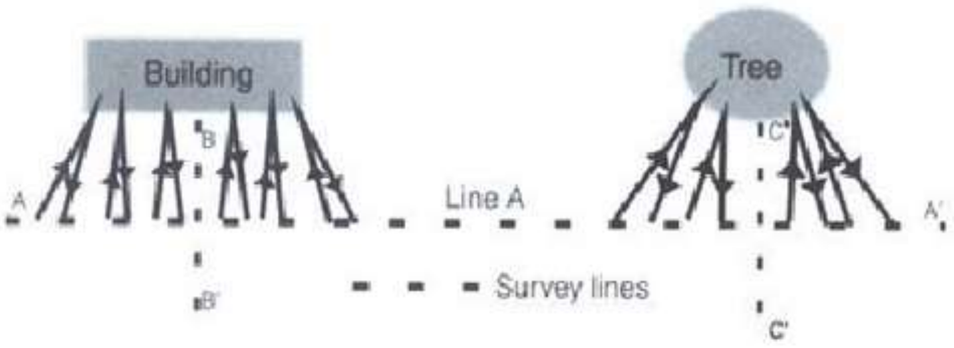
- Tx and Rx are placed on opposing sides of a target.
- Sometimes many Tx and Rx
- Used for:
  - Structural integrity of mine shafts
  - Borehole surveys
  - Finding internal structures within objects

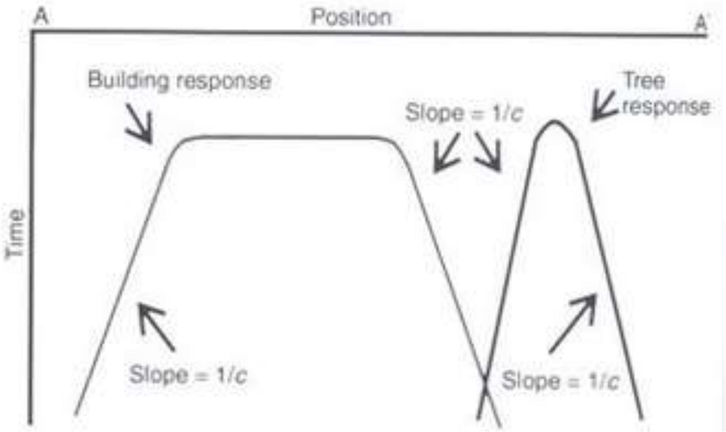


Noise – External Radiowave or Above Ground Reflection

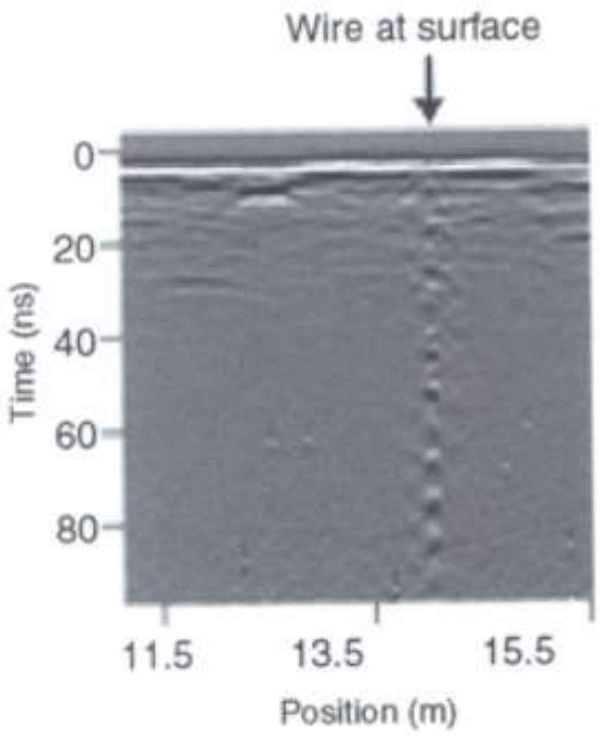








Noise - “Ringing”

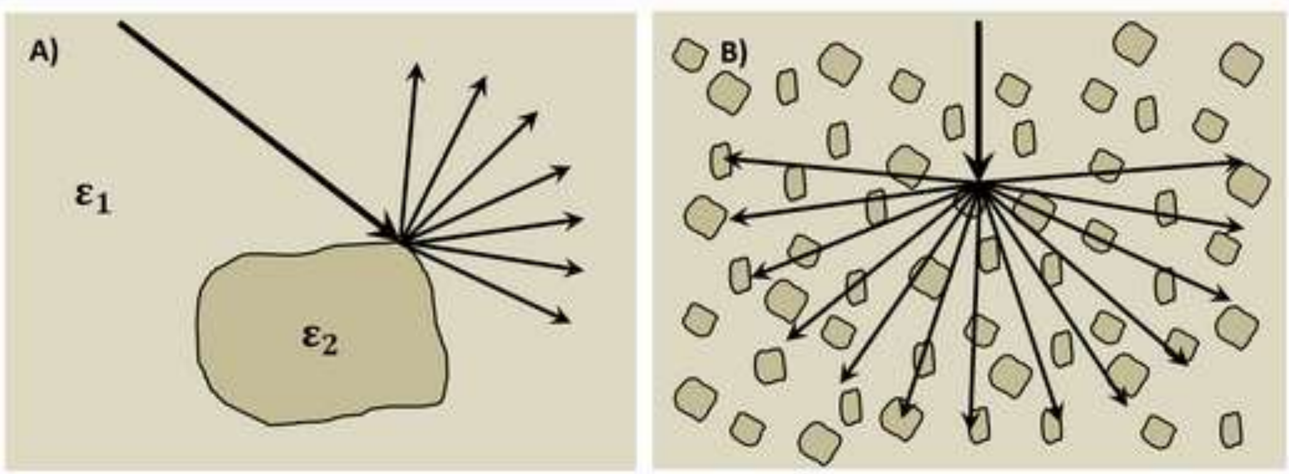


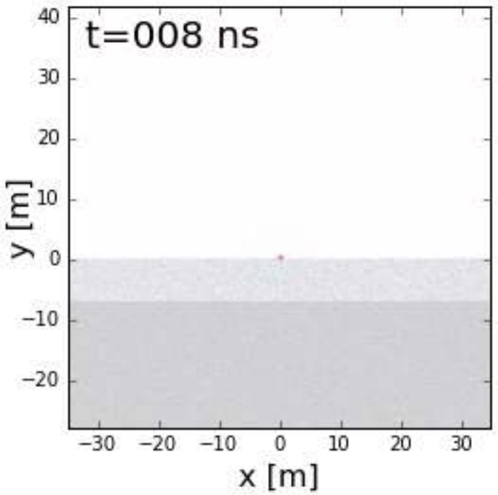
Wire below surface

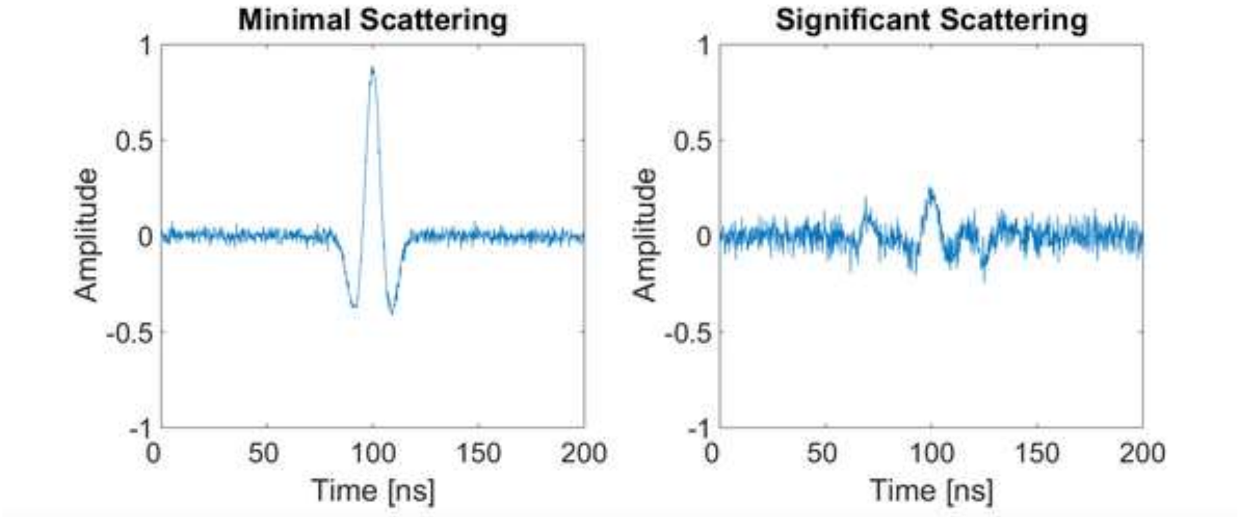
2 nearby objects

- Caused when signals reverberate in regular fashion
- Signal repeatedly bounces within a layer or between objects.

Noise – Scattering

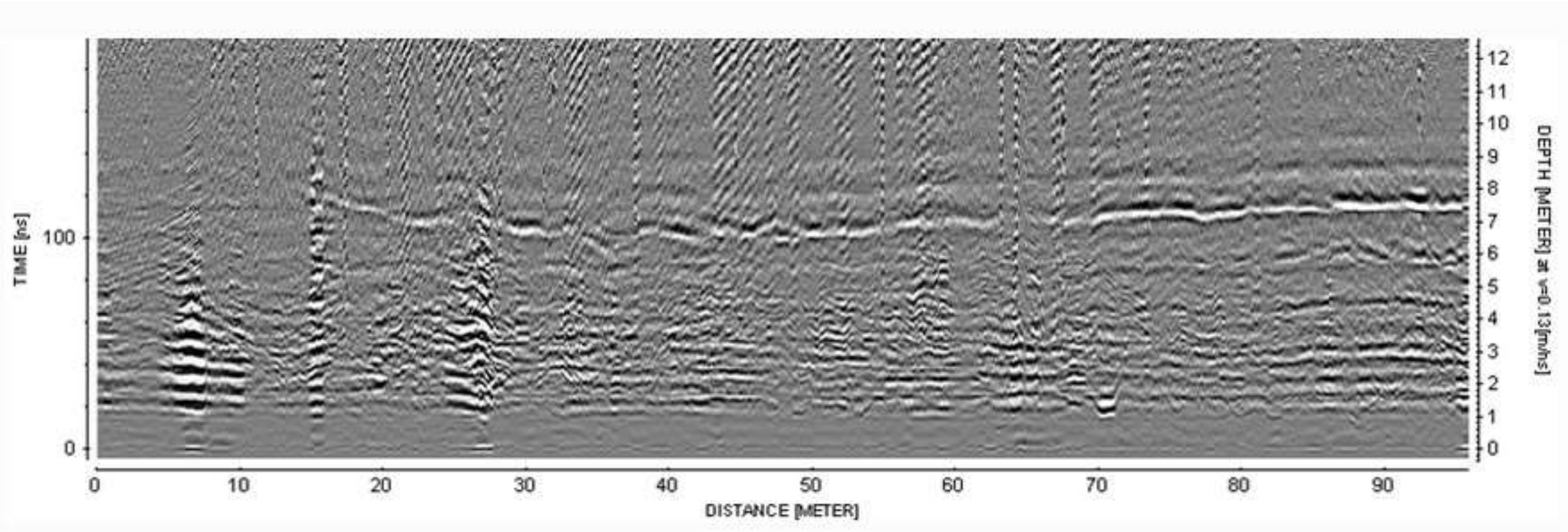






- Deviations in signal path due to localized non-uniformities.
- Reduces amplitude of usable signal and increases noise.

Processing – Time-depth Conversion

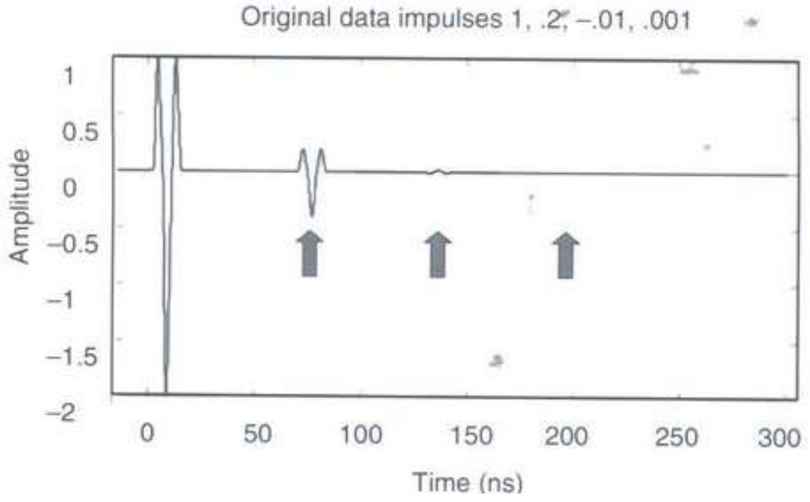


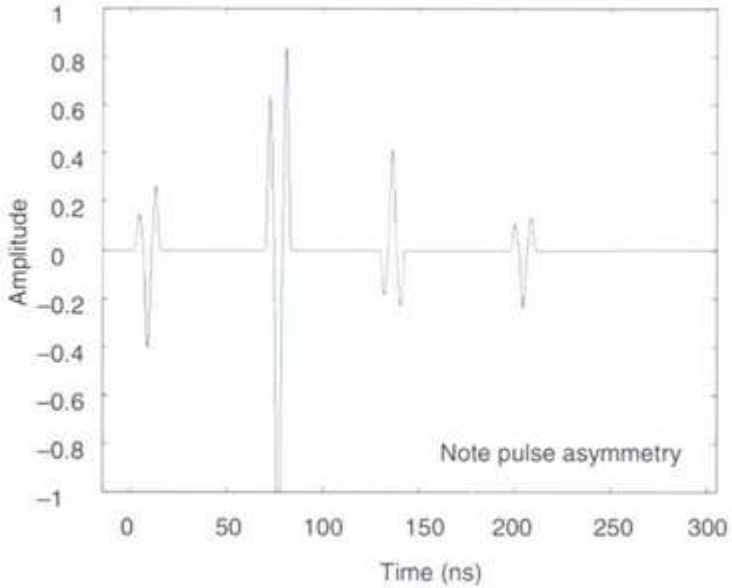
Apparent depth:

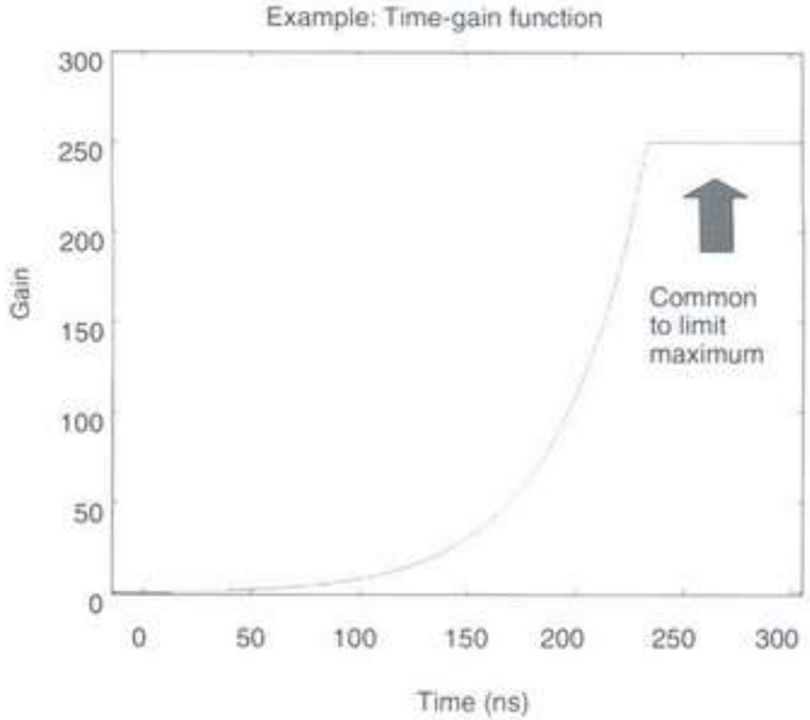
$$d_a = \frac{Vt}{2}$$

- Vertical axis usually 2-way travel time [ns]
- Get velocity first, then get an apparent depth

Processing – Gain Correction

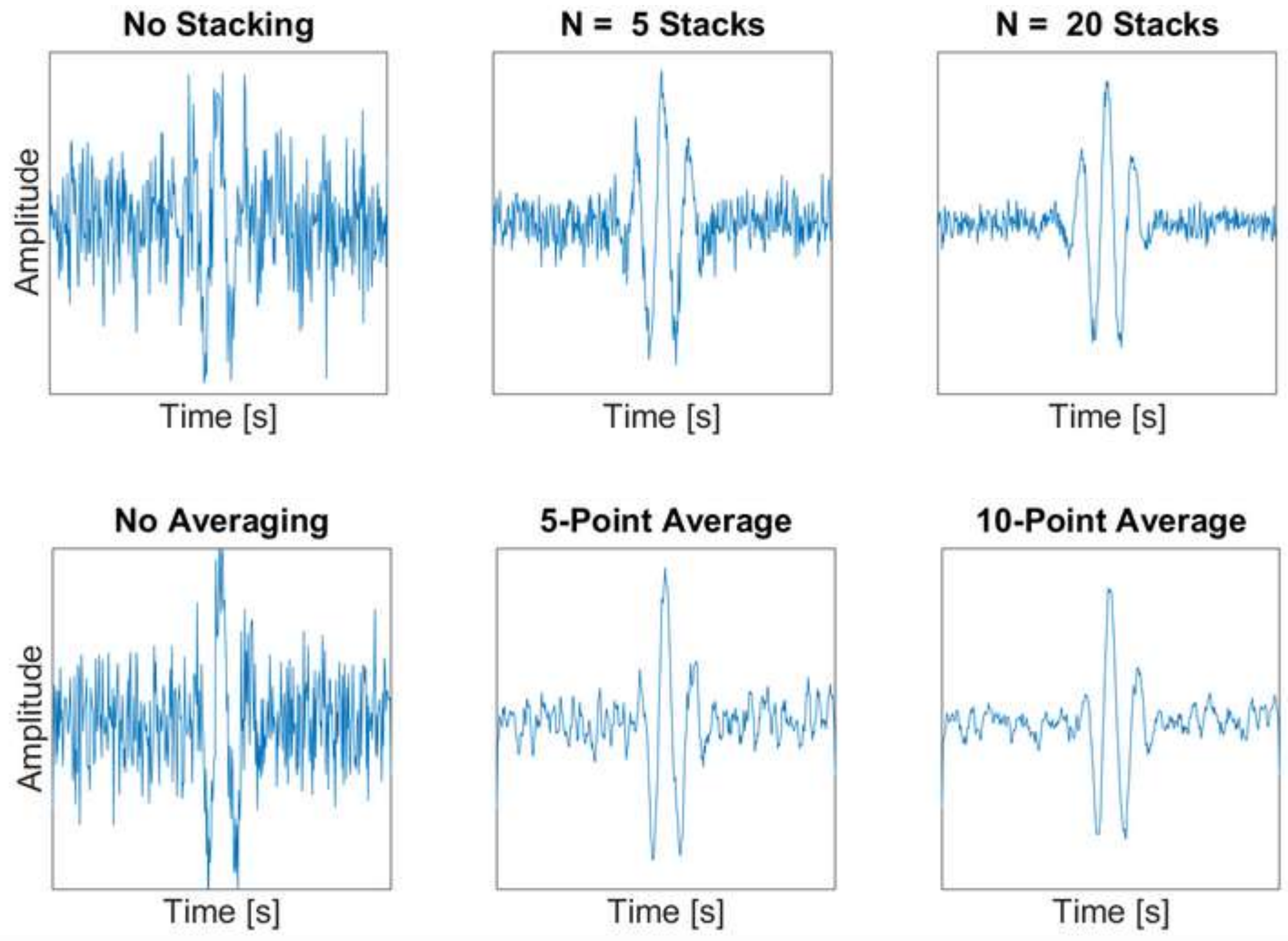






- Multiply raw data by a gain factor so that late signals can be recognized.
- Gain factor generally counteracts exponential decay in amplitude

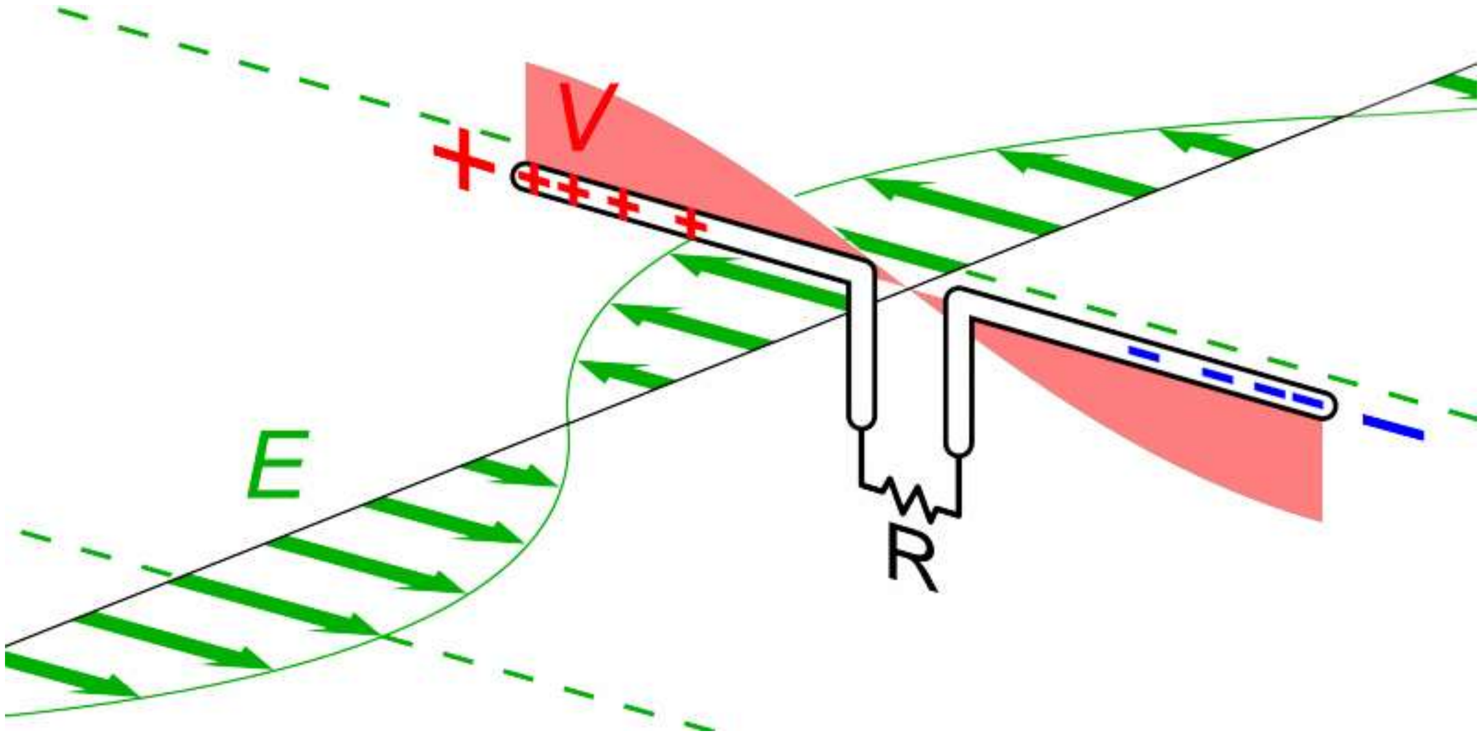
Processing – Stacking and Averaging



- Data from repeated shots are averaged (stacked)
- Stacking reduces the amplitude of incoherent noise

- Wavelet signal is smooth whereas incoherent noise is random
- Smoothing decreases amplitude of random noise relative to returning signals.

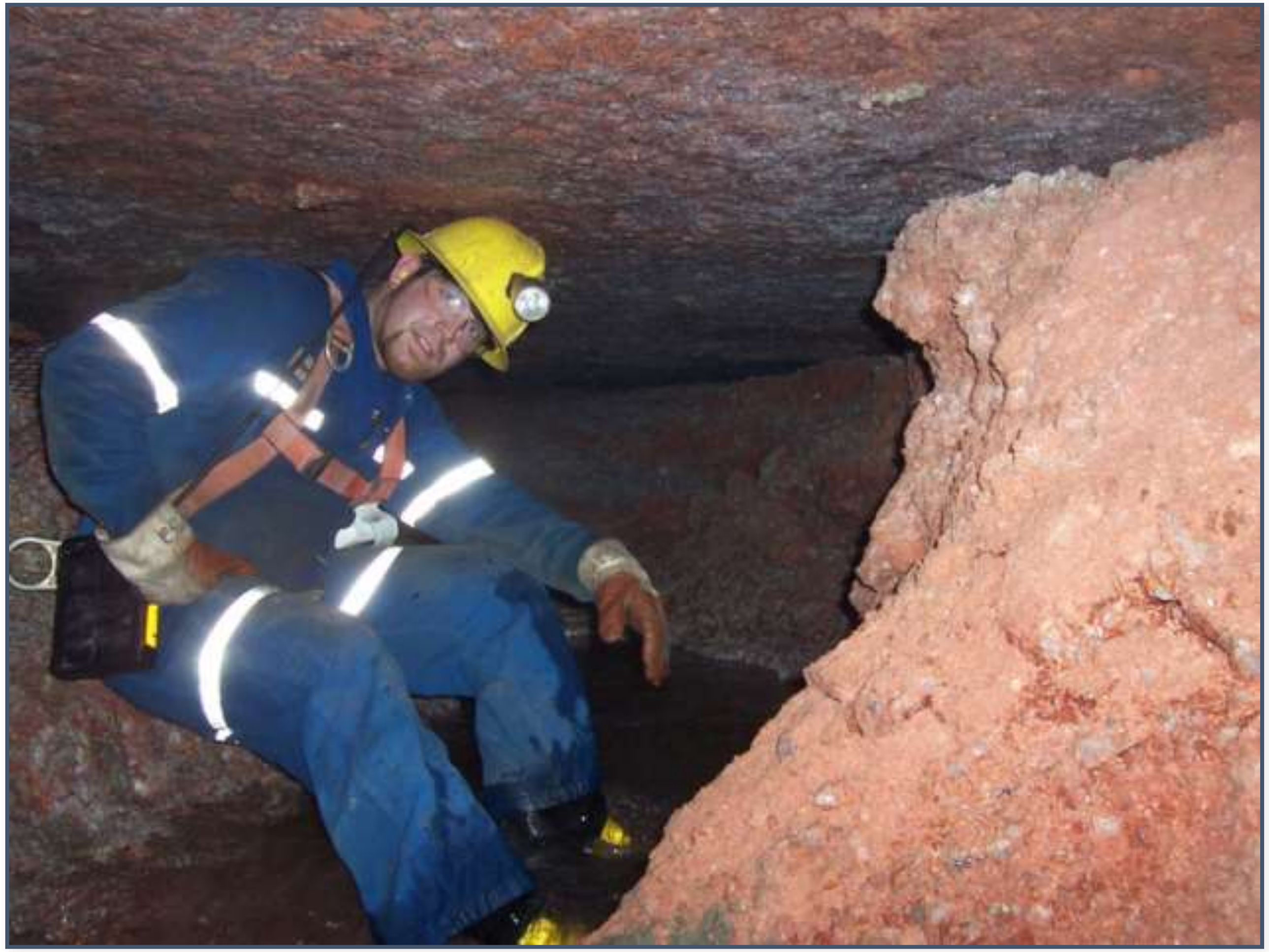
GPR Antenna

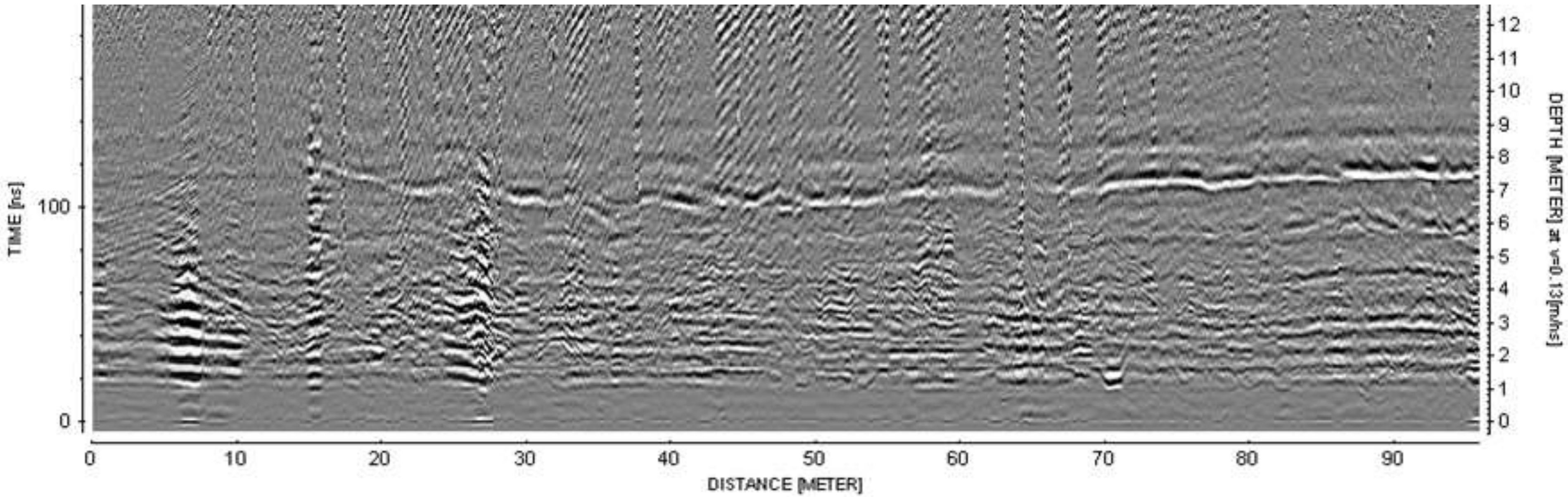


Half-wave dipole antenna:
Length is determined by the intended wavelength (or frequency) of operation

GPR Antenna

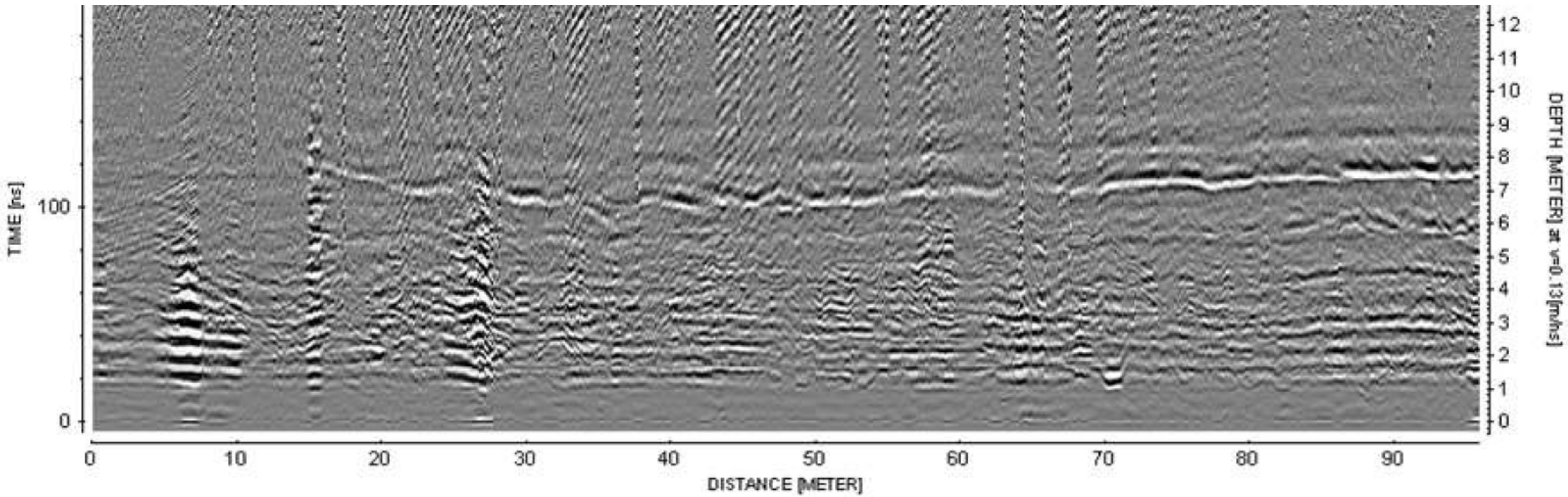
Water Hazard in Potash Mine





- Zero offset GPR survey performed.
- Arrival time to depth conversion performed

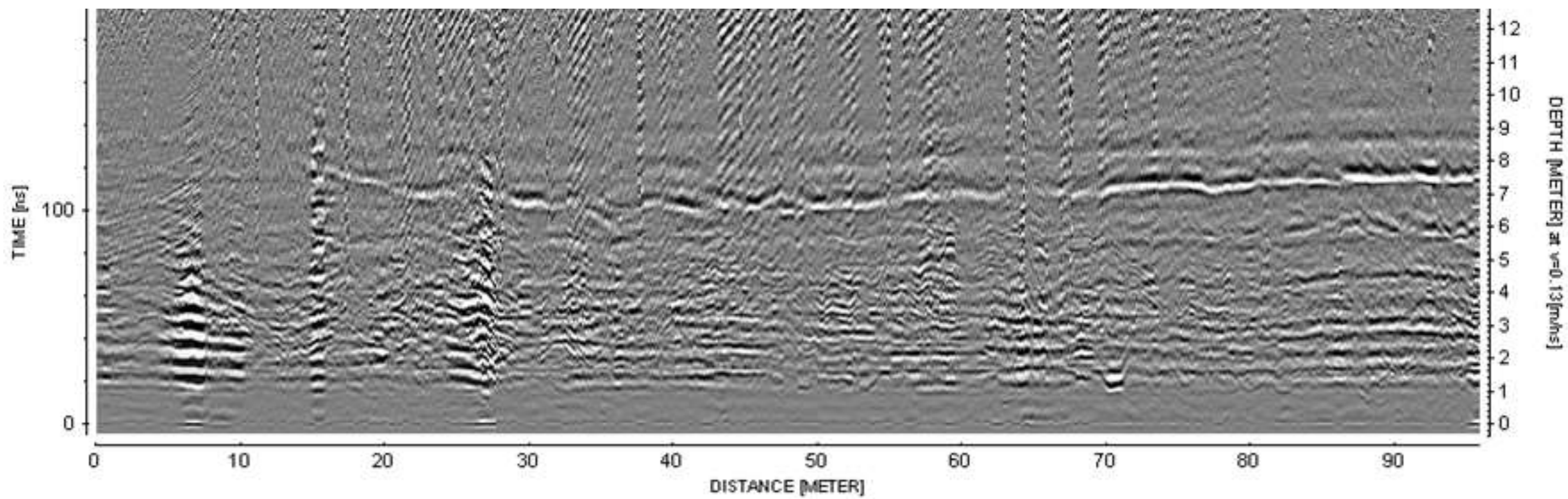
  Q: Without a direct ground wave measurement or hyperbola to obtain propagation speed, how could they do conversion?



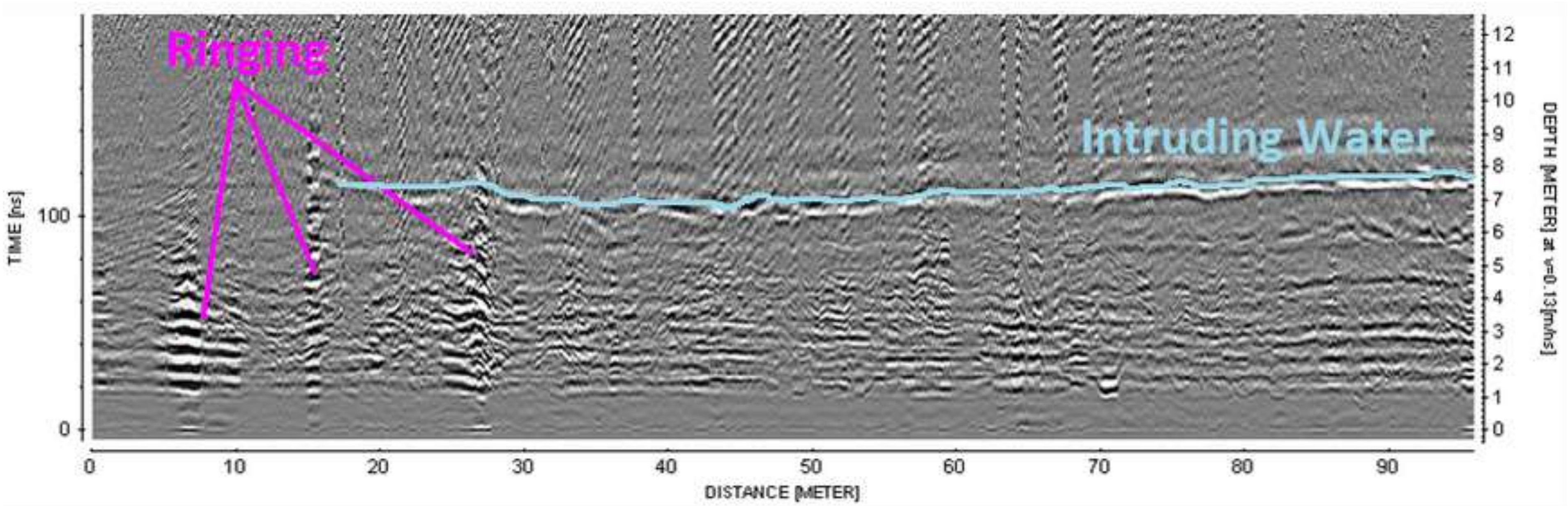
A: Potash in an anhydrite mineral.

From known physical properties, V ~ 0.13 m/ns

Apparent depth $d_a = V\, t / 2$



Q: What kinds of features do you see in the data?



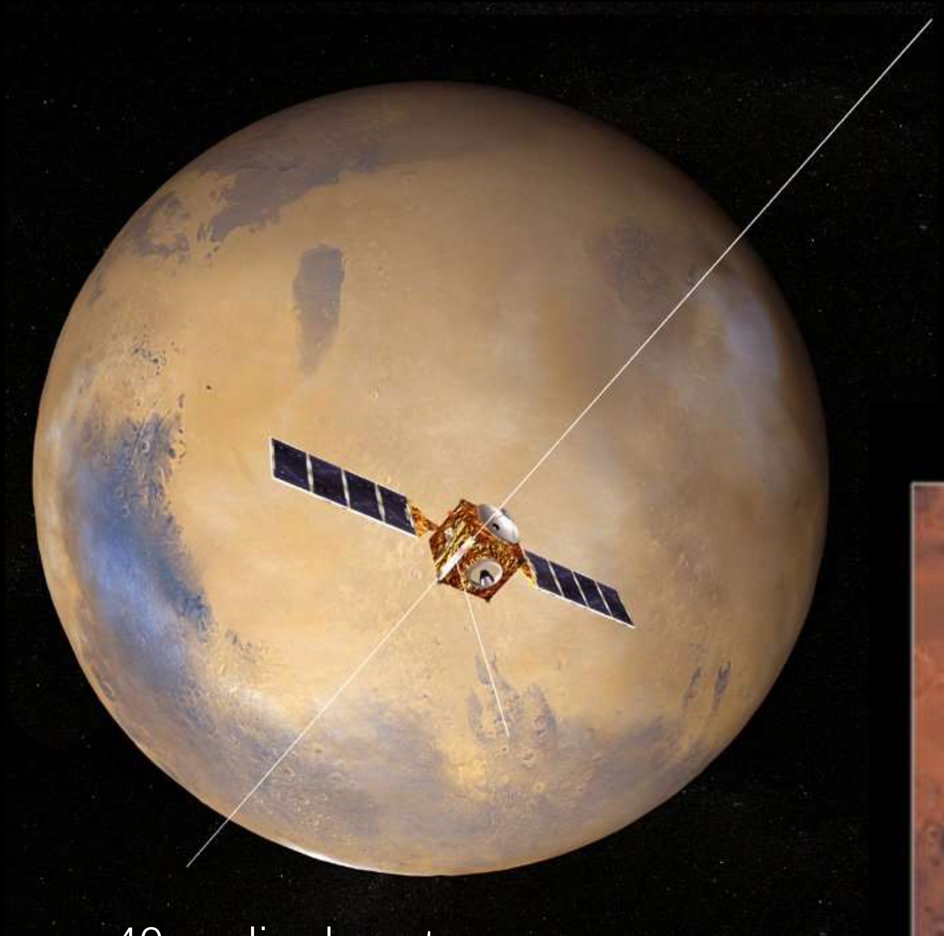
- Strong reflector from intruding water (7 - 8 m into the wall)
- Water is delineated and seems to be coming from the right
- Ringing from mine infrastructure

GPR on SUSTech Campus

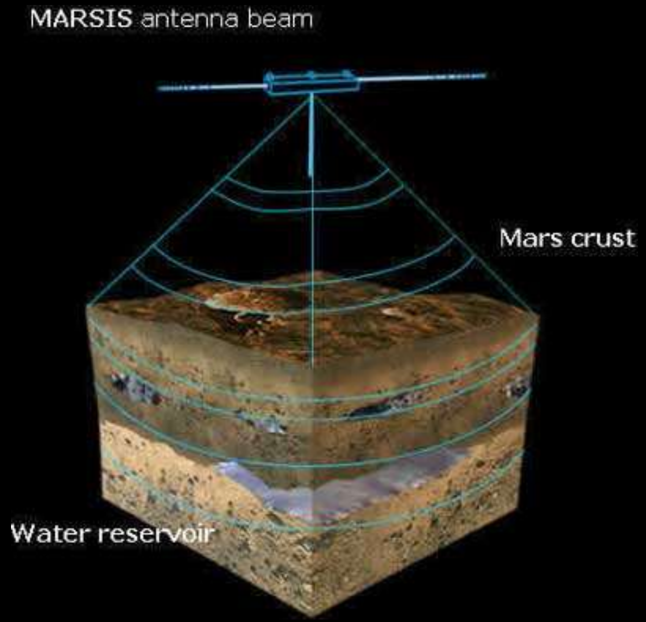
On SUSTech campus: search for buried power cables

- Frequency range: 100M to 1G Hz
- Depth of penetration: within 100 m
- High frequency: good resolution but shallow
- Low frequency: poor resolution but deep
- Good reflectors: water (ε_r = 81), metal (ε_r = infinity)

Mars Radar



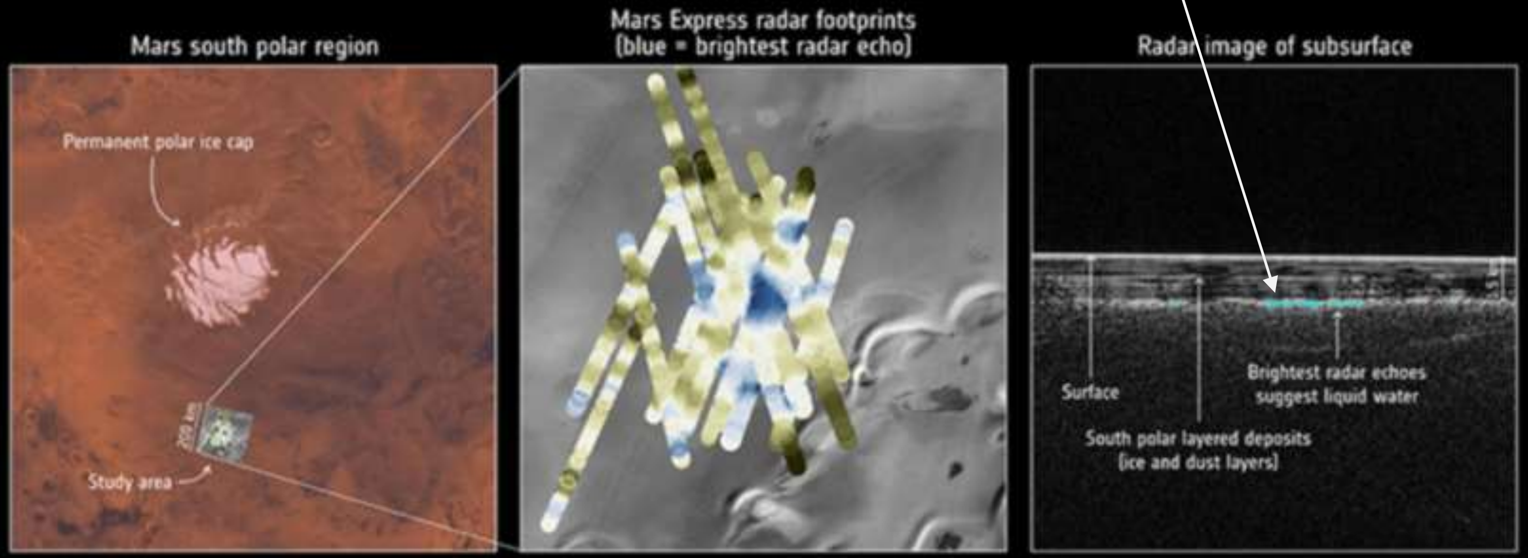
40 m dipole antenna
1.8 ~ 5.0 MHz



Mars Advanced Radar for Subsurface
and Ionosphere Sounding

MARSIS mission

Liquid water beneath ice cap



Summary of GPR

- EM at high frequency: Wave regime
- Physical properties utilized by EM/GPR
- Reflection, transmission, refraction and scattering
- Signal length scale and resolution
- Depth vs. spatial resolution
- GPR survey types
- GPR data analysis: velocity and depth
- GPR data processing
- GPR noise in practice
- GPR instruments: Antenna
- Applications: Water gushing in potash mines, MARS radar, Searching pipes.