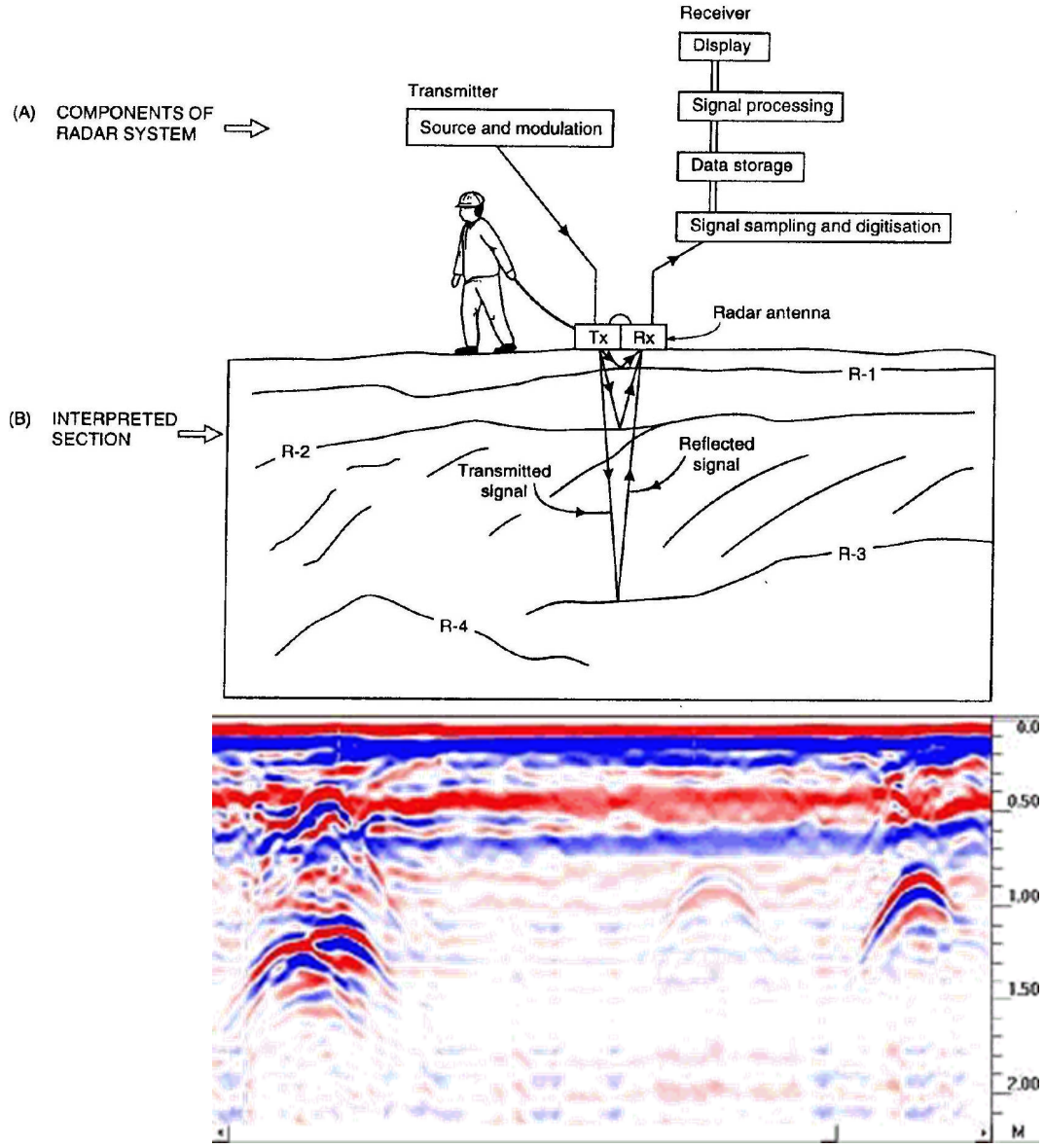
Ground Penetrating Radar (day 1)



EOSC 350 ‘06

Today's Topics

- Introduction to GPR

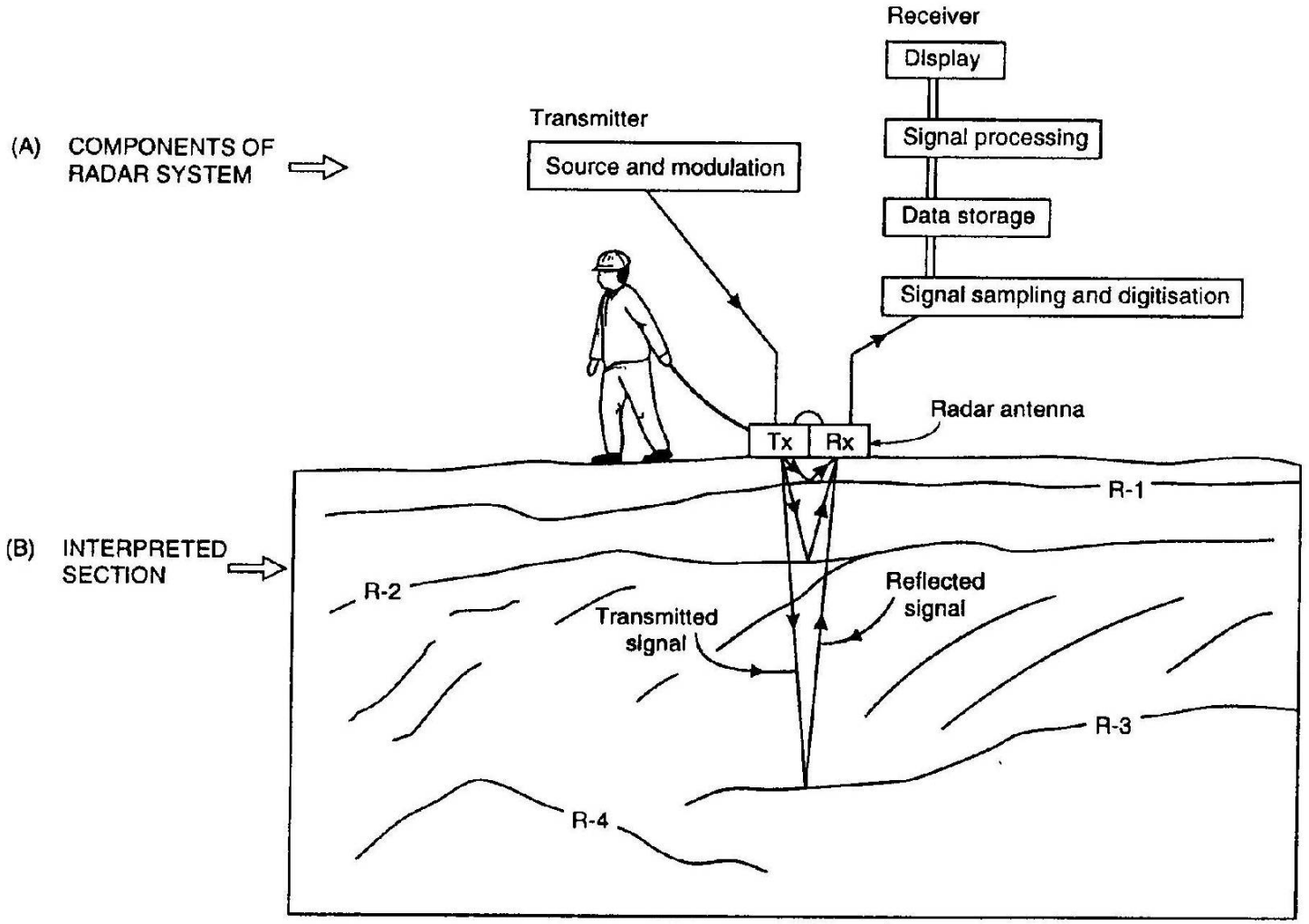
- Setup: Motivational Problems

- Physical Properties
  - Dielectric Permittivity and Radiowaves
  - Microwave Example

- Basic Principles:
  - Propagation of Radiowaves
  - Attenuation
  - Reflection and Refraction

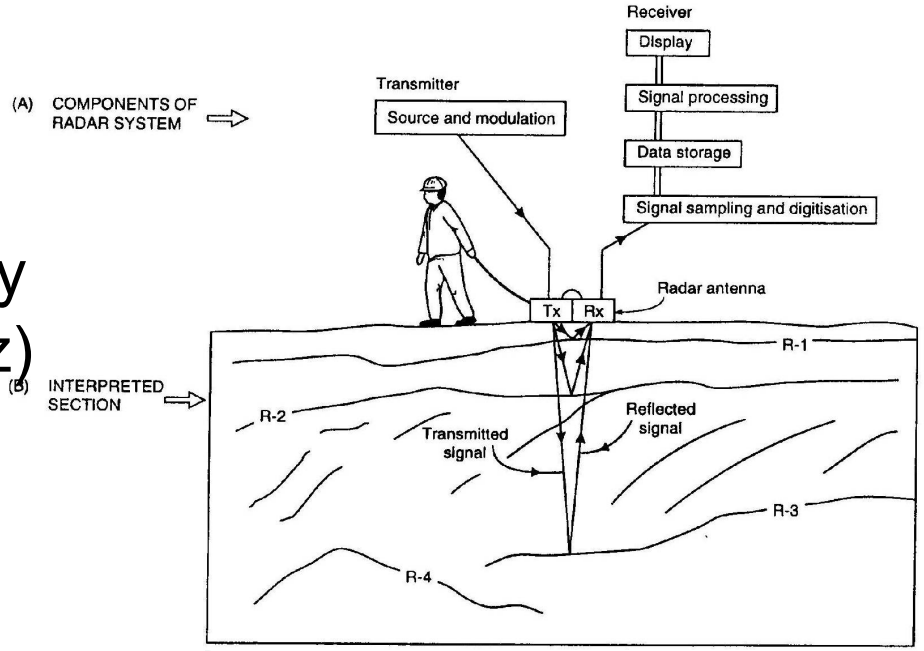
**See GPG introduction, physical properties and basic principles pages*

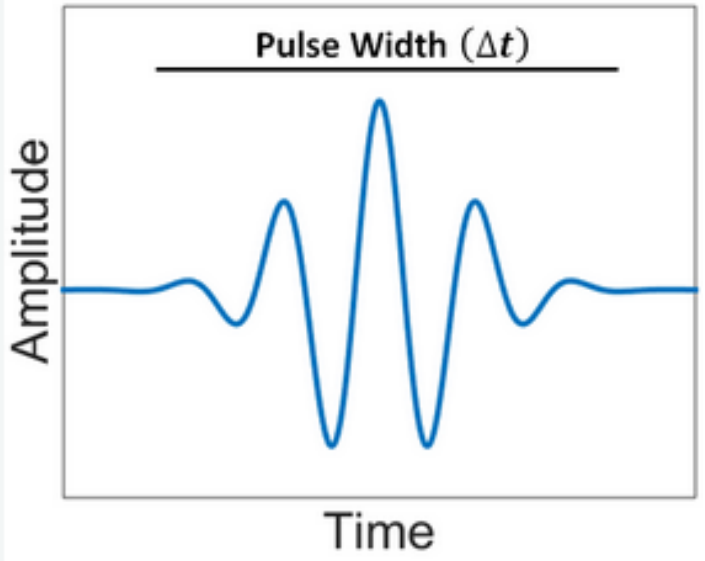
Introduction to GPR



Introduction to GPR

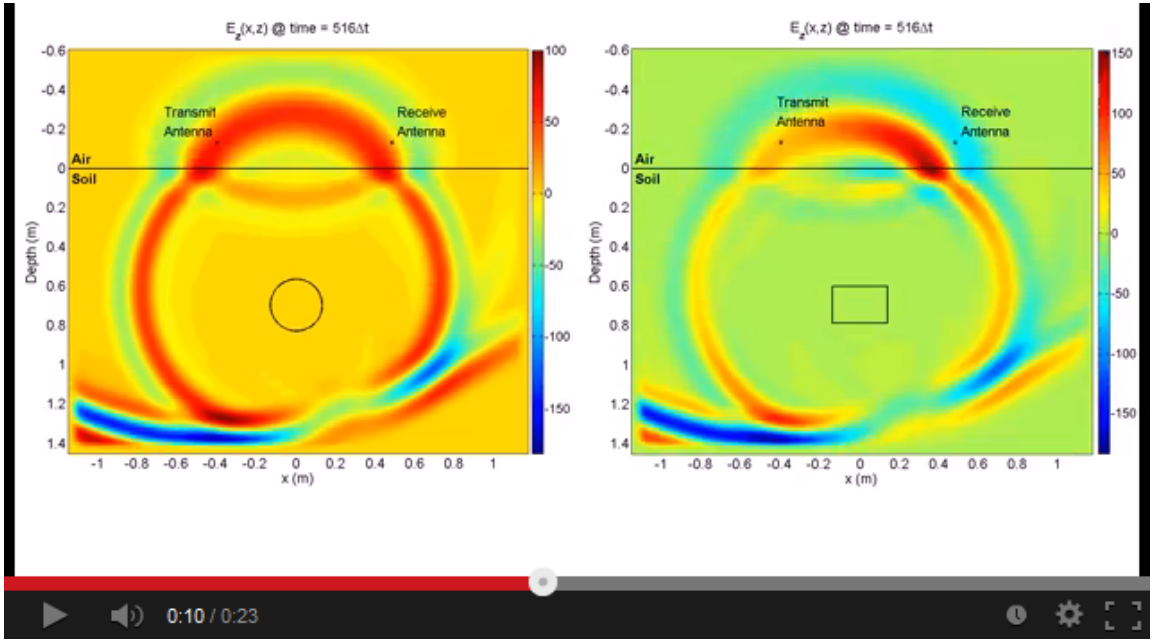
- GPR is an EM method (depends on ε, σ, and μ)
- Uses a pulse of high-frequency radiowaves (100s MHz to GHz)
- Generally shallow surveys (10s of metres or less)
- Radiowaves reflect and refract at boundaries
  → Theory very similar to seismic
- Radiowave propagation depends on Earth's EM properties

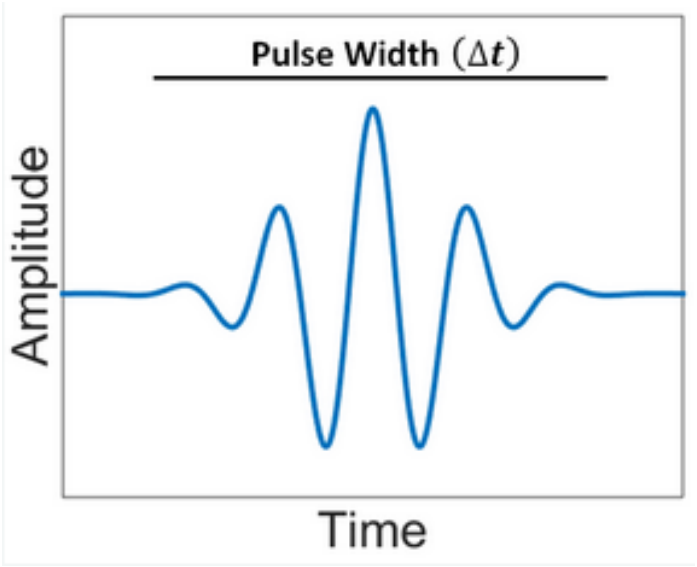




Introduction to GPR: 2D Example

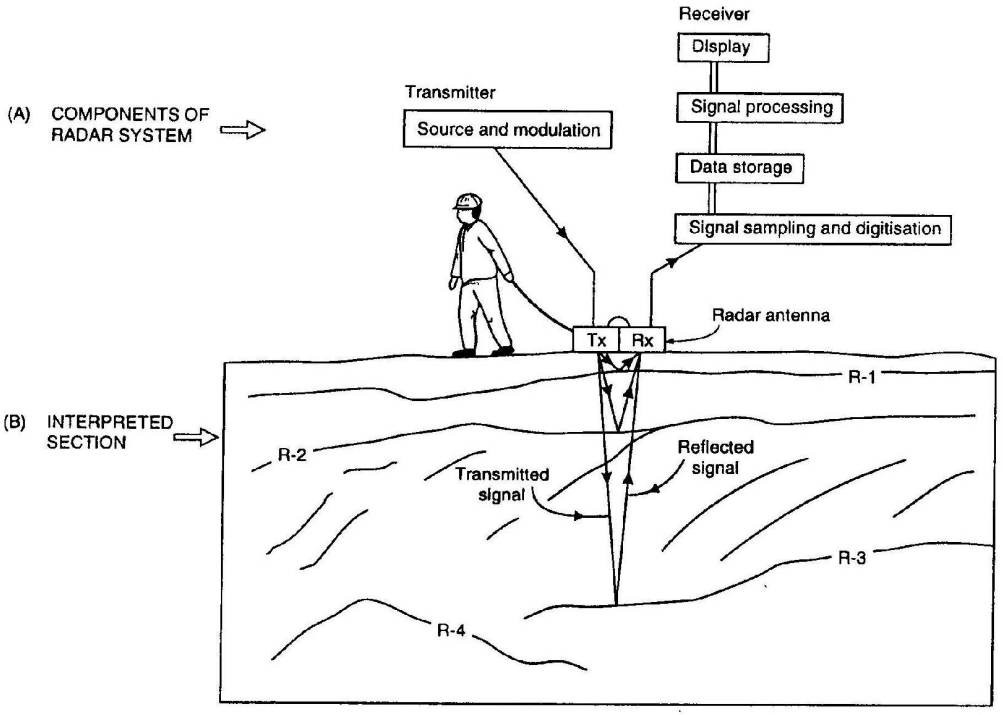
- Sends a **pulse** of waves **not** continuous waves
- What features/behaviours do you see?
- http://www.youtube.com/watch?v=eqfgP4qVK4s



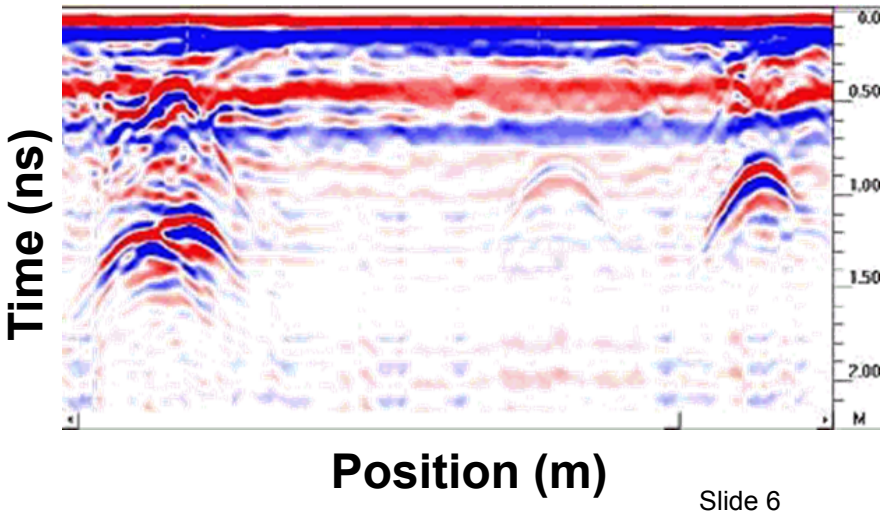


Introduction to GPR

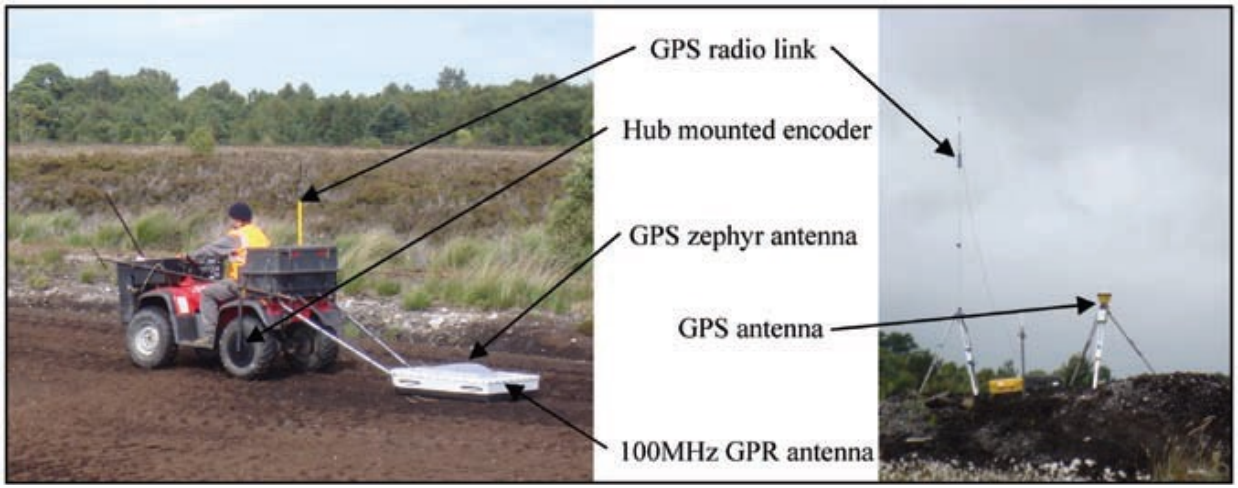
- Returning radiowave signals are measured
- These signals are represented using a **radargram**
- Radargrams essentially seismograms for GPR



Radargram example



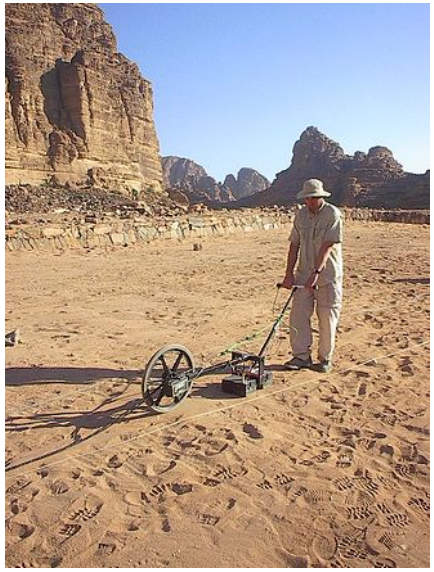
Some Motivational Problems



Mapping Peat Thickness (Ireland)

Mapping Ice Thickness (Antarctica)

Urban Geotechnical Problems



Archaelogy (Jordan)

Some Motivational Problems

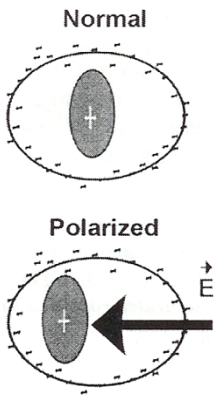
- Looking for buried pipes, objects
- Investigating concrete structures, roads
- Ice/snow: avalanche, search and rescue
- Near surface soil conditions: salinity, saturation
- Geotechnical work (tunnels)
- Forensics
- Archaeology

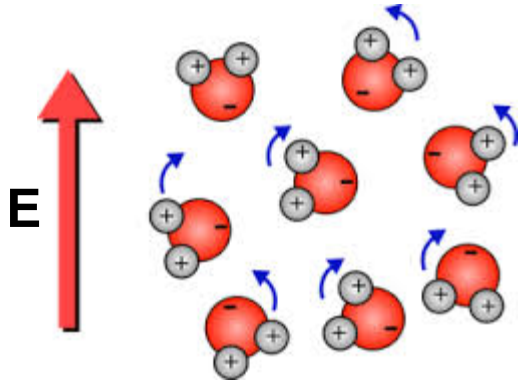
http://sensoft.ca/

Physical Properties

Dielectric Permittivity (ε):

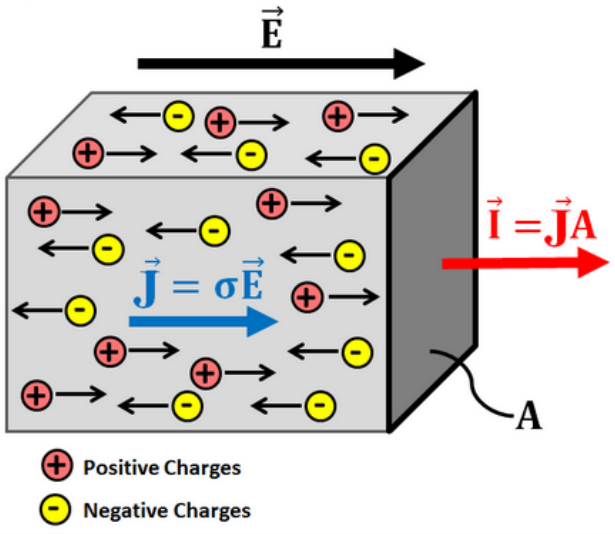
How easily a material is electrically polarized





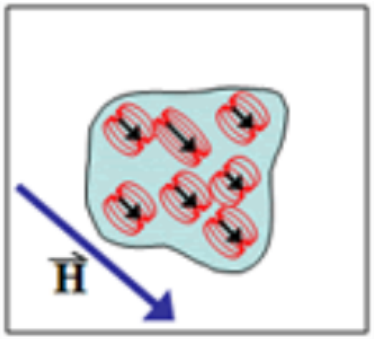
Electrical Conductivity (σ):

How easily electrical charges flow through a material



Magnetic Permeability (μ):

How strongly a material supports magnetism



Physical Properties

Dielectric Permittivity (ε):

→ Considered the **diagnostic physical** property for GPR
→ Impacts velocity and reflection/refraction of radiowaves
→ Significantly impacted by water content ($\varepsilon_r = 80$)

Electrical Conductivity (σ):

→ Impacts attenuation (amplitude loss) of GPR signals

Magnetic Permeability (μ):

→ Only important if things are very susceptible (generally ignored)

Physical Properties

Dielectric Permittivity: ε

Magnetic Permeability: μ

$$\varepsilon_r = \varepsilon / \varepsilon_0$$

Relative Permittivity:

$$\mu_r = \mu / \mu_0$$

Relative Permeability:

$\varepsilon_0 = 8.85 \times 10^{-12}$ F/m

$\mu_0 = 1.26 \times 10^{-6}$ H/m

$1 \leq \varepsilon_r \leq 80$

Physical Properties

Dielectric Permittivity: ε

Magnetic Permeability: μ

Relative Permittivity: $\varepsilon_r = \varepsilon / \varepsilon_0$

Relative Permeability: $\mu_r = \mu / \mu_0$

$\varepsilon_0 = 8.85 \times 10^{-12}$ F/m

$\mu_0 = 1.26 \times 10^{-6}$ H/m

$1 \leq \varepsilon_r \leq 80$

$\mu_r = 1$

Dielectric Permittivity and Radiowaves

- Water has strongest effect on ε in geologic materials.
- **Velocity** of radar signals is (usually) most affected by ε.

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

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

$$c = 3 \times 10^8 m/sec$$

$$c = 0.3 m/ns$$

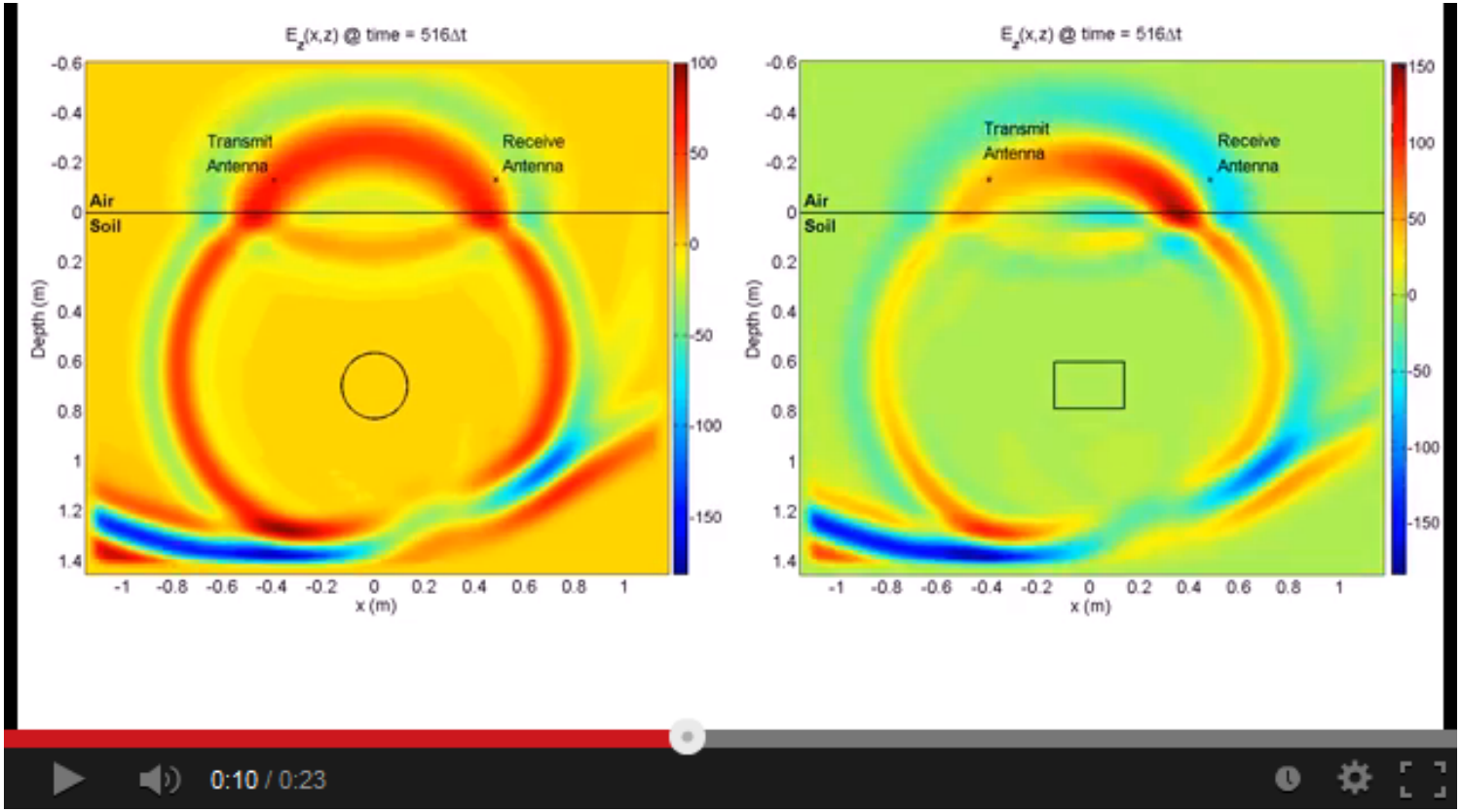
$\varepsilon\downarrow r = \varepsilon/\varepsilon\downarrow 0$

Introduction to GPR: 2D Example

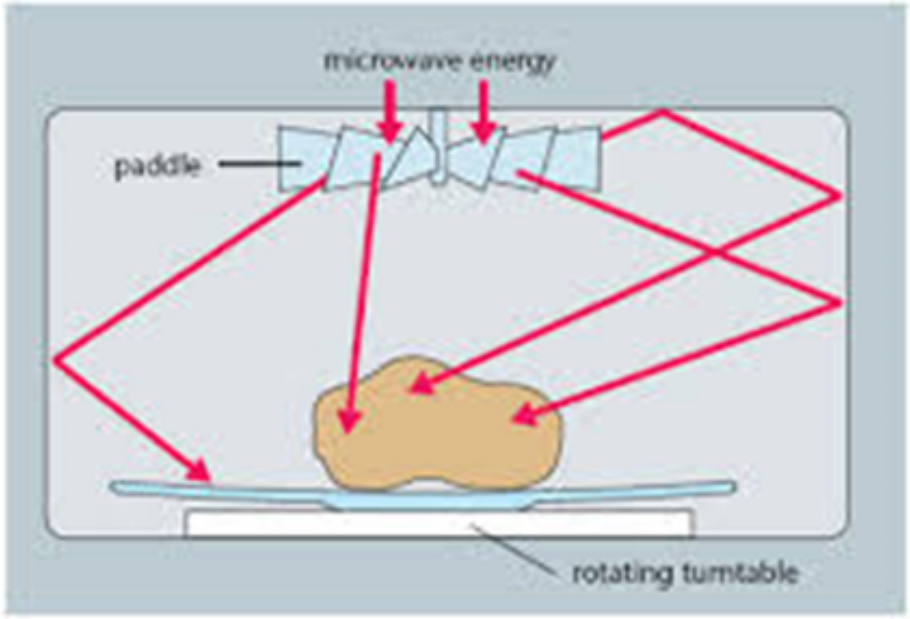
- What has faster propagation velocity?
- What has larger dielectric permittivity?

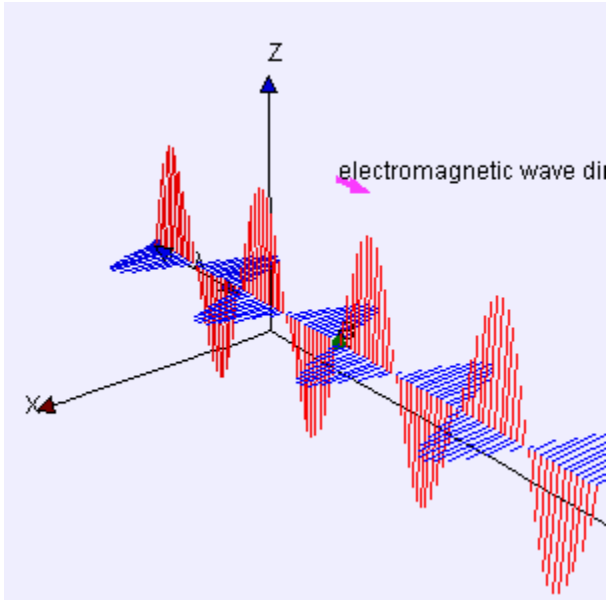
$$v = \frac{c}{\sqrt{\epsilon_r}}$$

- http://www.youtube.com/watch?v=eqfgP4qVK4s



Microwave Oven Example





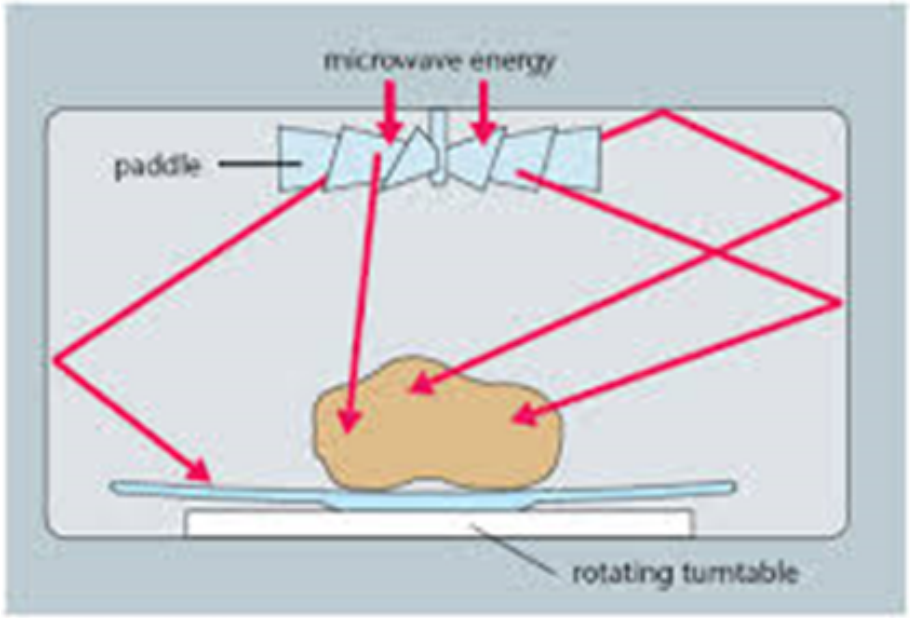
- Radiowaves and microwaves support oscillating electric and magnetic fields (why ε,σ and μ are all significant)

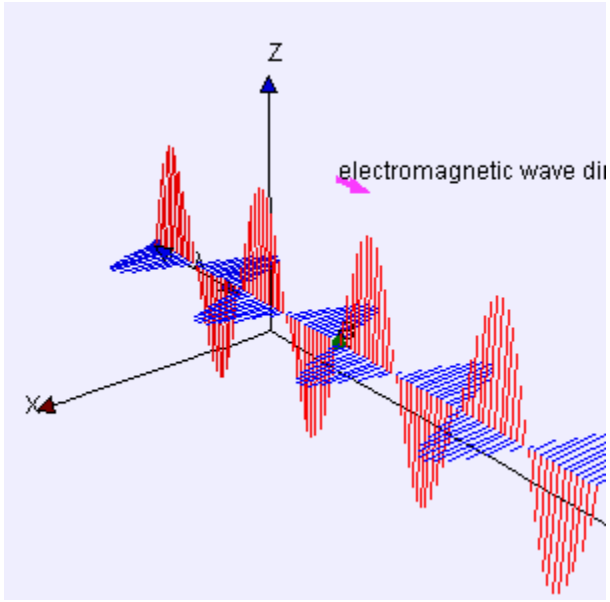
- Microwaves use very high frequencies (~ 2.45 GHz)

$$\mathbf{L}=c/f=3.00\times10\uparrow8\ m/s/2.45\times10\uparrow9\ s\approx12\ cm$$

- Wavelength:

Microwave Oven Example

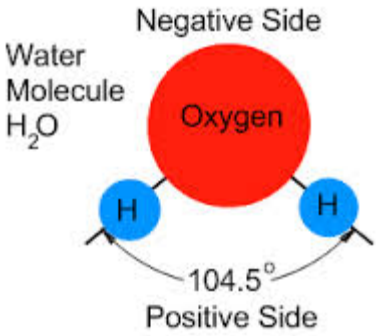




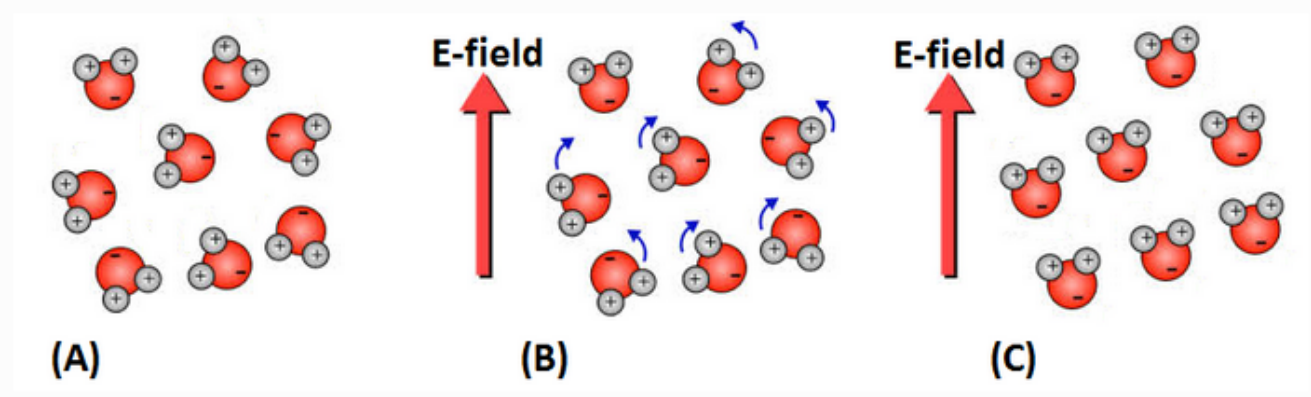
- Microwaves (and radiowaves) reflect off conductive walls
- Microwaves (and radiowaves) don’t interact with plastic turntable
- Microwaves energy absorbed by water in food

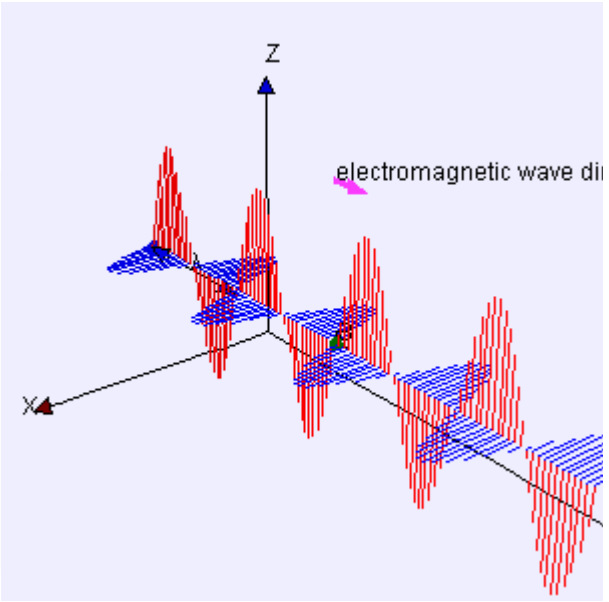
Microwave Oven Example

- Water molecules are naturally polarized



- Water molecules align strongly with electric fields (large permittivity)
- Reorientation of water molecules happens at the frequency of the microwaves (2.45 GHz is 2.45 billion times per second!!!)





The Magic of Microwave Ovens

1. Microwaves reach food

2. Microwaves cause rapid re-orientation of water molecules in food (because of ε_{lr})

3. 2.45 GHz is the resonance frequency for water
   → Energy absorbed and turned into kinetic energy (heat)

4. Water molecules transfer heat to the rest of the food

Microwave Oven Recap

- Microwaves (and radiowaves) are high-frequency, short wavelength waves
- Conductive objects reflect microwaves (and radiowaves) very efficiently.
- The operating frequency has a significant impact on how microwaves (and radiowaves) interact with materials.
- Materials containing water are strongly polarized by microwaves (and radiowaves)

Questions: Recap

Q: What geophysical survey is most comparable to GPR?

Q: What is the scale of GPR surveys? Applications?

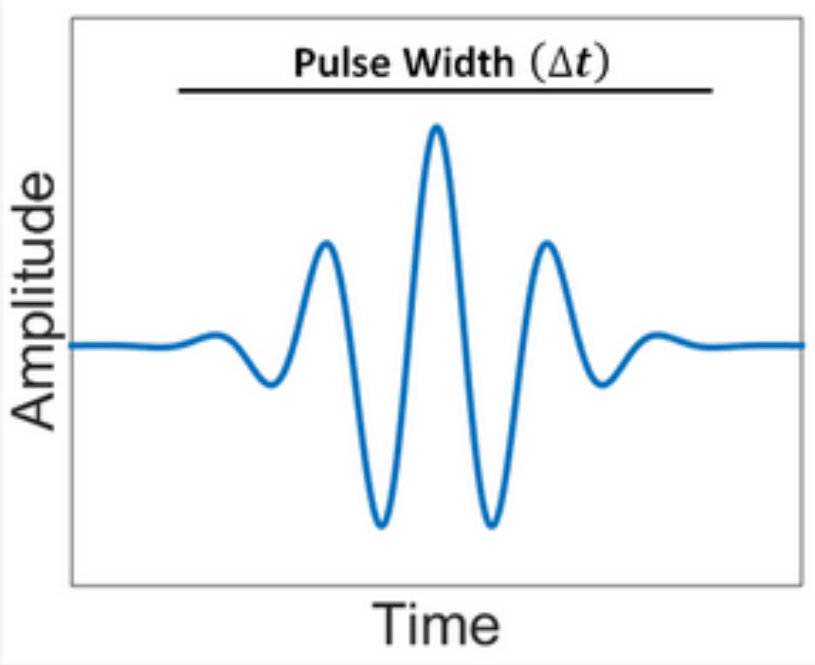
Q: What is the diagnostic physical property for GPR?

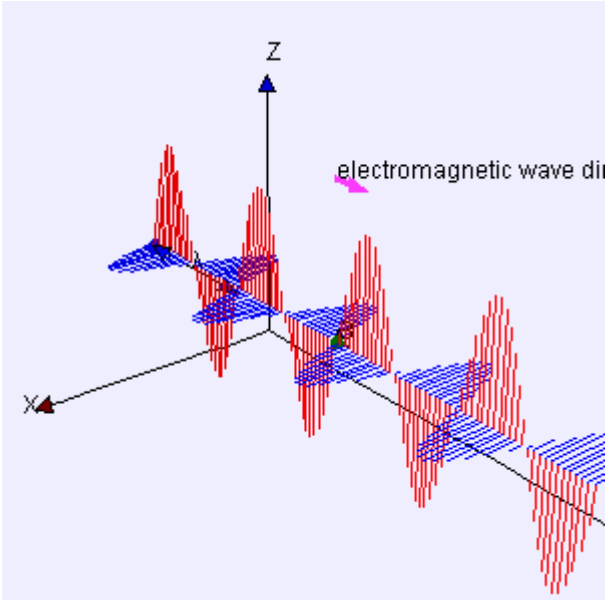
Q: What impacts this physical property the most?

Q: What is the signal that GPR sends into the ground? Is it continuous or a pulse?

Radiowave Propagation

- GPR sends a **pulse** of EM waves. **Not continuous!**



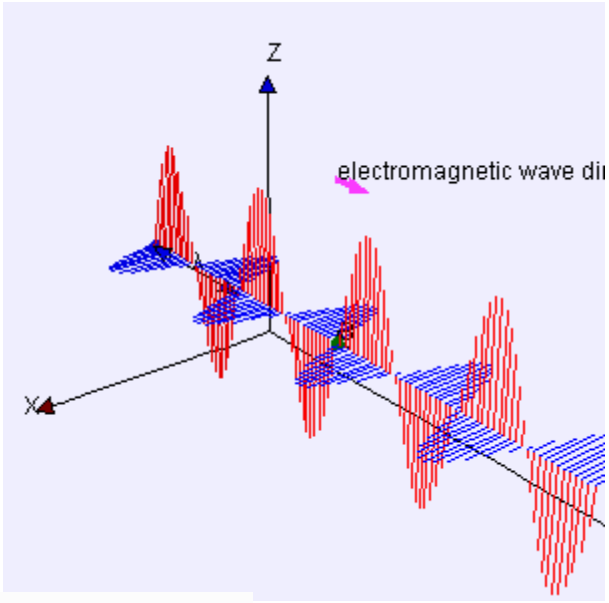


- GPR is 100s MHz to GHz which are **radiowaves**

Radiowave Propagation

- EM waves carry oscillating electric and magnetic fields
  at a particular frequency

- EM waves move through
  different materials at different speeds



- 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 ($\mu_r = 1$): $$V = \frac{c}{\sqrt{\varepsilon_r}}$$

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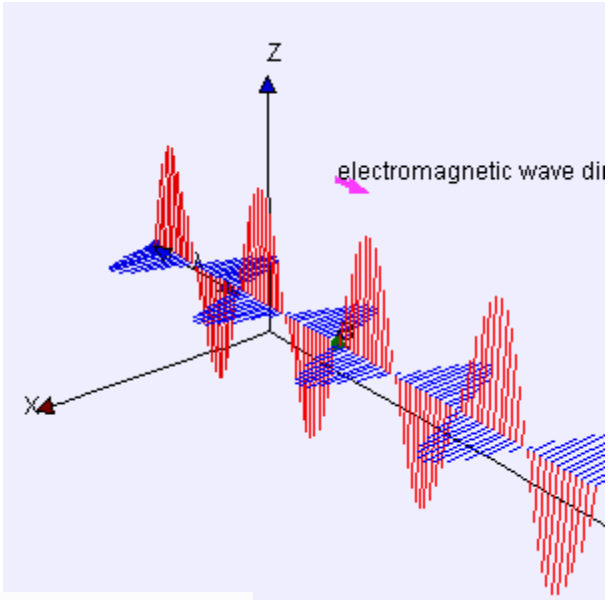

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Radiowave Propagation

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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**

Radiowave Propagation

- Velocity decreases as ε_r increases: $V = \frac{c}{\sqrt{\varepsilon_r}}$

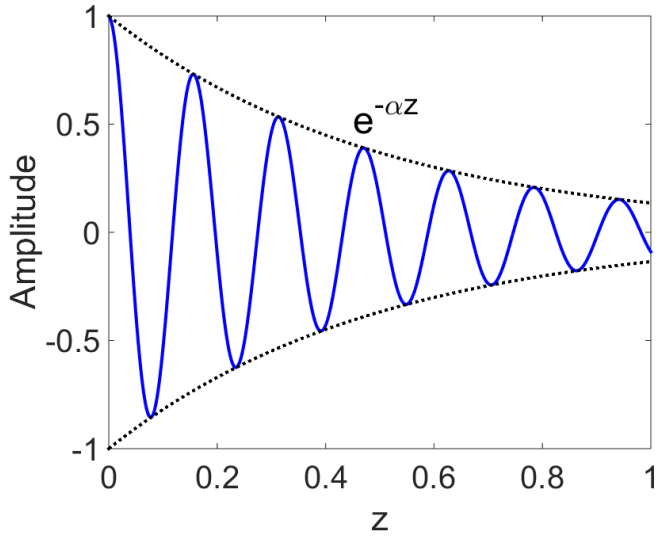
- Radiowaves always travel faster in the air than in the Earth.

- Radiowaves travel slower in water saturated sediments (ε_r = 80 for water)

Wave Attenuation

- Defines the rate of amplitude loss a wave experiences as it travels:

$$\frac{|\mathbf{A}|}{|\mathbf{A_0}|} = e^{-\alpha z}$$



- EM waves experience an exponential amplitude loss as they travel.

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

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

Wave Attenuation

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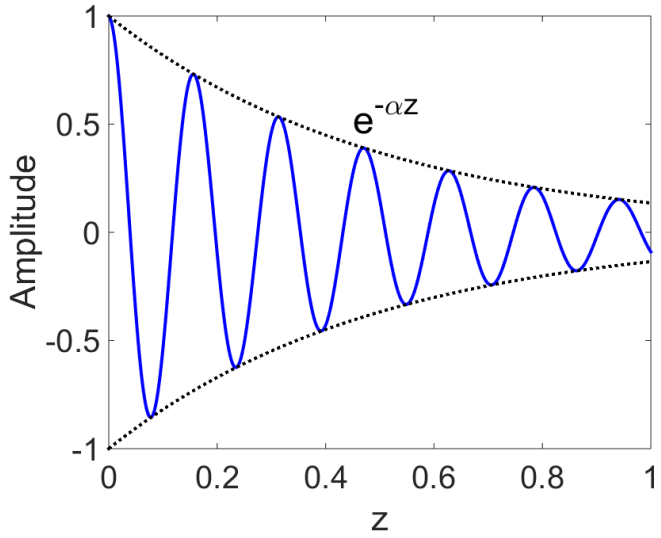

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Limestone	4-8	0.5-2.0	0.12
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Clays	5-40	2- 1000	0.06
Granite	4-6	0.01-1.0	0.13
Dry salt	5-6	0.01-1.0	0.13
Ice	3-4	0.01	**0.16**

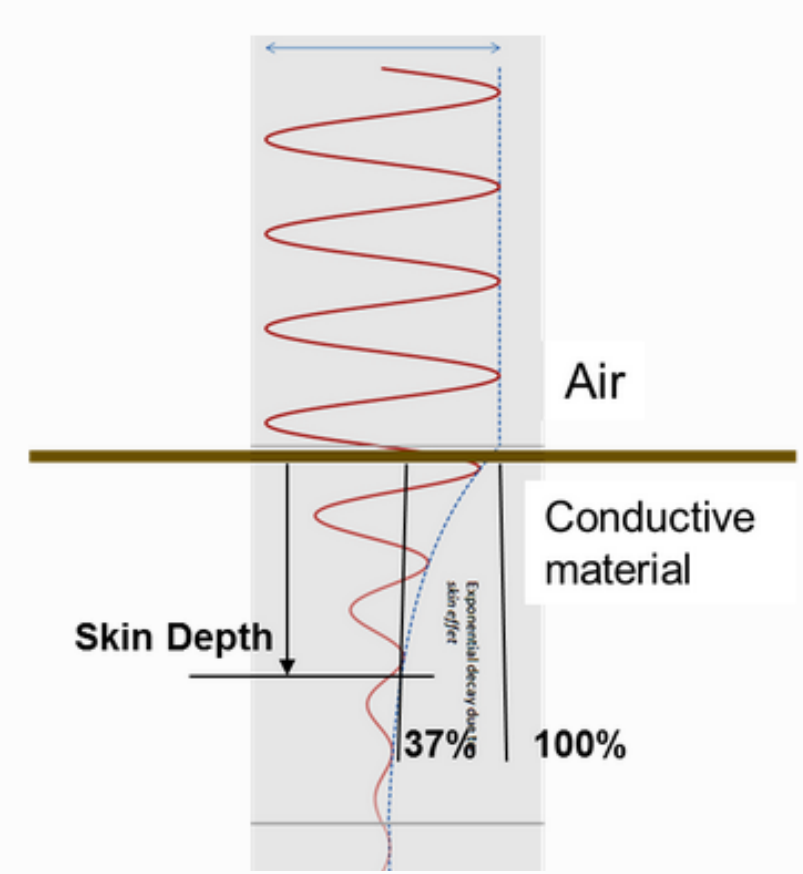
- Radiowaves attenuate quickly if conductivity is large

Radiowave Attenuation: Skin Depth

- **Skin Depth:** Distance at which a wave is reduced to 37% of its original amplitude

- Aumming Earth is non-magnetic ($\mu_r = 1$):

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



- The skin depth is smaller if the frequency of the radiowaves is higher.
- The skin depth is larger in materials with lower conductivities.
- The skin depth is larger is materials with higher dielectric permittivities.

Questions: Recap

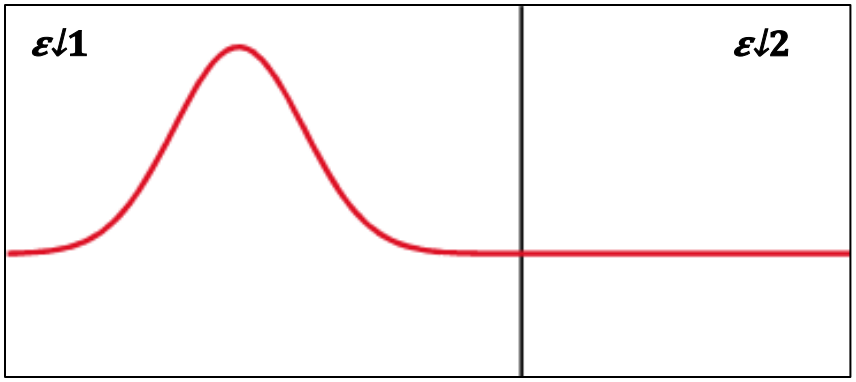
Q: What happens to wave amplitude as it propagates?

Q: Is the wave velocity higher/lower in water saturated sediments?

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

Q: What happens to skin depth at higher frequencies?

Reflection and Transmission



$$R = \frac{\text{Reflected Amplitude}}{\text{Incident Amplitude}} = \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}} \qquad -1 < R < 1$$

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

- If $\varepsilon_{\downarrow 1} \approx \varepsilon_{\downarrow 2}$, most of the wave is transmitted
- If $\varepsilon_{\downarrow 1} \ll \varepsilon_{\downarrow 2}$ or $\varepsilon_{\downarrow 1} \gg \varepsilon_{\downarrow 2}$, most of the wave is reflected

Reflection and Transmission

$$R = \frac{\text{Reflected Amplitude}}{\text{Incident Amplitude}} = \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}} \qquad -1 < R < 1$$

Material	e_R
Air	1
Distilled water	80
Fresh water	80
Sea water	80
Dry sand	3- 5
Saturated sand	20-30
Limestone	4-8
Shales	5-15
Silts	5-30
Clays	5-40
Granite	4-6
Dry salt	5-6
Ice	3-4

Example:

Dry Sand

---------- R ~ 0.101

Limestone

Example:

Dry Sand

---------- R ~ 0.429

Wet Sand

Example:

Air

---------- R ~ 0.799

Sea Water

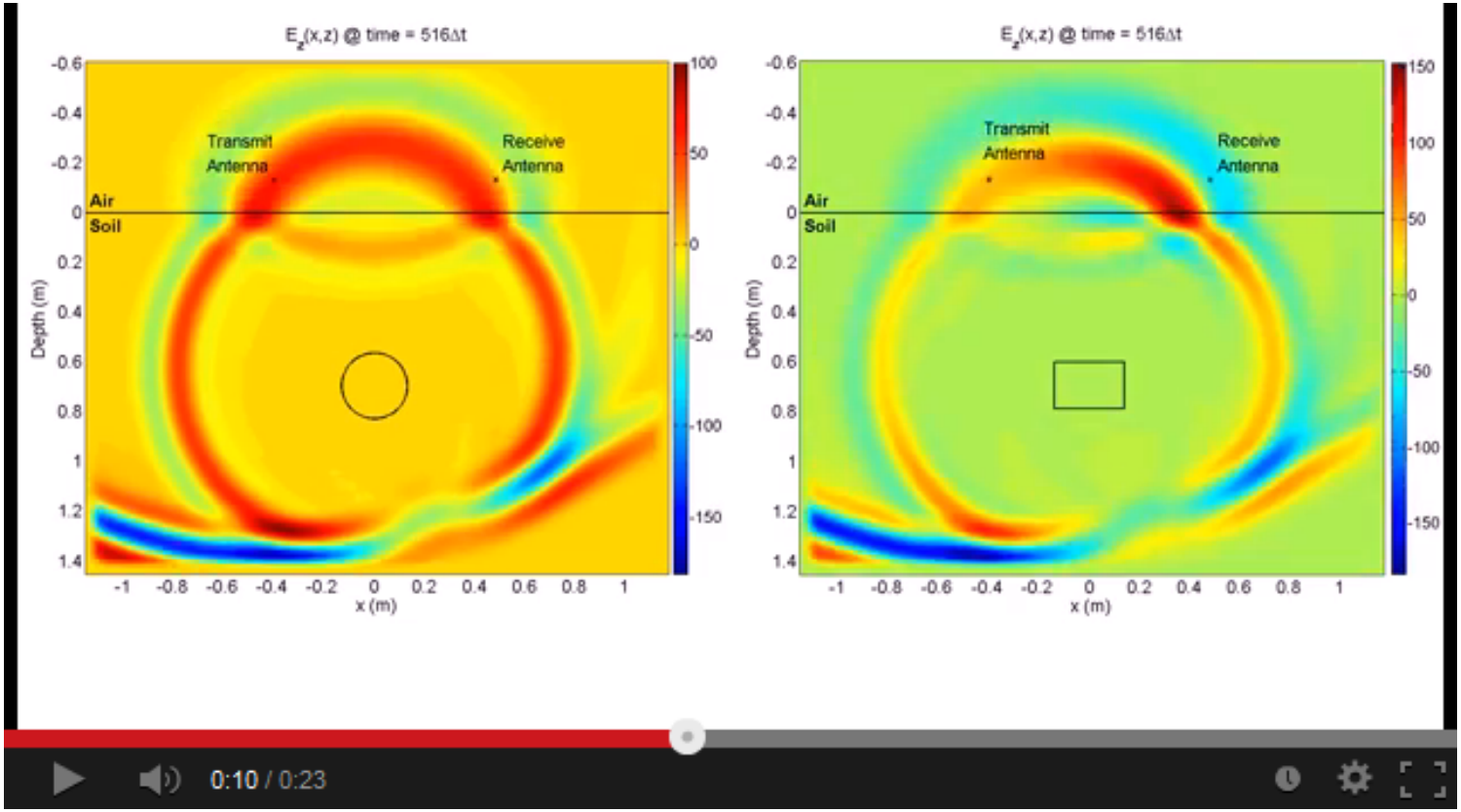
Reflection from Conductors

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

- Shows V → 0 as σ → ∞
- Thus radiowaves don't propagate in perfect conductors
- Waves get completely reflected

Reflection and Transmission

- What can we said about ε_1 and ε_2 ?
- Does wave go through conductor or reflect?
- http://www.youtube.com/watch?v=eqfgP4qVK4s



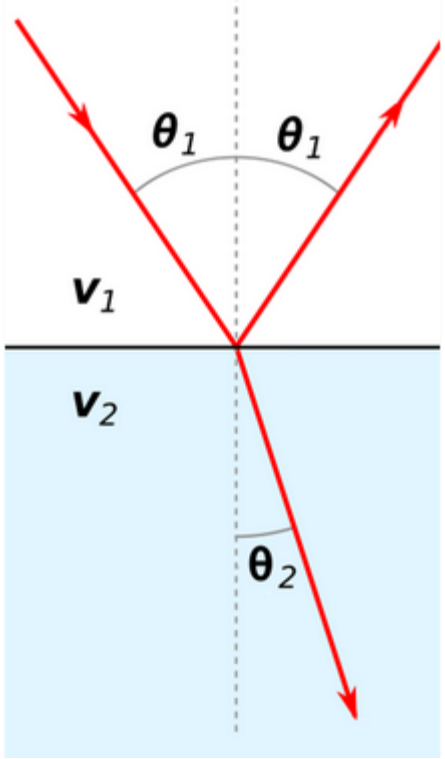
Refraction

- Snell's Law:

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

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

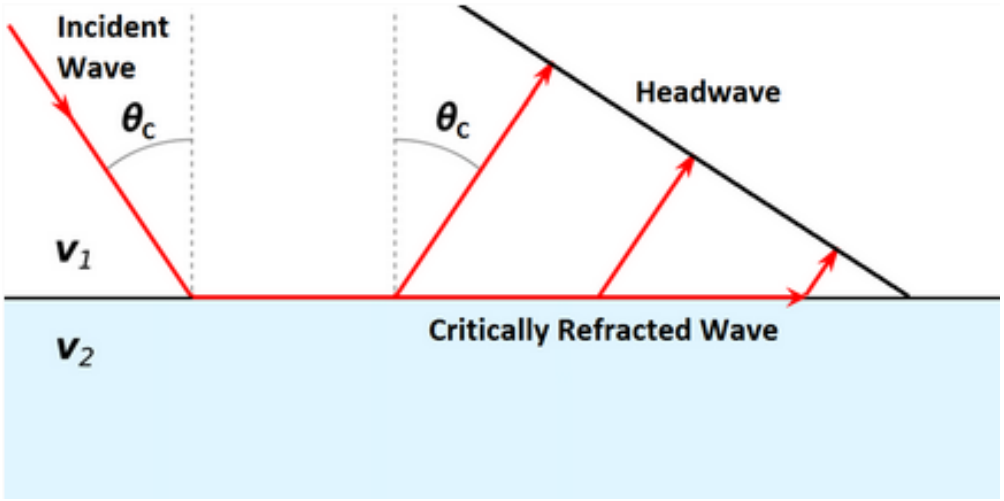
$$\sqrt{\varepsilon_1}\sin\theta_1 = \sqrt{\varepsilon_2}\sin\theta_2$$



Critical Refraction

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

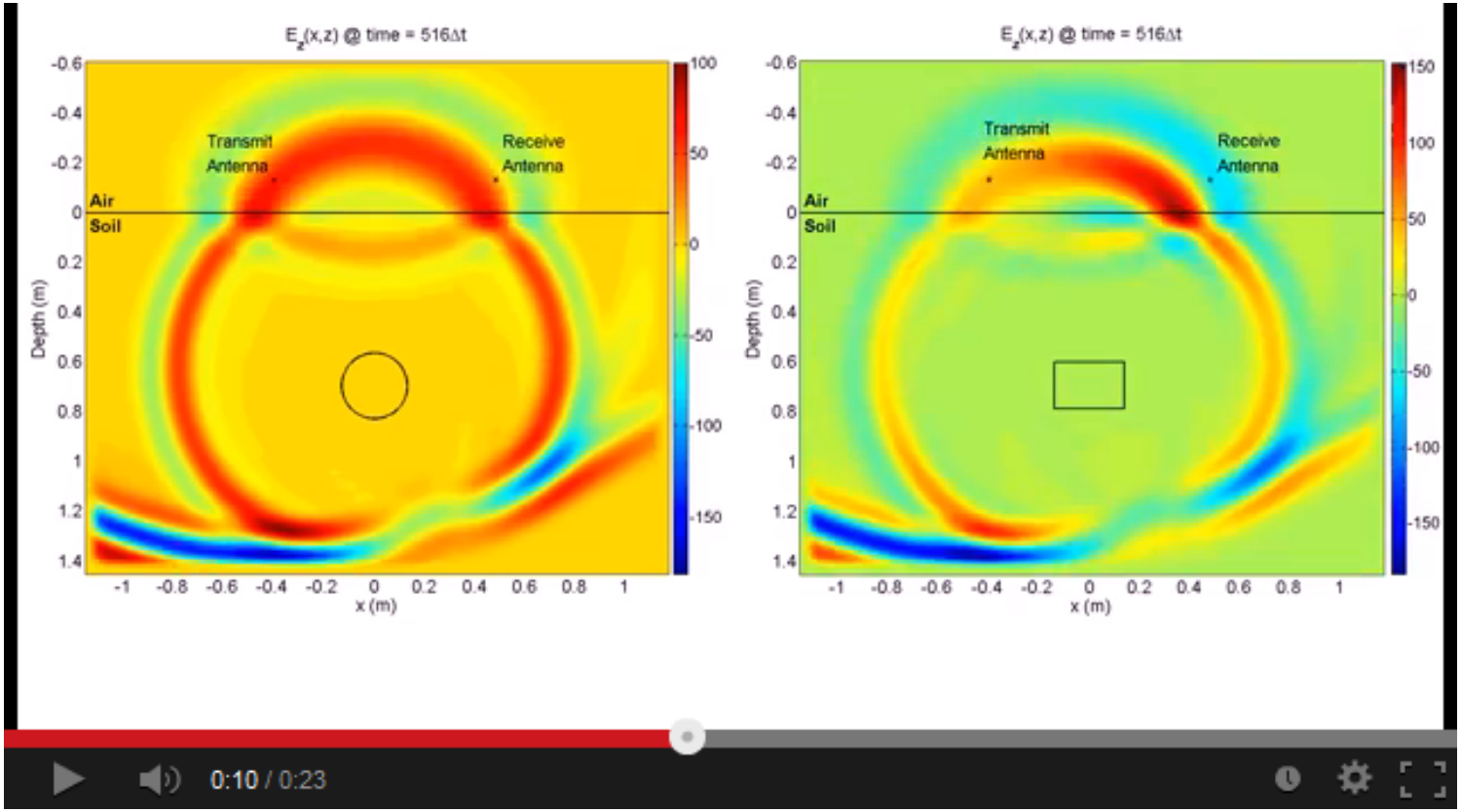
Requires $V_1 < V_2$



Refraction

- Can we see any refraction?

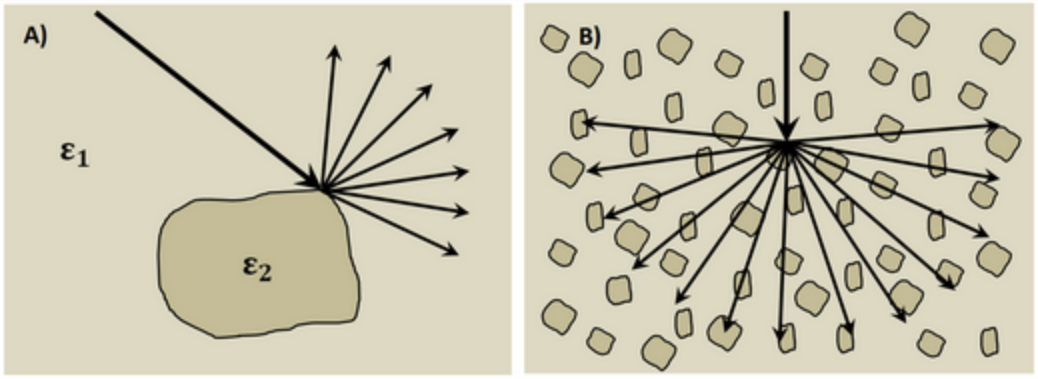
- http://www.youtube.com/watch?v=eqfgP4qVK4s



Scattering

Deviations in ray paths due to localized non-uniformities.
→ leads to noisy data.
→ decreases amplitude of usable signal

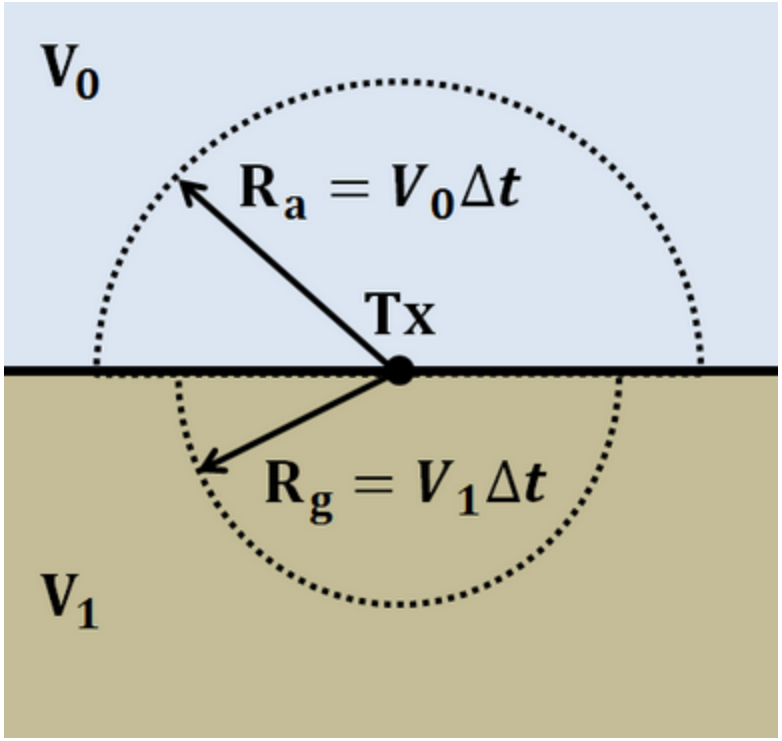
- Irregular surface shape of larger buried objects (below left).
- Rocky soils, which are a large contributor to the scattering of GPR signals (below right).
- Gas bubbles trapped in ice.
- Clutter made up of small buried objects



Geometrical Spreading

- As the wave front travels, it spreads geometrically
- The rate of geometrical spreading depends on the velocity
- Spreading causes the radiowave to lose amplitude

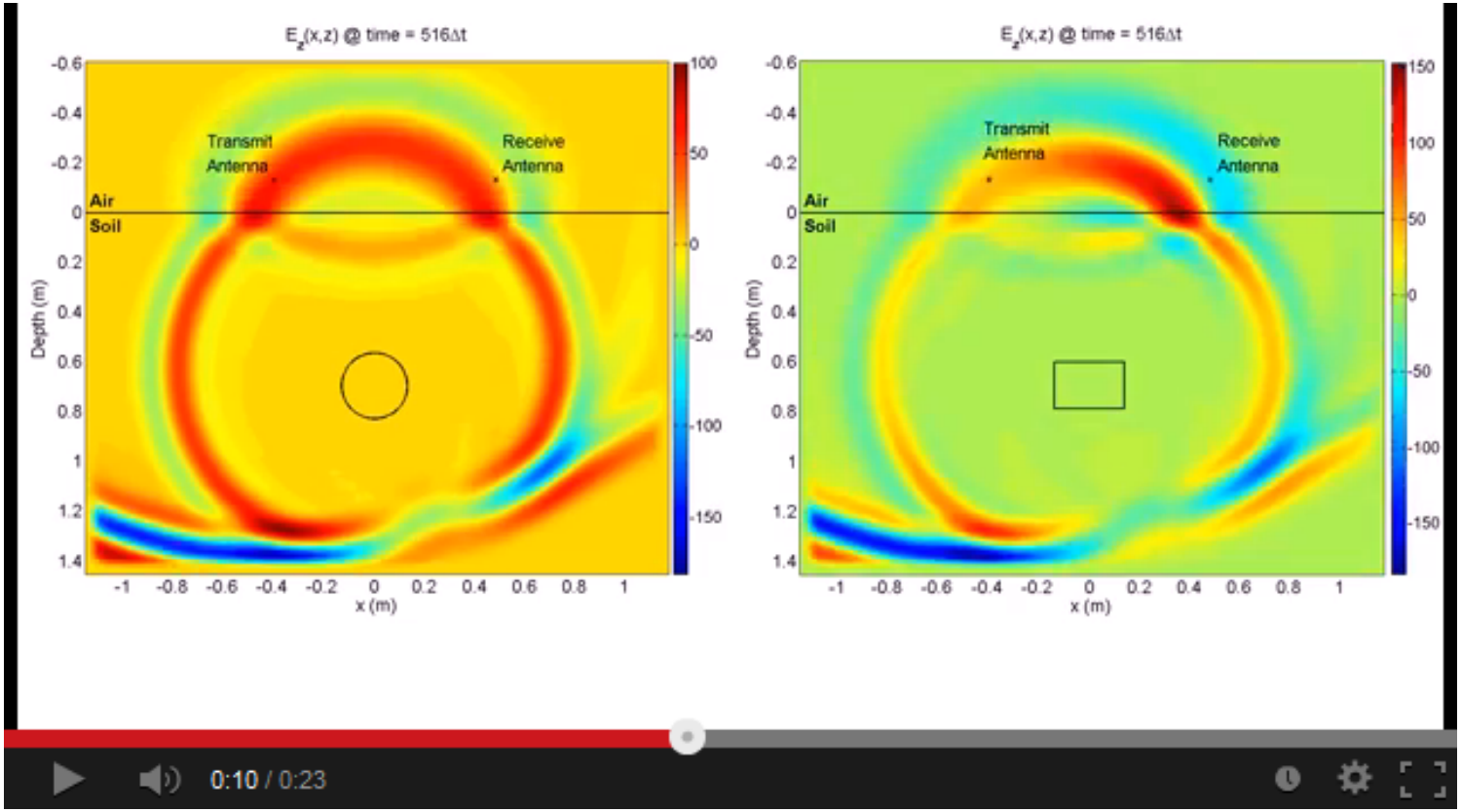
$$\frac{|\mathbf{A}|}{|\mathbf{A_0}|} \propto \frac{1}{R}$$



Geometrical Spreading

- Can we see geometrical spreading?

- http://www.youtube.com/watch?v=eqfgP4qVK4s



Material Recap

- Radiowaves reflect at boundaries where the velocity/ dielectric permittivity changes:

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

- Conductors are large reflectors of radiowaves

- Snell's law applies to GPR:

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

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

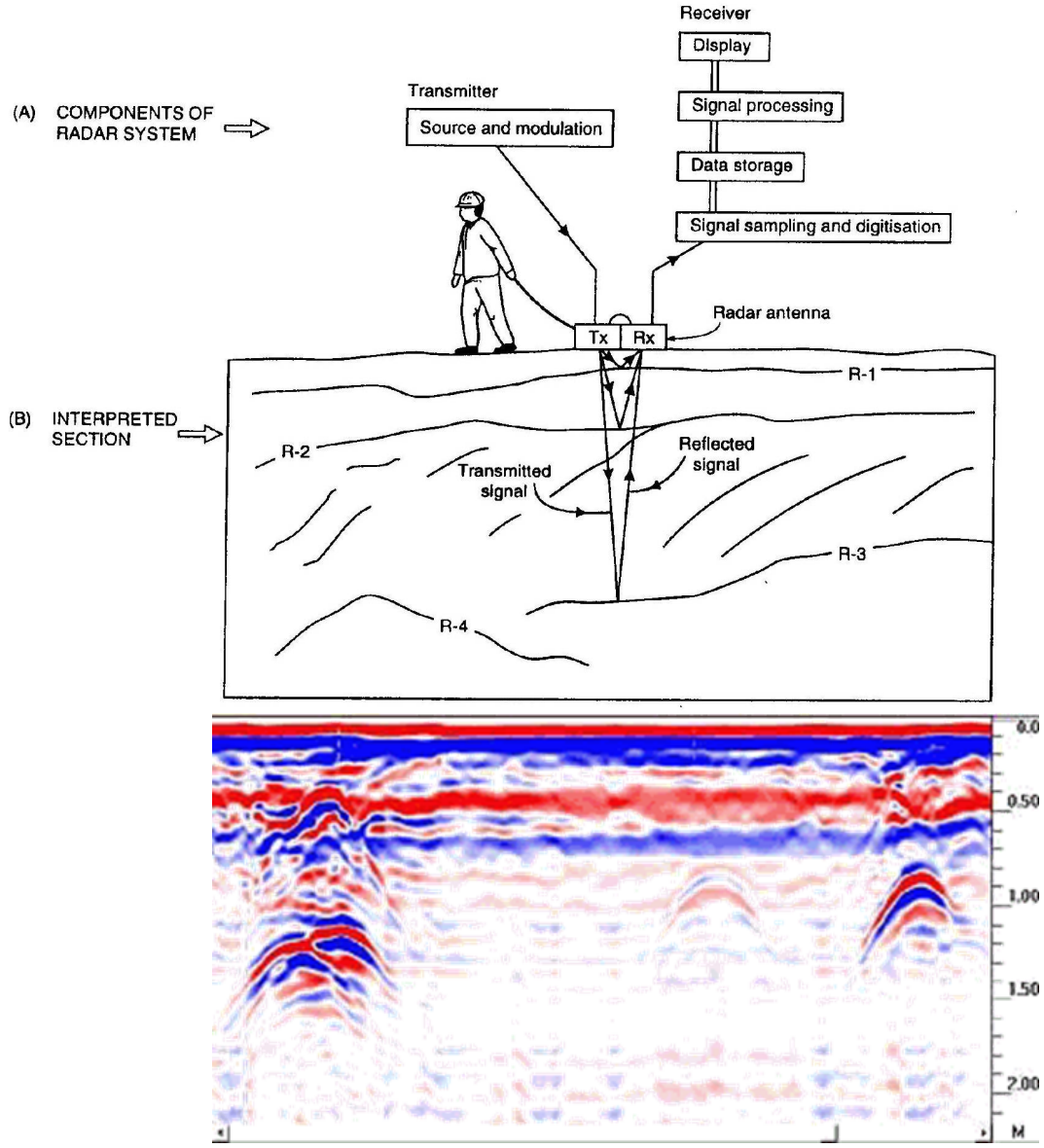
Quesitons Recap

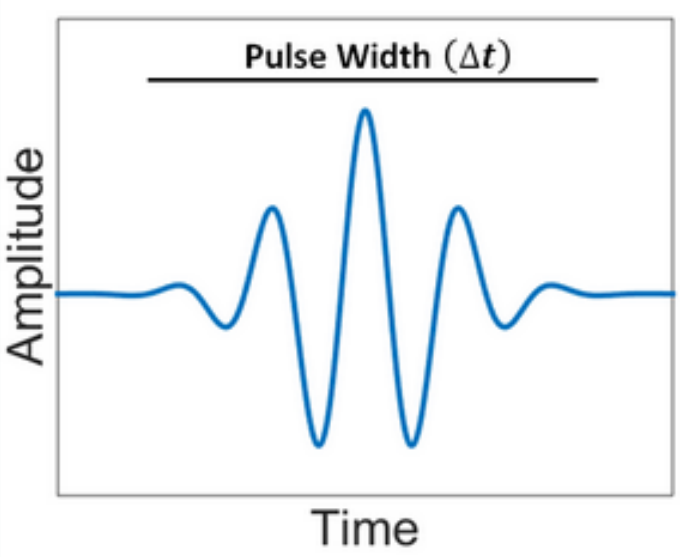
Q: What happens to a wave that undergoes geometrical spreading?

Q: Why is scattering an issue?

Quesitons About Material?

Ground Penetrating Radar (day 2)





From Last Time

- Permittivity (ε) is the diagnostic physical property but electrical conductivity (σ) plays an important role.

- Radiowaves propagate at different speeds in different materials:

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

- Radiowaves attenuate (lose amplitude) while they propagate:

Skin depth:

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

From Last Time

- Radiowaves reflect at boundaries where the velocity/ dielectric permittivity changes:

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

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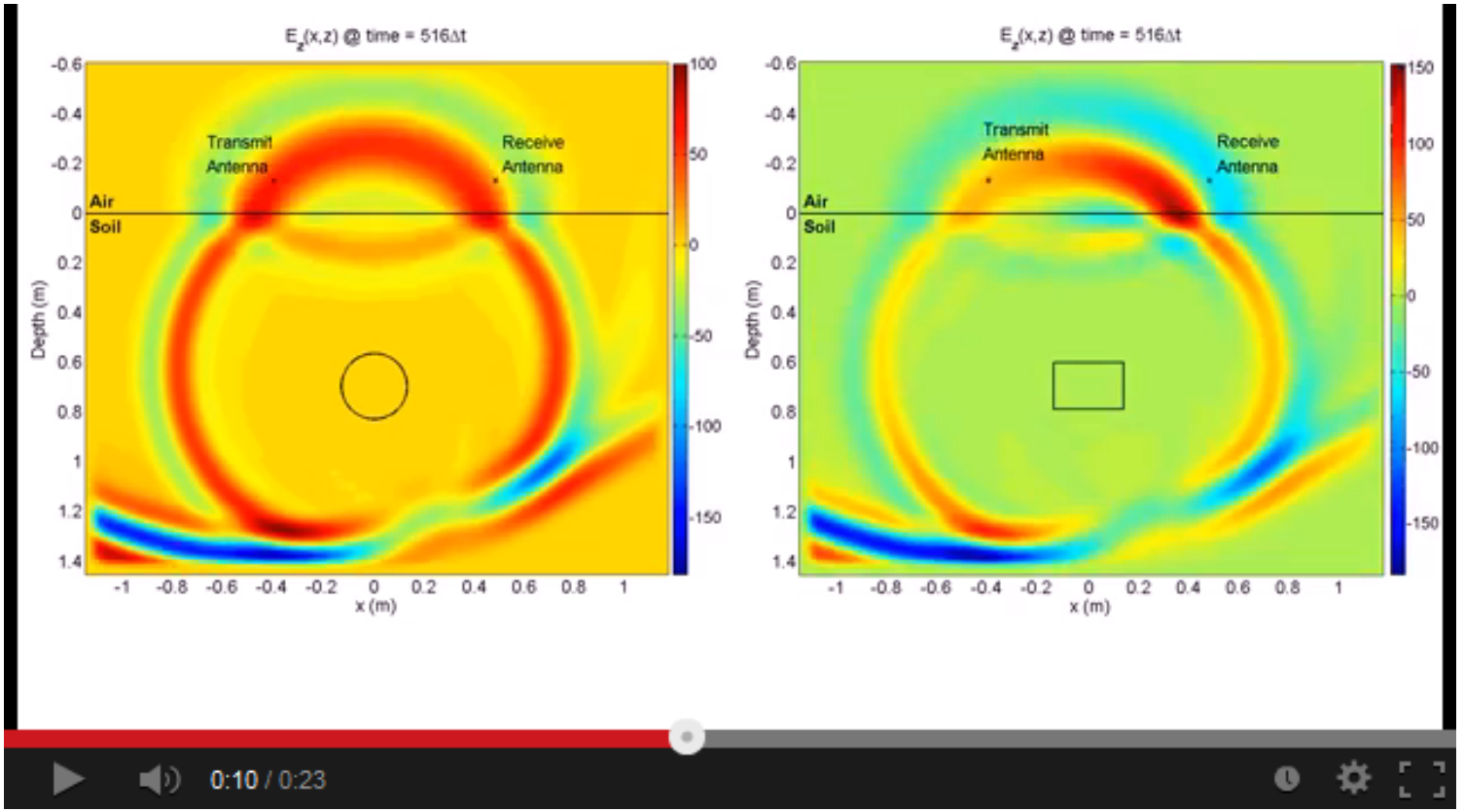
$$\sqrt{\varepsilon_1}\sin\theta_1 = \sqrt{\varepsilon_2}\sin\theta_2$$

Today's Topics

- Ray paths
- Common survey configurations and some applications
- The source wavelet signal
- Resolution
- Probing distance
- Sources of Noise

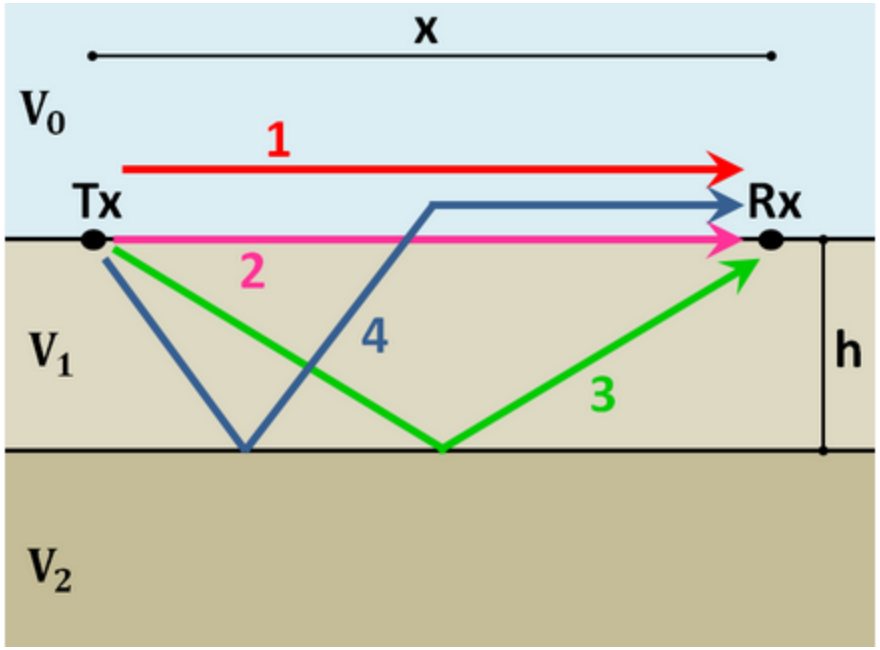
Ray Path vs. Wavefront

- http://www.youtube.com/watch?v=eqfgP4qVK4s

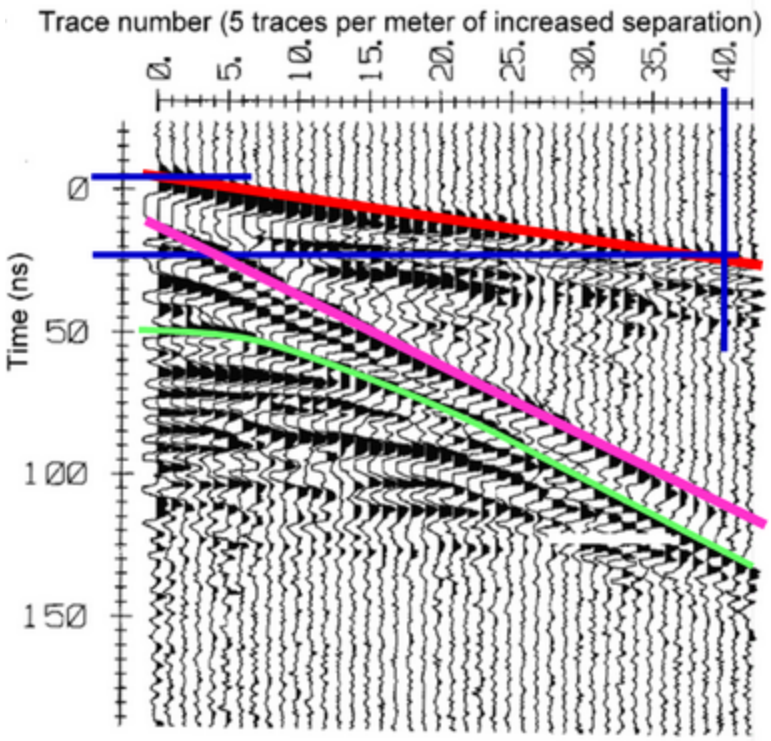


2-Layer Example

Model

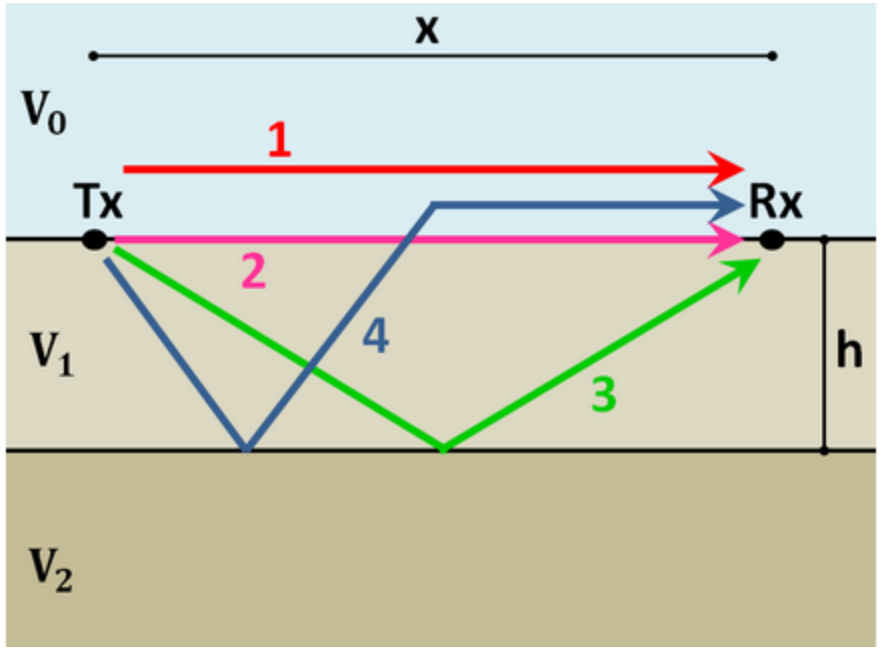


Radargram

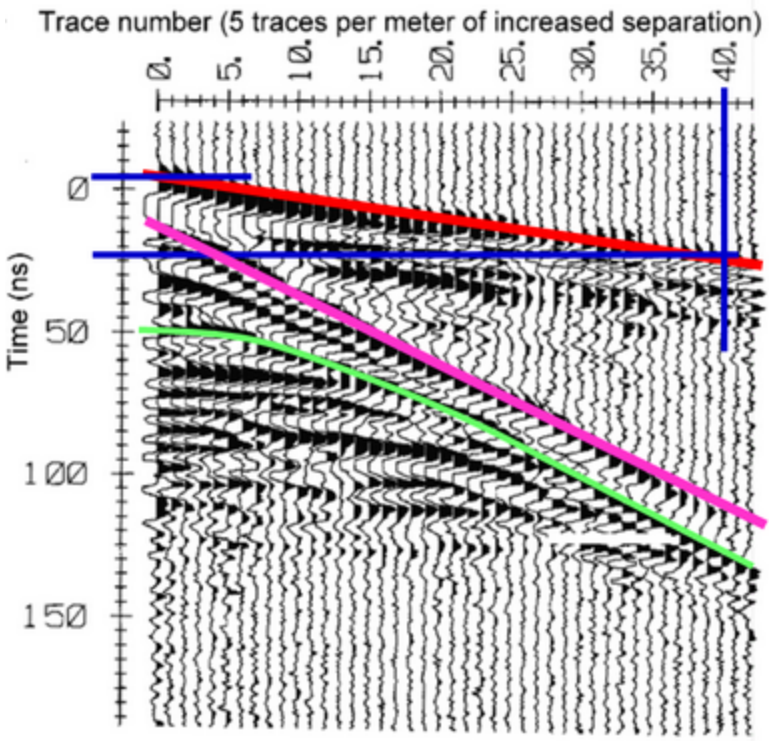


2-Layer Example

Model



Radargram



1) Direct Air Wave

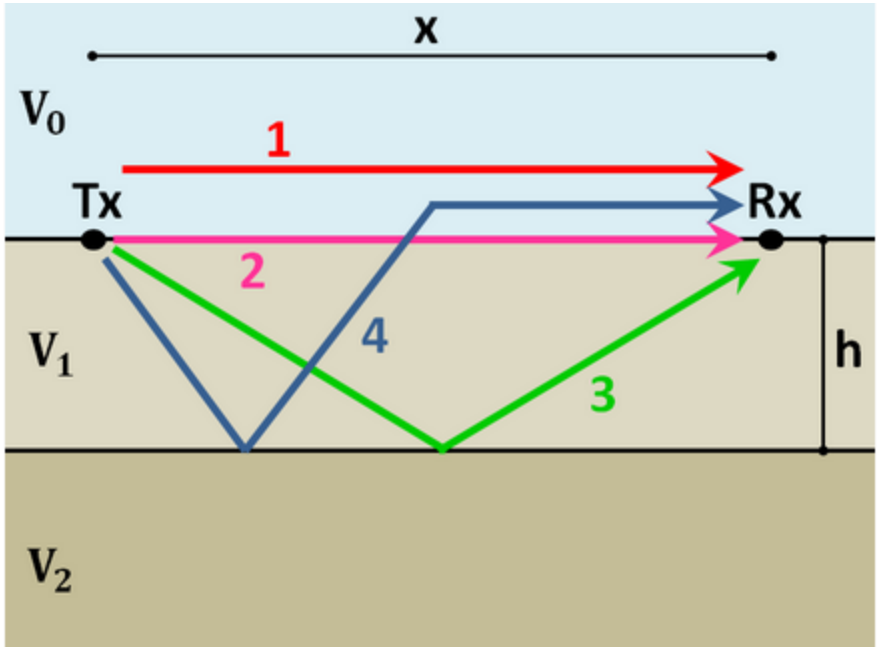
Travel Time: $t_{air} = \frac{x}{c}$

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

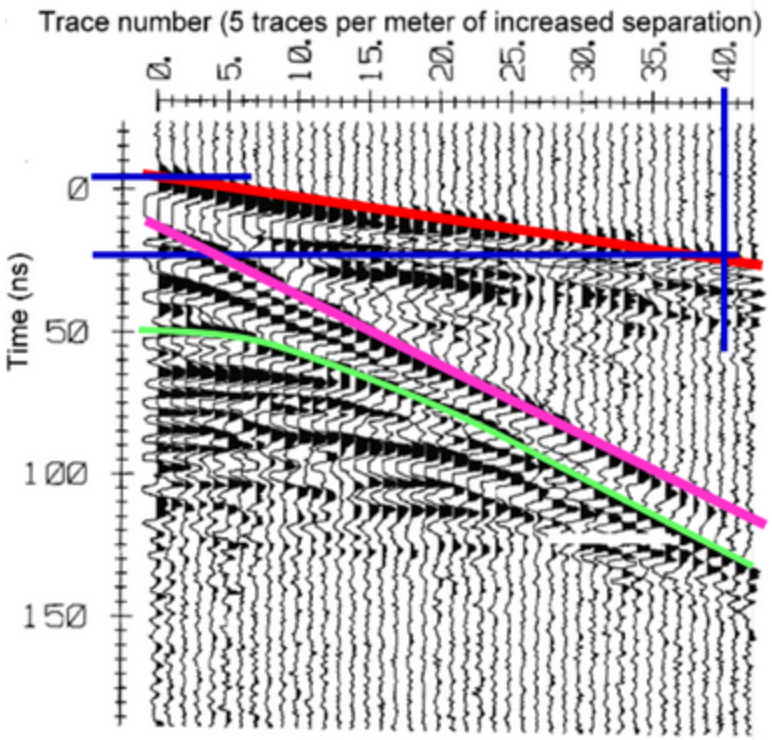
$c = 3.00 \times 10^8$ m/s

2-Layer Example

Model



Radargram



2) Direct Ground Wave

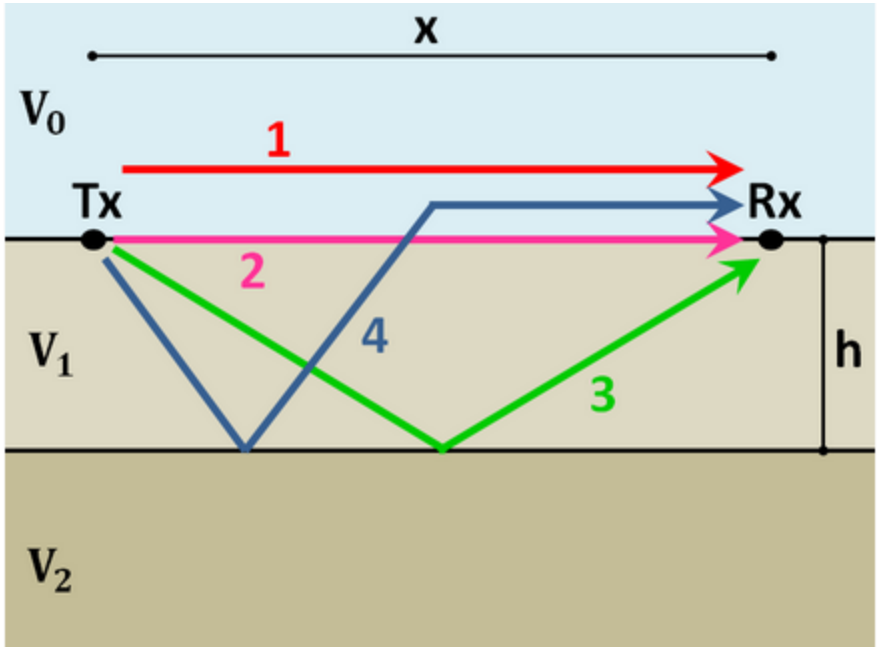
Travel Time: $t_{ground} = \frac{x}{V_1}$

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

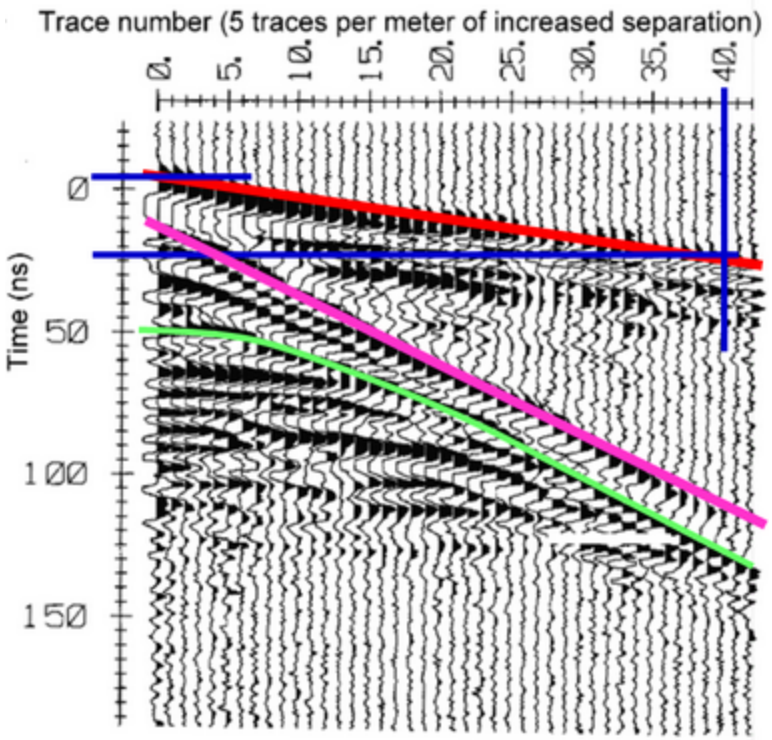
$V_1 < c$

2-Layer Example

Model



Radargram

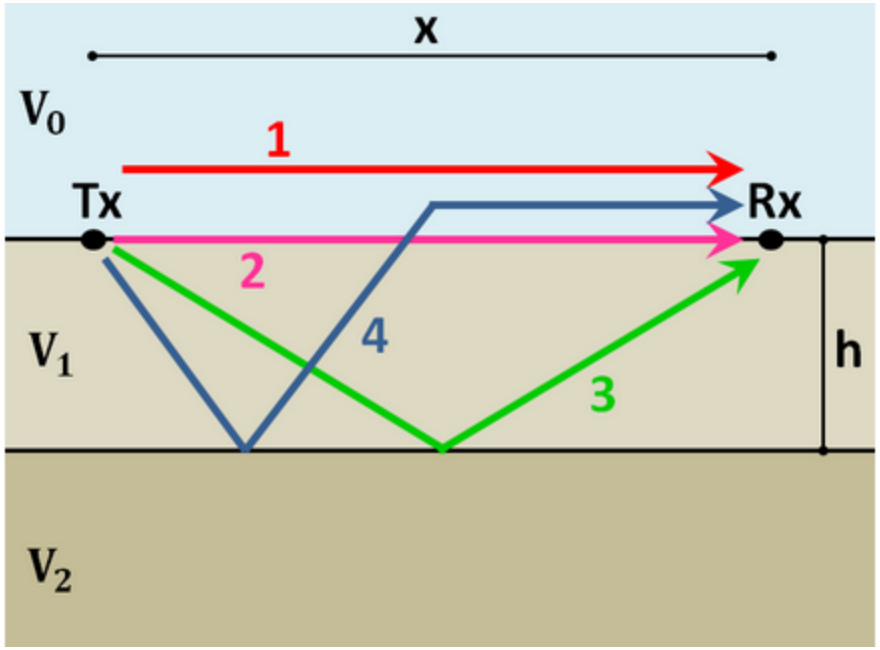


3) Reflected Wave

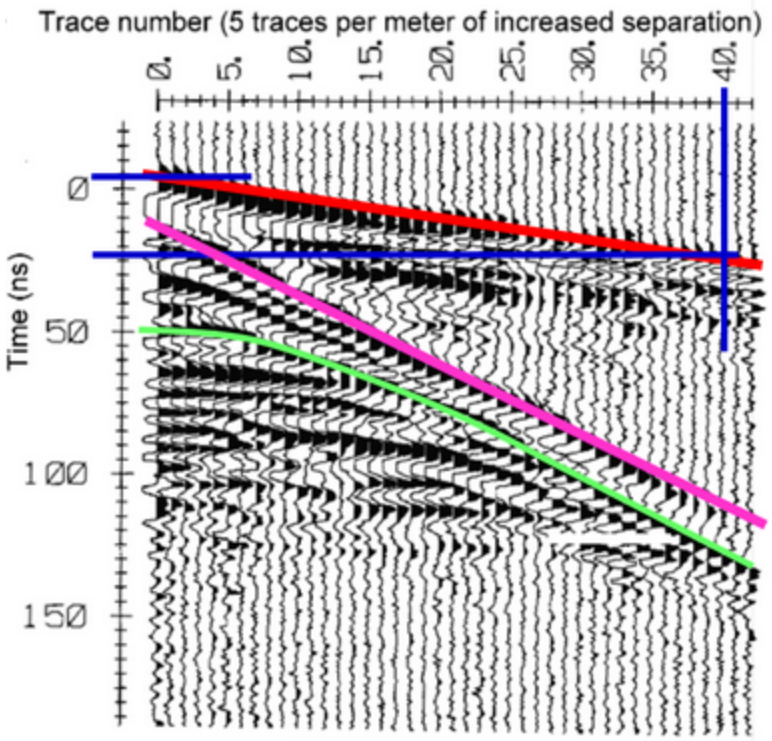
Travel Time: $$t_{ref} = \frac{\sqrt{x^2 + 4h^2}}{V_1}$$

2-Layer Example

Model



Radargram



4) Refracted Wave

Travel Time: $t_c = \frac{x}{c} + \text{Constant}$

$V_1 < V_0$

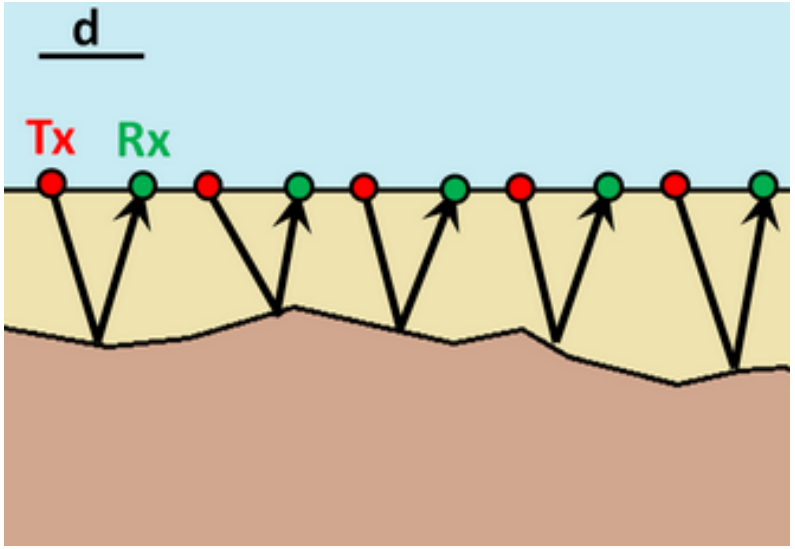
Recap Questions

Q: What is the difference between a wavefront and a ray path?

Q: Can a wave be critically refracted at the surface?

Common Offset Survey

- Tx-Rx distance is fixed
- Tx-Rx is moved for every shot
- Most common GPR survey
- Good for:
  - Finding horizontal interfaces
  - Locating discrete objects
- **Zero offset** survey has Tx-Rx coincident (same location)



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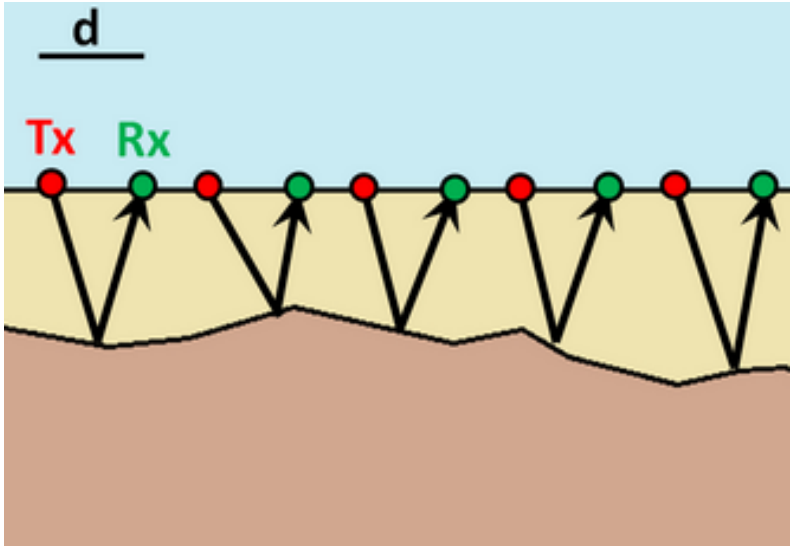
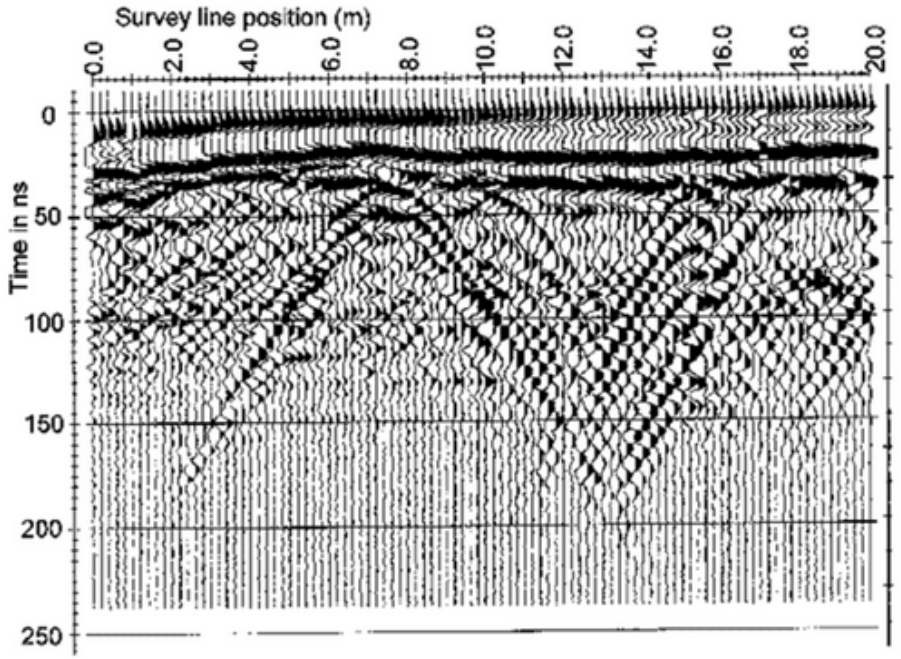
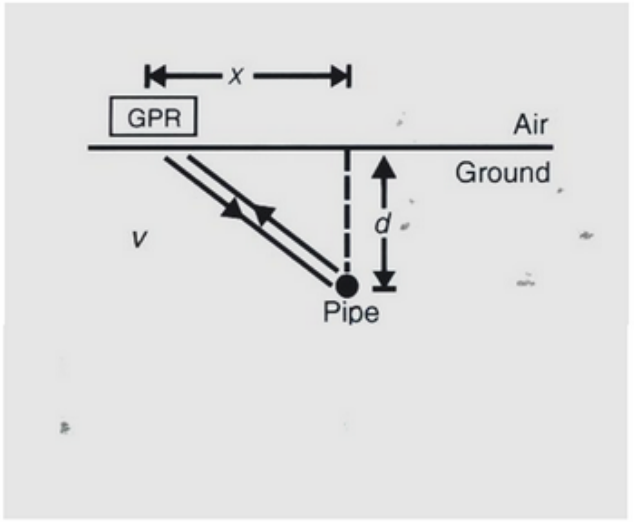


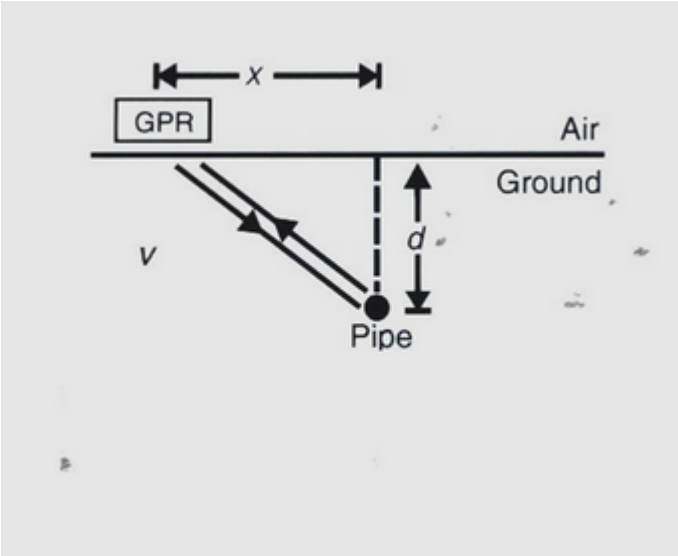
Zero Offset Survey: Finding Objects

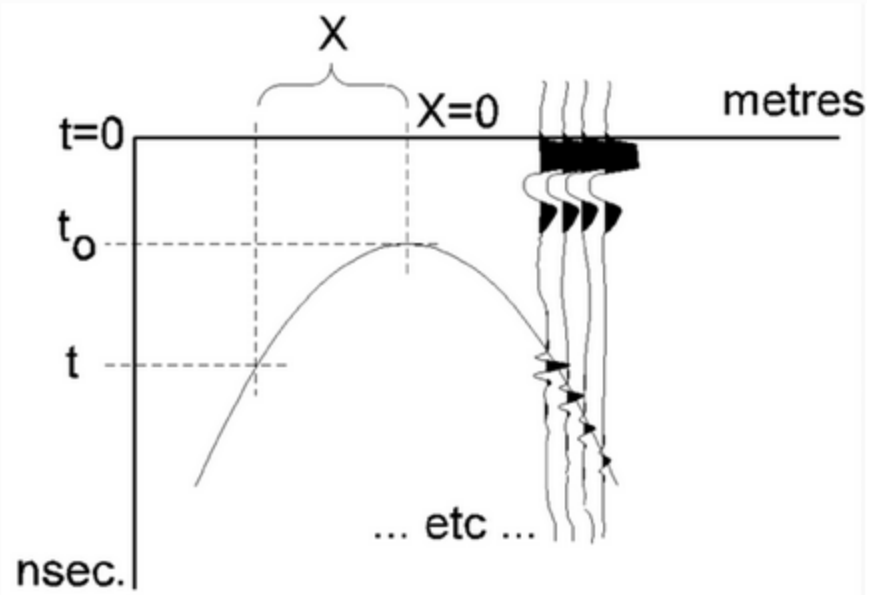




- Discrete objects act as point reflectors
- Makes hyperbolic shape in radargram
- Travel time: $$t = \frac{2\left(x^2 + d^2\right)^{1/2}}{V}$$

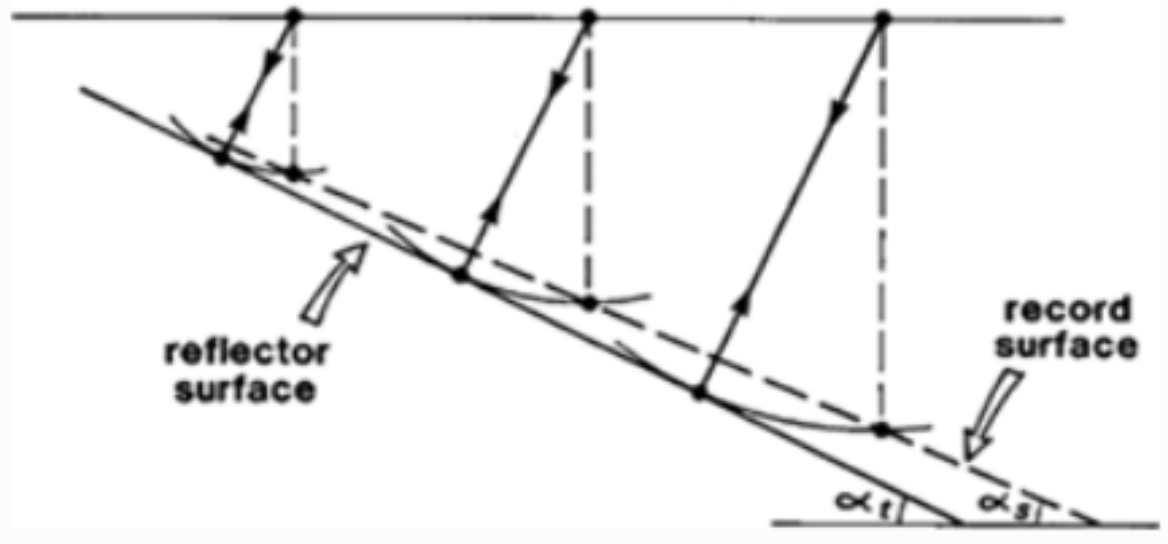
Zero Offset Survey: Finding Objects





- Travel time: $t = \dfrac{2\left(x^2 + d^2\right)^{1/2}}{V}$
- Minimum travel time: $t_0 = 2d/V$
- Obtaining Velocity: $V = \sqrt{\dfrac{4x^2}{t^2 - t_0^2}}$

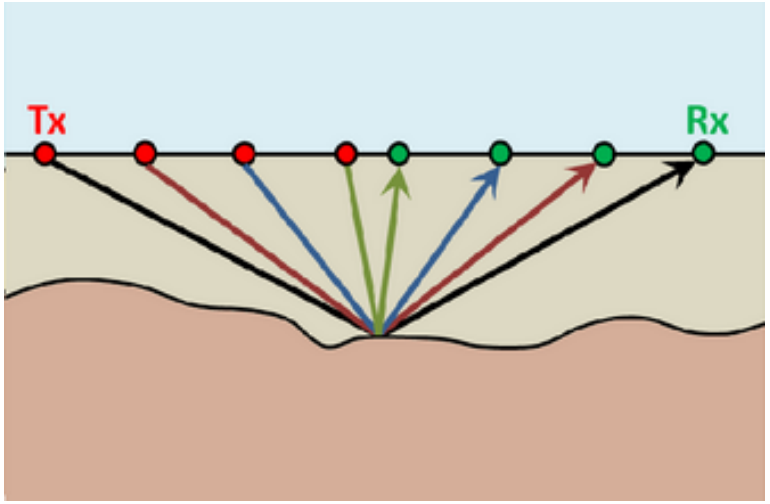
Zero Offset Survey: Dipping Layers



- Zero offset reflection is perpendicular to surface
- Can lead to underestimate of depth and slope of layer
- Can be corrected using **migration correction (GPG)**

Common Midpoint Survey

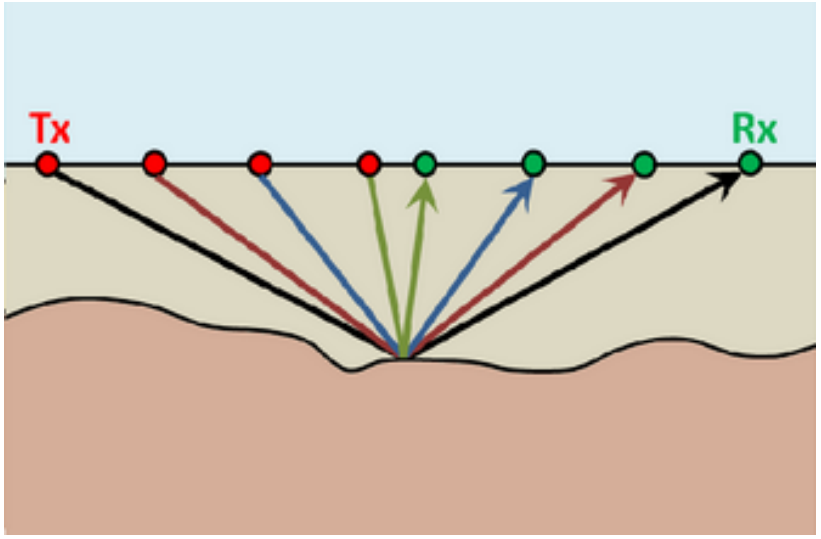
- Tx-Rx distance varies
- Midpoint between Tx-Rx is left constant
- Good for:
  - Finding horizontal interfaces



Common Midpoint Survey

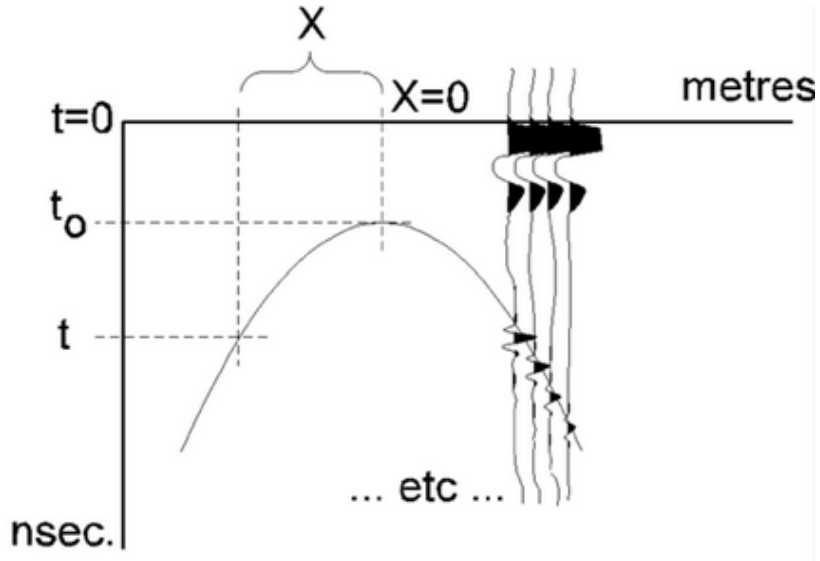
- Travel time off same reflection point make a hyperbola:

$$t = \frac{2\left(x^2 + d^2\right)^{1/2}}{V}$$



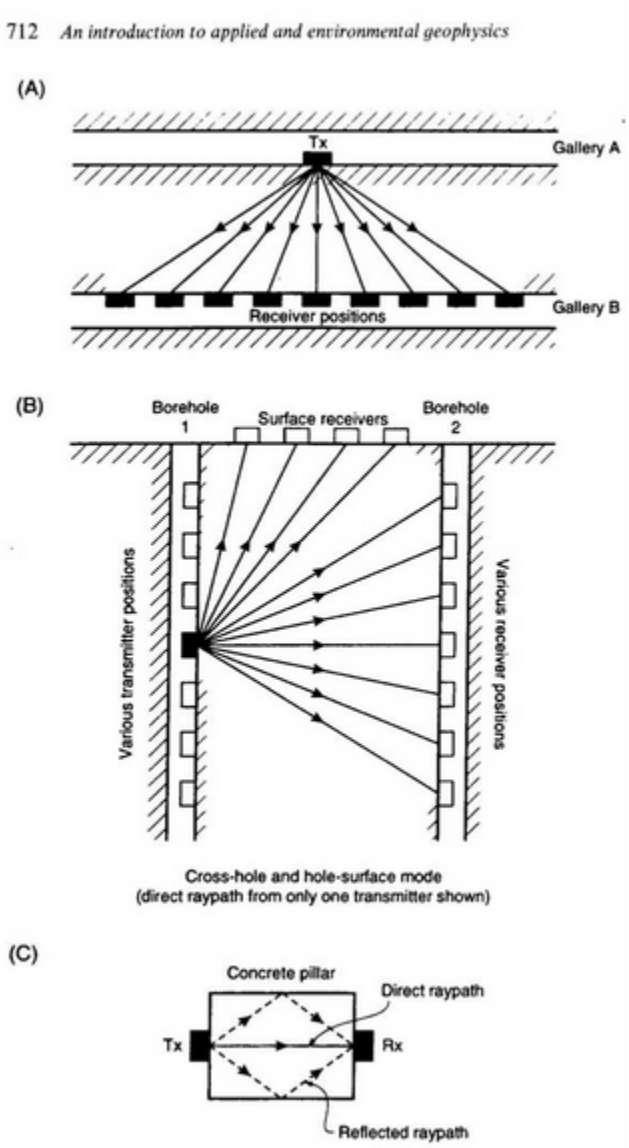
- Can use hyperbola to get velocity and layer depth

- Reading not hyperbola:
  - Indicates uneven/dipping interface



Transillumination Survey

- 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 stuctures within objects

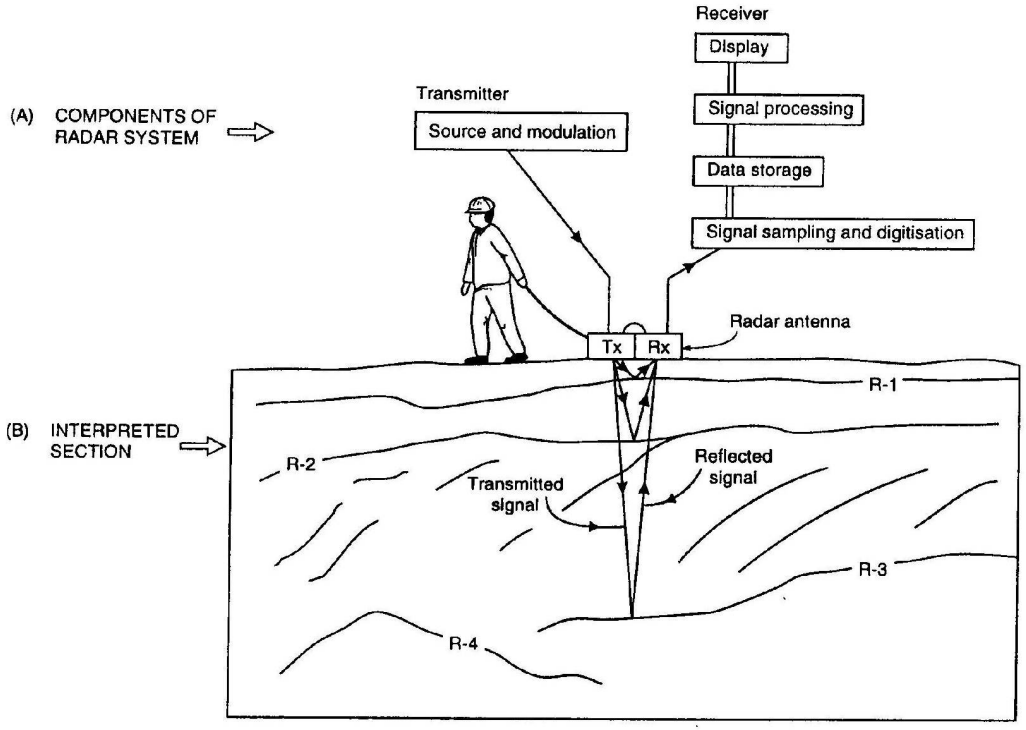


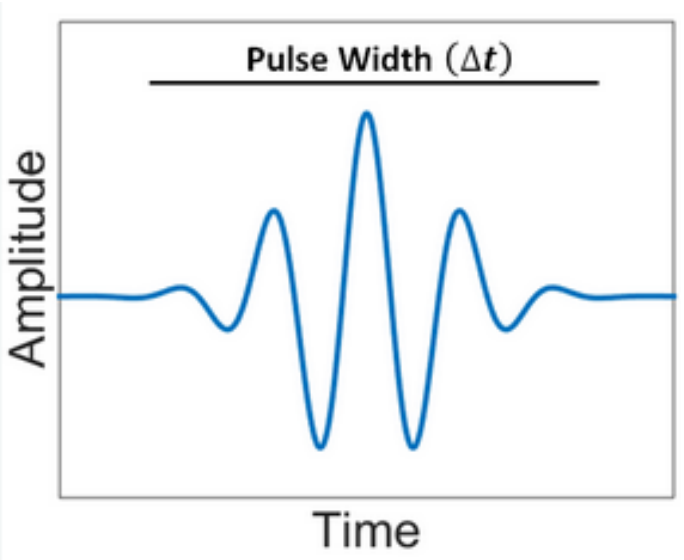
Recap Questions

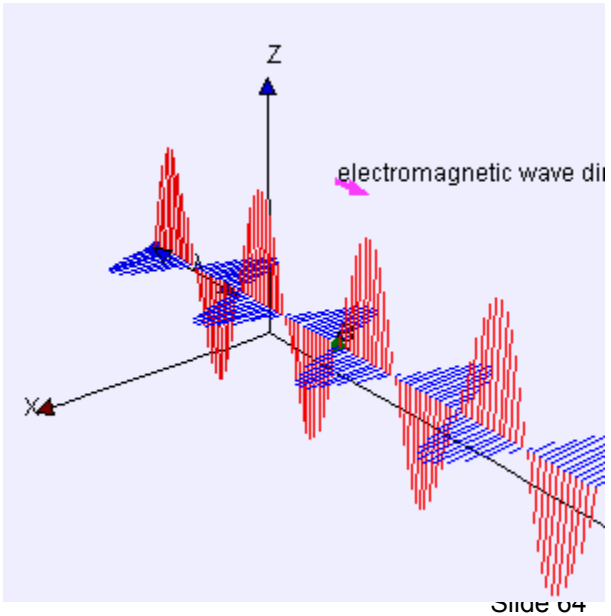
Q: What is the most commonly used survey configuation?

Q: What kind of signatures do objects make in radargrams?

GPR Source Signal





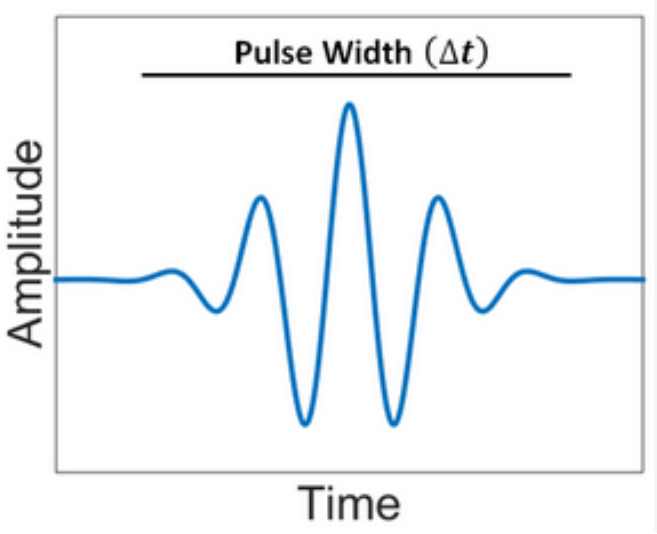


Examine properties of the source pulse

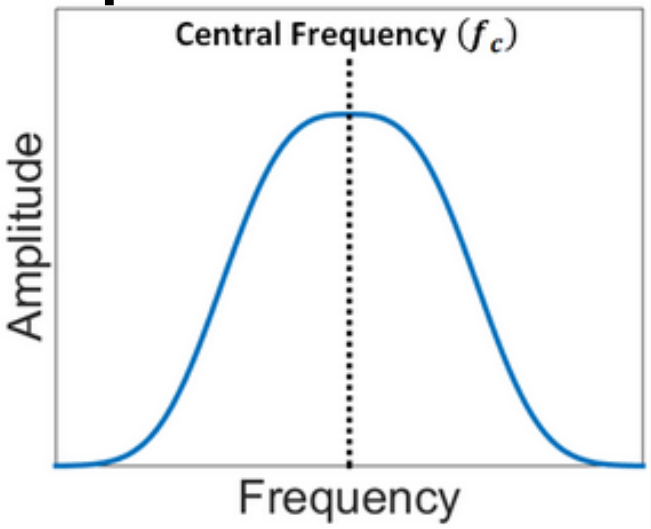
GPR Source Signal: Wavelet

- **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

Wavelet



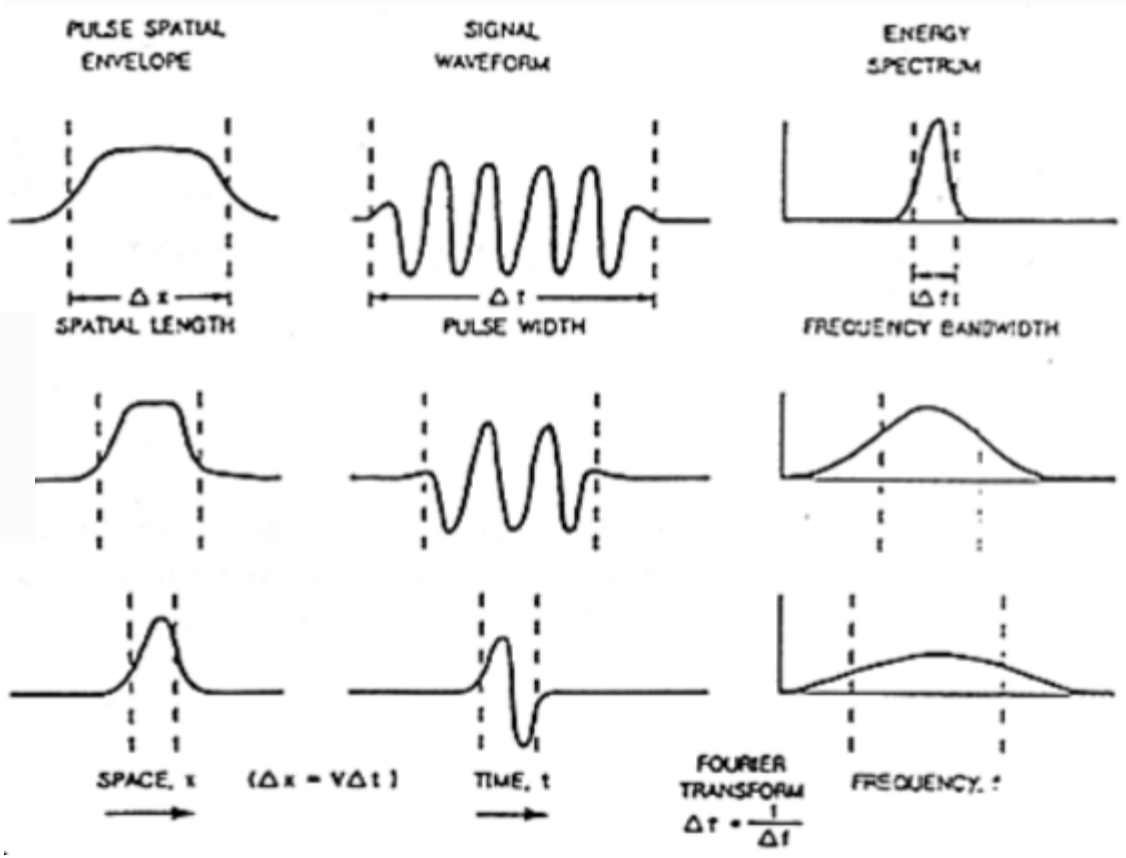
Frequencies in Wavelet



GPR Source Signal: Wavelet

- Shorter pulses contain a wider range of frequencies
- Shorter pulse overall contain higher frequencies
- Spatial length increases as pulse length increases

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



GPR Source Signal: Spatial Length

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

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

- 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

GPR Source Signal: Spatial Length

- Since $f\lambda c = 1/\Delta t$, the spatial width is given by:

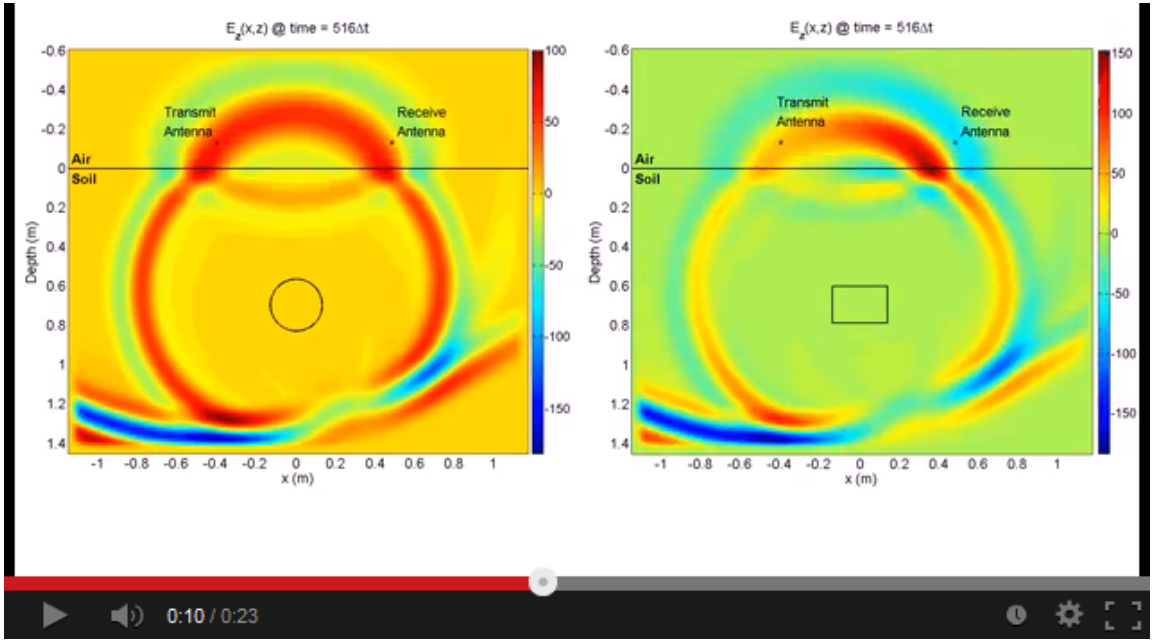
$$\lambda = V\,\Delta t = \frac{c\,\Delta t}{\sqrt{\varepsilon_r}}$$

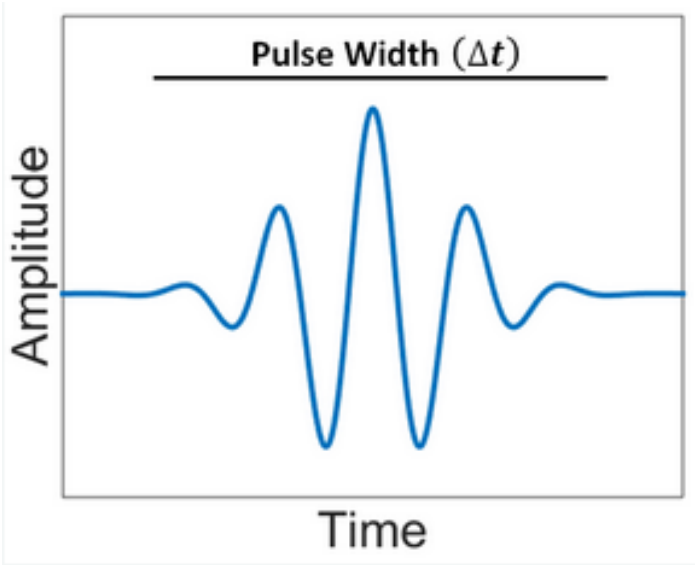
- Shorter pulse width → Higher frequencies

→ Shorter pulse length

Introduction to GPR: 2D Example

- Does the reflected signal coming up to the surface becomes stretched or contracted?
- Why is this?
- http://www.youtube.com/watch?v=eqfgP4qVK4s





Resolution of GPR Surveys

- **Resolution:** Smallest features which can be distinguished using the survey.

- Resolution depends on:
  - The frequency of the GPR signal
  - The physical properties of the ground
  - The dimensions and separations of features

Resolution of GPR Surveys: Layers

¼ wavelength rule:

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

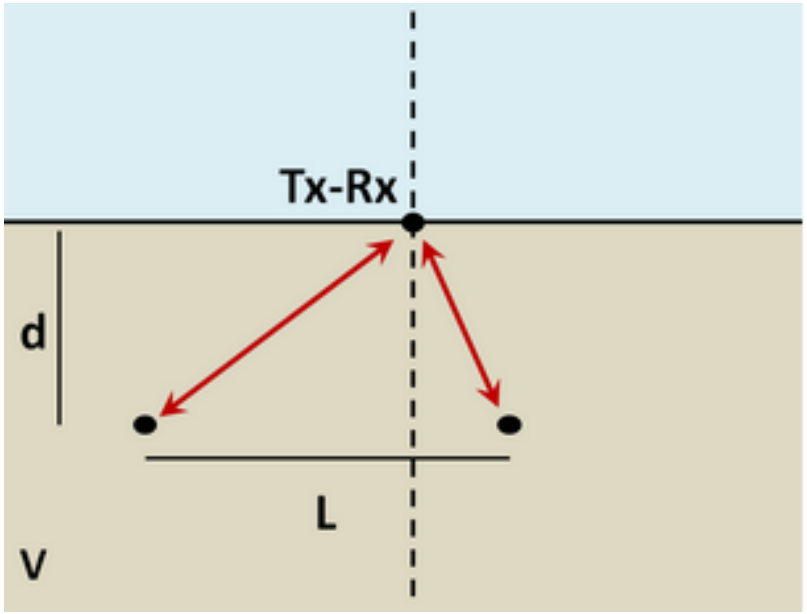
$$L > \frac{c}{4 f_c \sqrt{\varepsilon_r}} = \frac{c \Delta t}{4 \sqrt{\varepsilon_r}}$$

Resolution of GPR Surveys: Separation

- If objects are too close to one another:
  - The two way travel time is almost the same
  - The two returning wavelet signals will overlap
  - They will appear to be one object

- **For zero offset survey**

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



Probing Distance

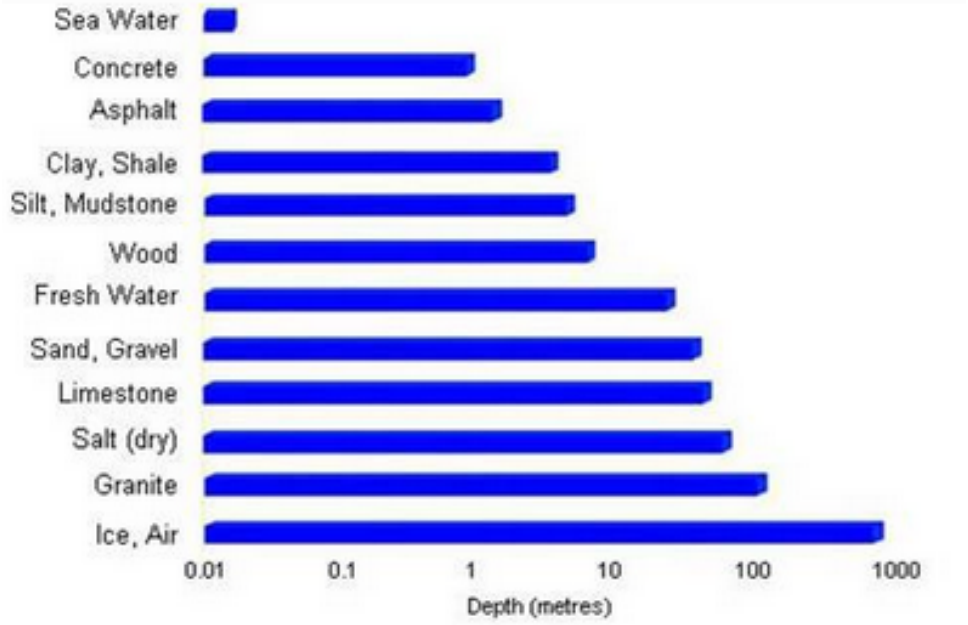
- Maximum depth at which GPR can be used to get information about subsurface

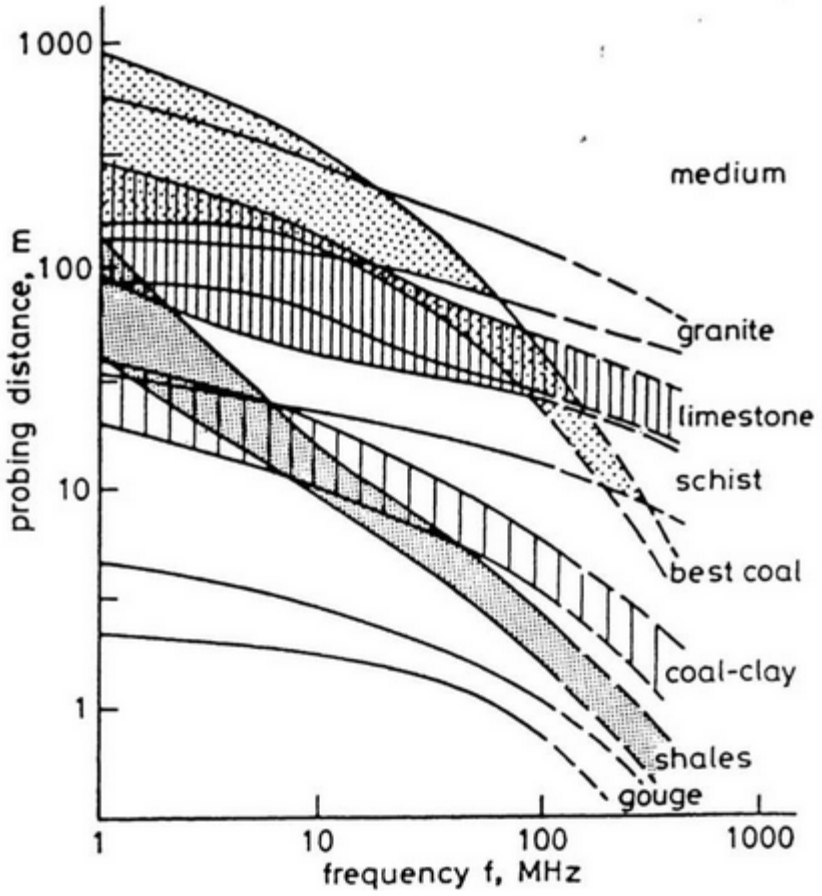
- Probing distance is approximation **3 skin depths:**

$$D = 3\delta \approx \begin{cases} 1510\sqrt{\dfrac{1}{\sigma f}} & \text{for } \omega\varepsilon \ll \sigma \\ 0.0159\dfrac{\sqrt{\varepsilon_r}}{\sigma} & \text{for } \omega\varepsilon \gg \sigma \end{cases}$$

Probing Distance

- Generally decreases as frequency increases
- Is lower for more conductive materials and non-dielectric materials





Recap Questions

Q: If a GPR signal contains more high frequency waves, is its pulse length longer or shorter?

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

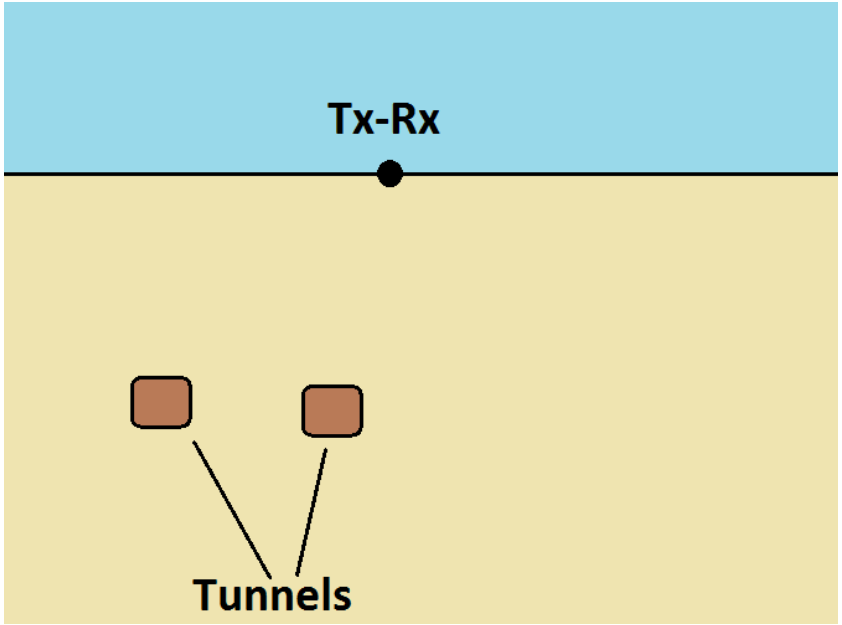
Q: How thick does a layer need to be for us to see it?

Q: What happens when objects are too close together?

Q: Does probing distance increase/decrease as frequency increases?

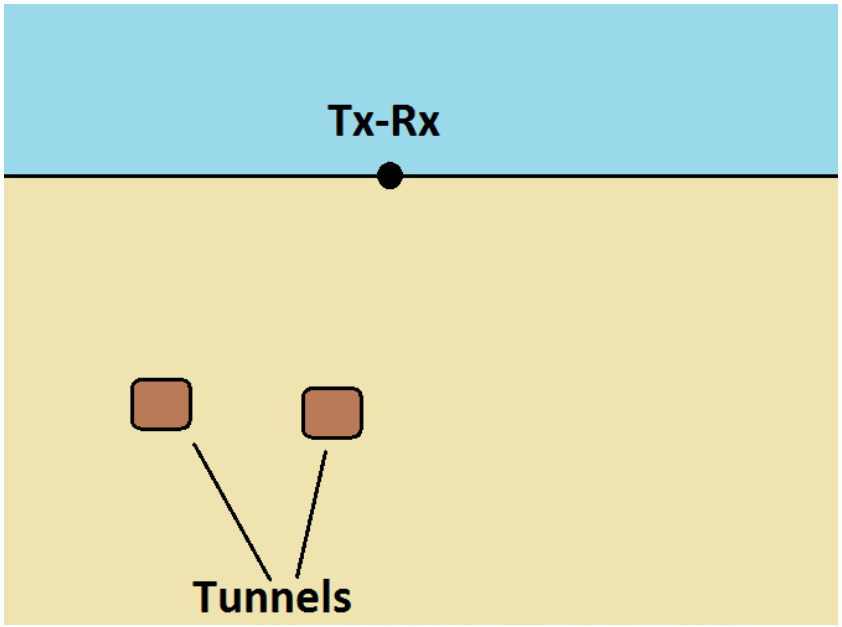
Probing Distance vs. Resolution

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

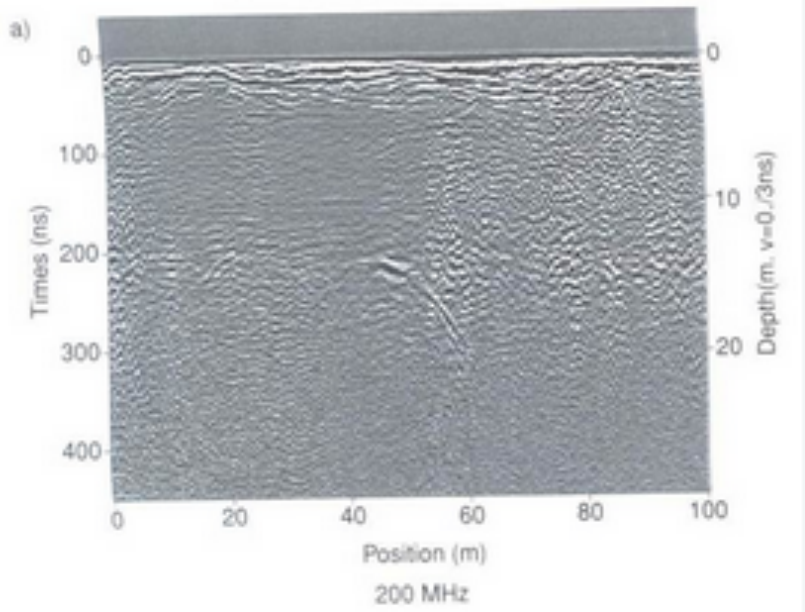


Radargram 200 MHz

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

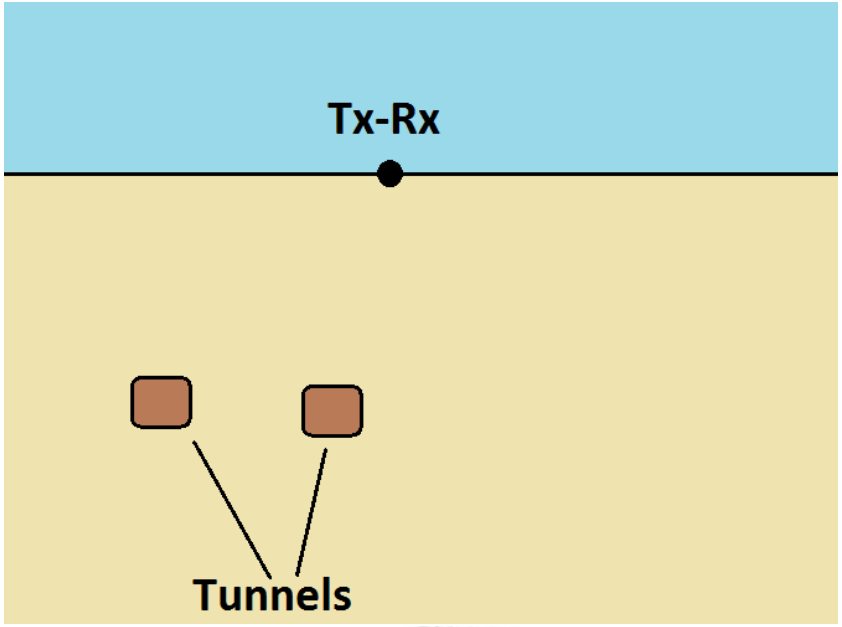


- Too much attenuation of signal
- Probing distance insufficient

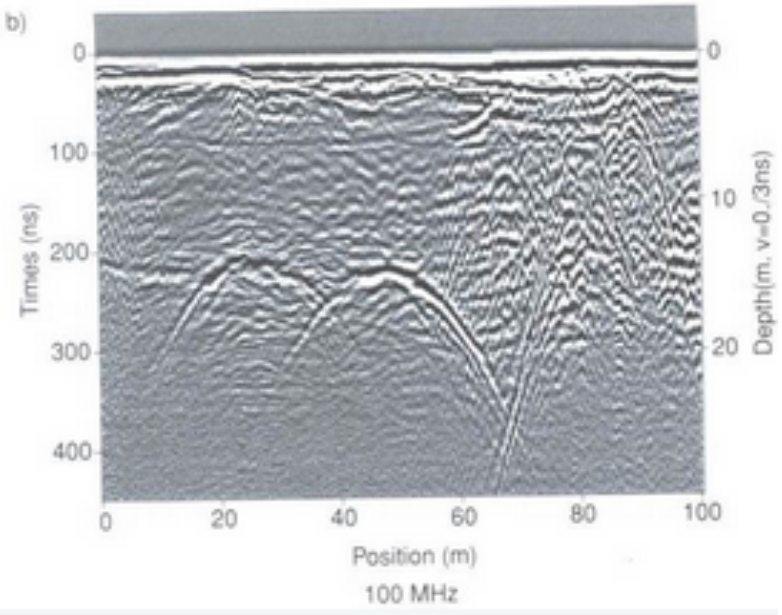


Radargram 100 MHz

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

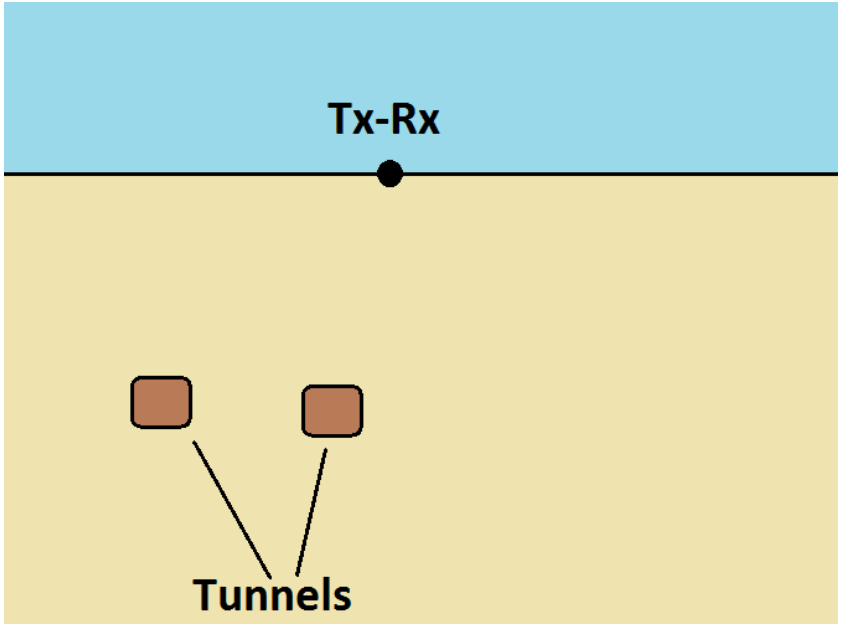


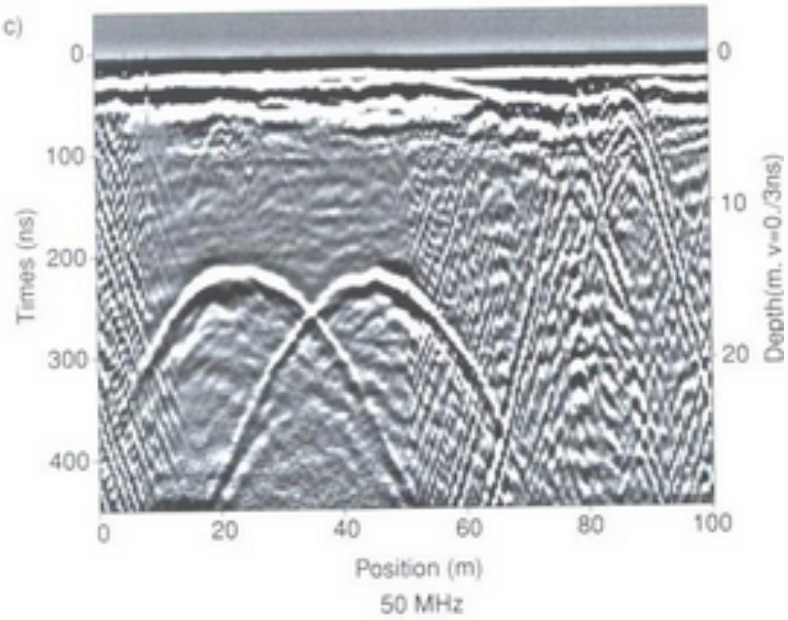
- Lower resolution
- Can see tunnels



Radargram 50 MHz

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





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

Recap of Example

- There is a compromise between resolution and probing distance:

Higher frequencies → Better resolution

Layers: $L > \dfrac{c}{4f_c\sqrt{\varepsilon_r}} = \dfrac{c\Delta t}{4\sqrt{\varepsilon_r}}$

Objects: $L > \sqrt{\dfrac{V\,d}{2f_c}}$

Higher frequencies → Lower probing distance

$$D = 3\delta \approx \begin{cases} 1510\sqrt{\dfrac{1}{\sigma f}} & \text{for } \omega\varepsilon \ll \sigma \\ 0.0159\dfrac{\sqrt{\varepsilon_r}}{\sigma} & \text{for } \omega\varepsilon \gg \sigma \end{cases}$$

Recap Questions:

Q: If higher frequencies give better resolution, what does that say about pulse width?

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

Q: What are some things you want to know before chosing an operating frequency?

Noise and GPR

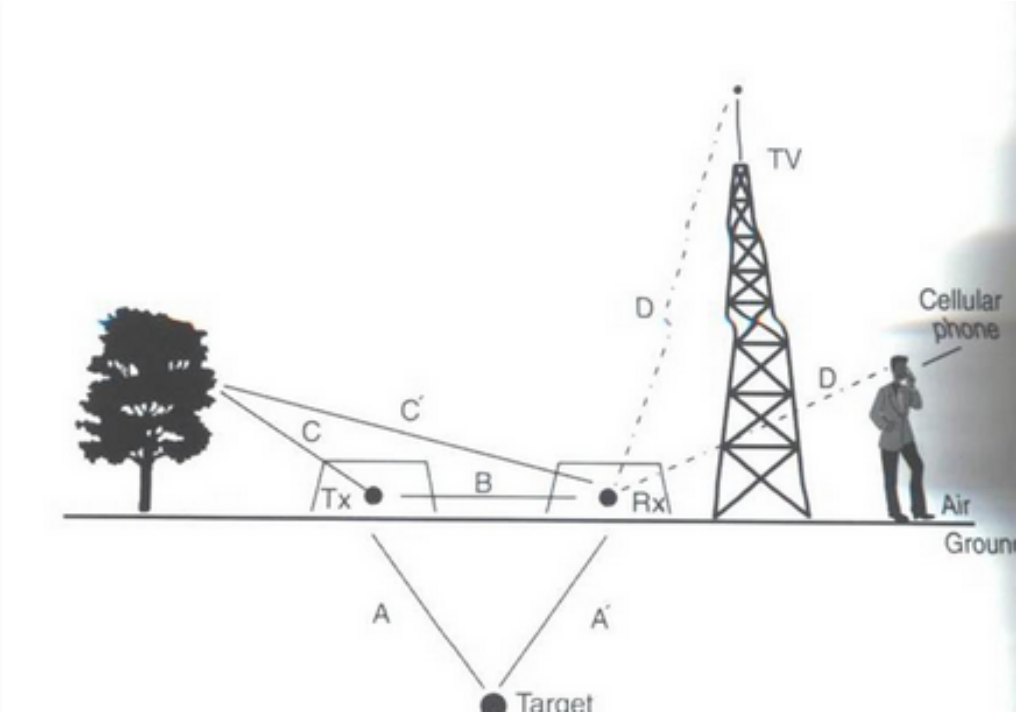
- **Any** signal which interfers from useful signals from GPR targets.

Examples:

- External radiowave sources
- Above ground objects
- Ringing
- Scattering

Interference from other Radiowave Sources

- Radio towers
- Cell phones
- Power Lines



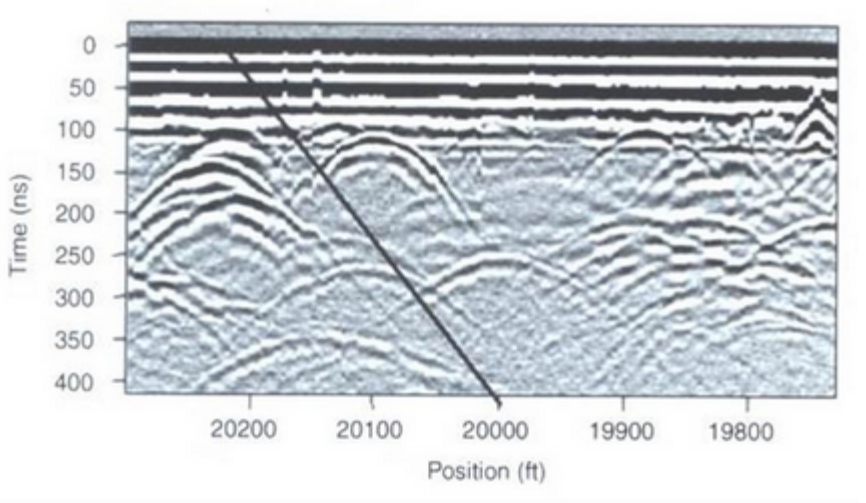
- Tx and Rx usually shielded to avoid these signals

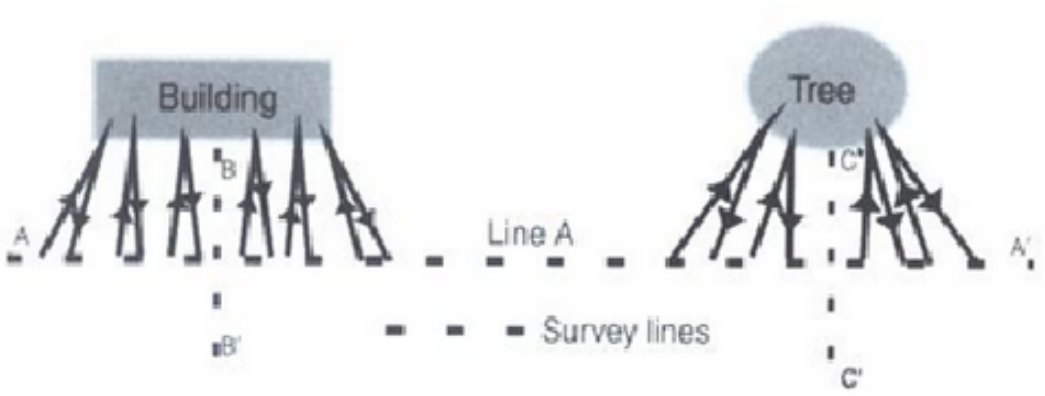
Noise from Above Ground Objects

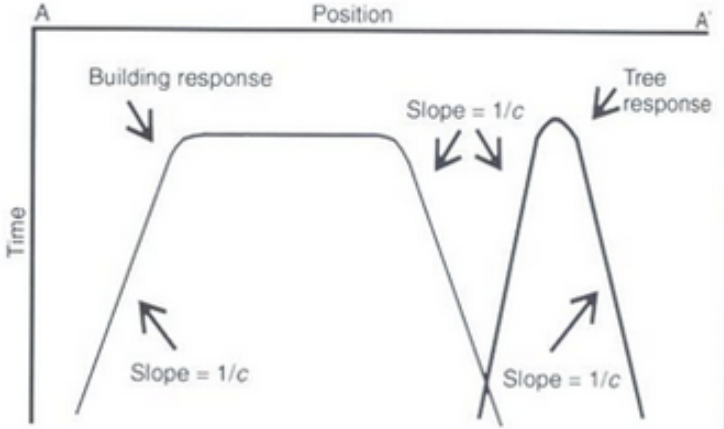
- Signals can reflect off neaby building and trees.
- Two-way travel time:

$$t = \frac{2\left(x^2 + d^2\right)^{1/2}}{V}$$

- Makes hyperbolas in zero offset surveys

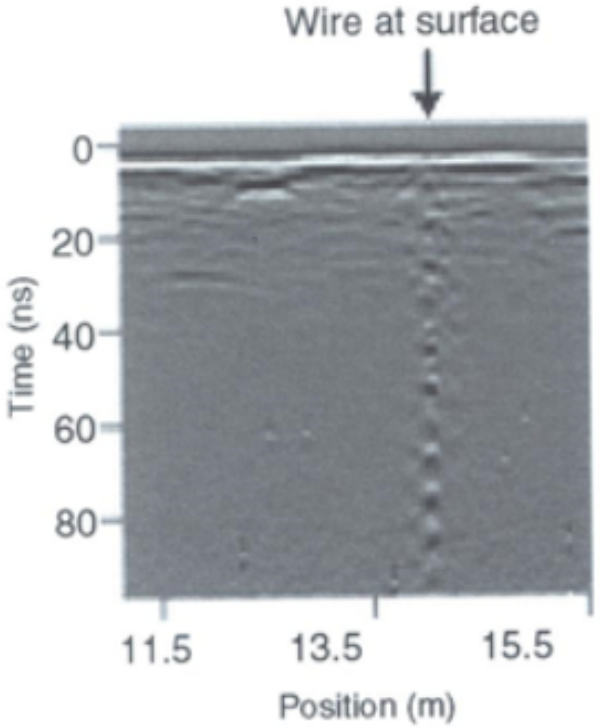






Noise from "Ringing"

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

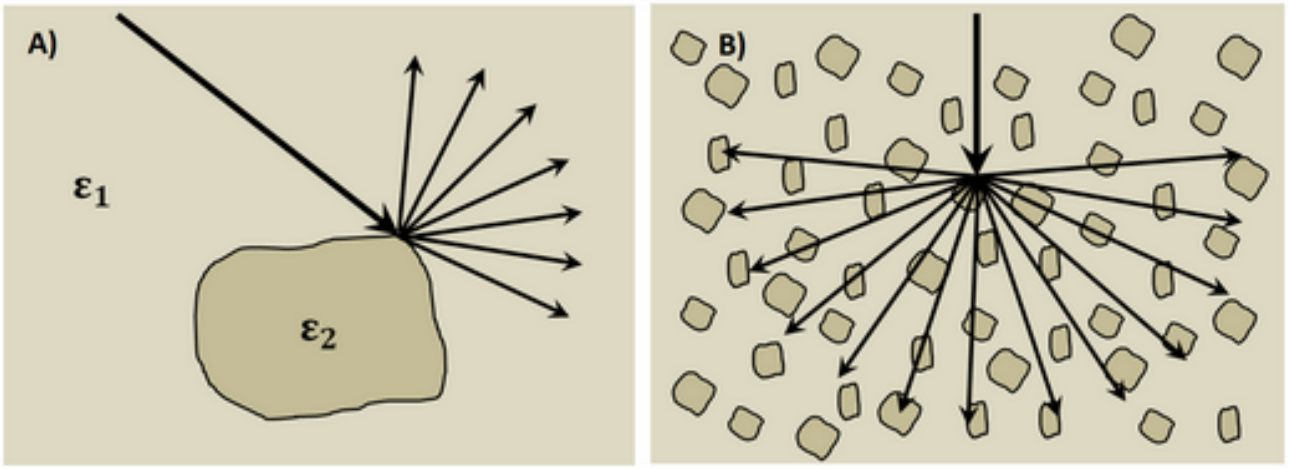


Wire below surface

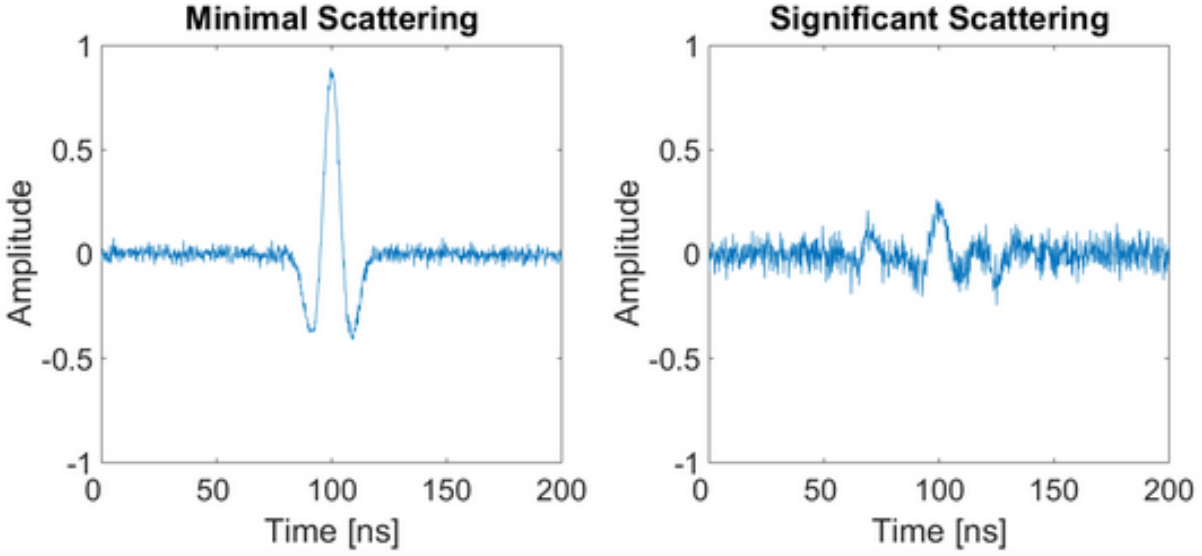
2 nearby objects

Noise from Scattering

- Deviations in signal path due to localized non-uniformities.

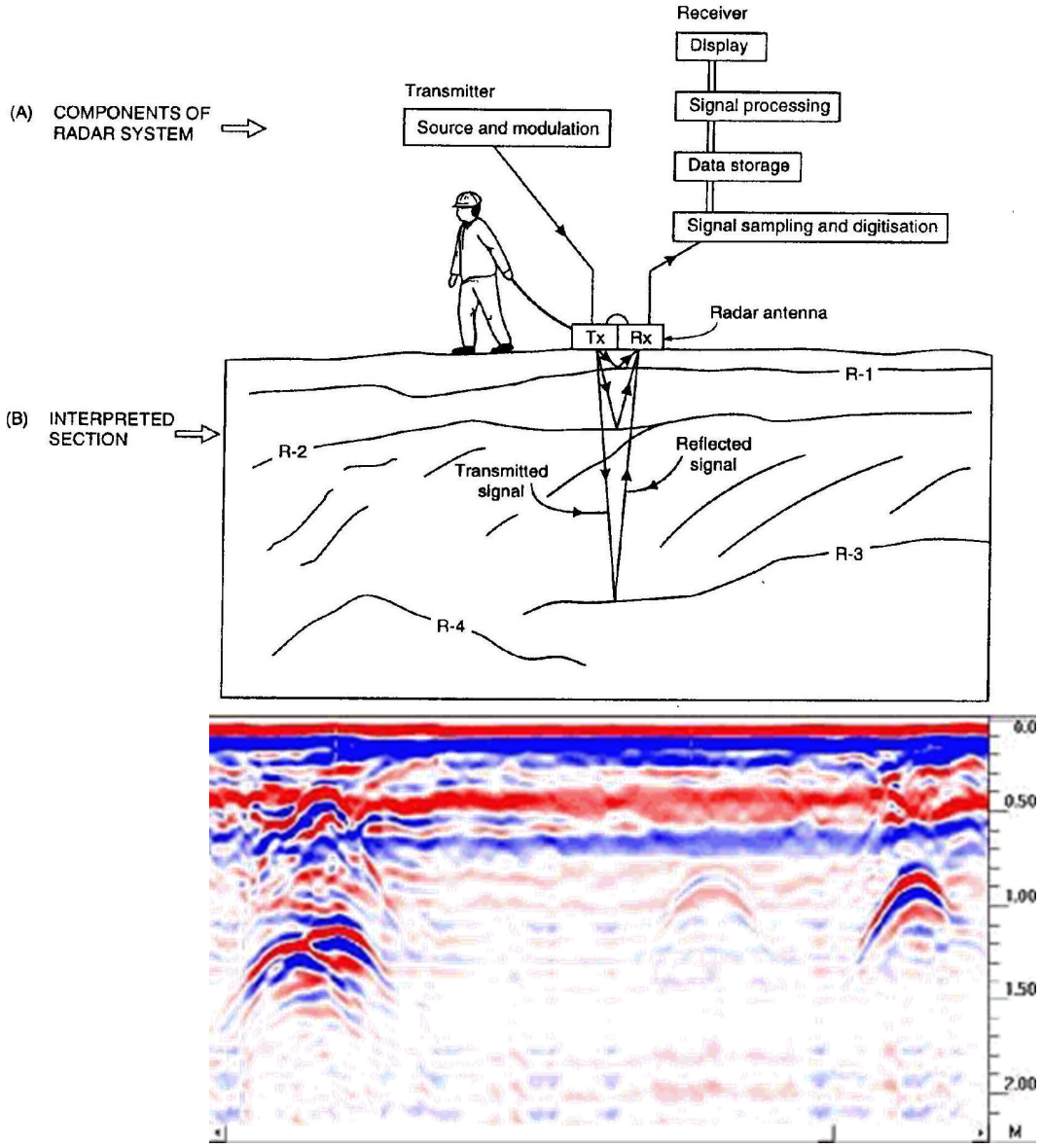


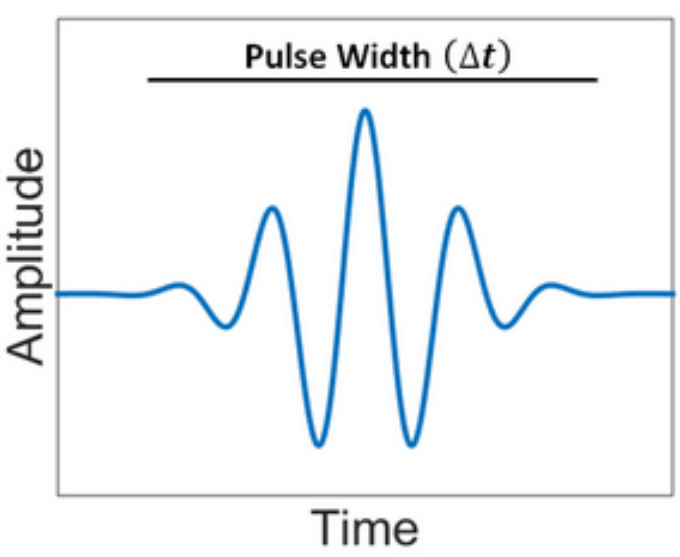
- Reduces amplitude of usable signal and increases noise.



Questions About Material?

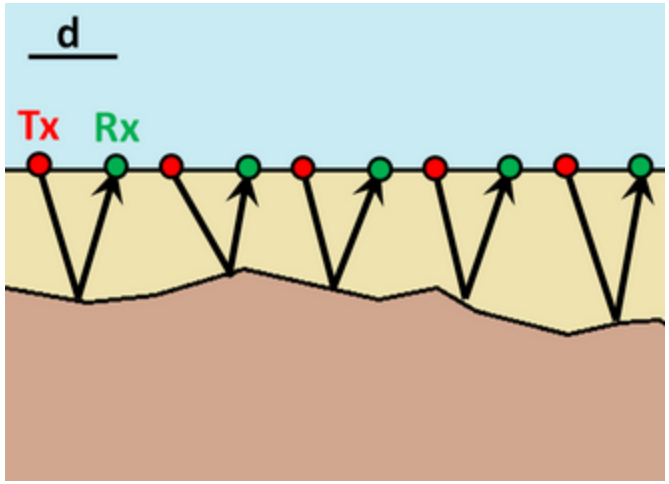
Ground Penetrating Radar (day 3)



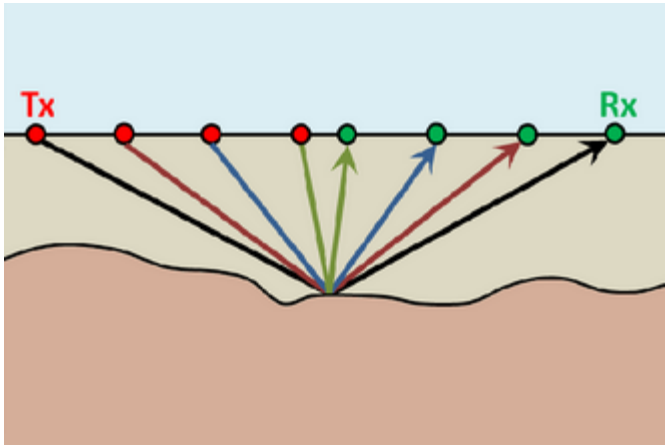


From Last Time

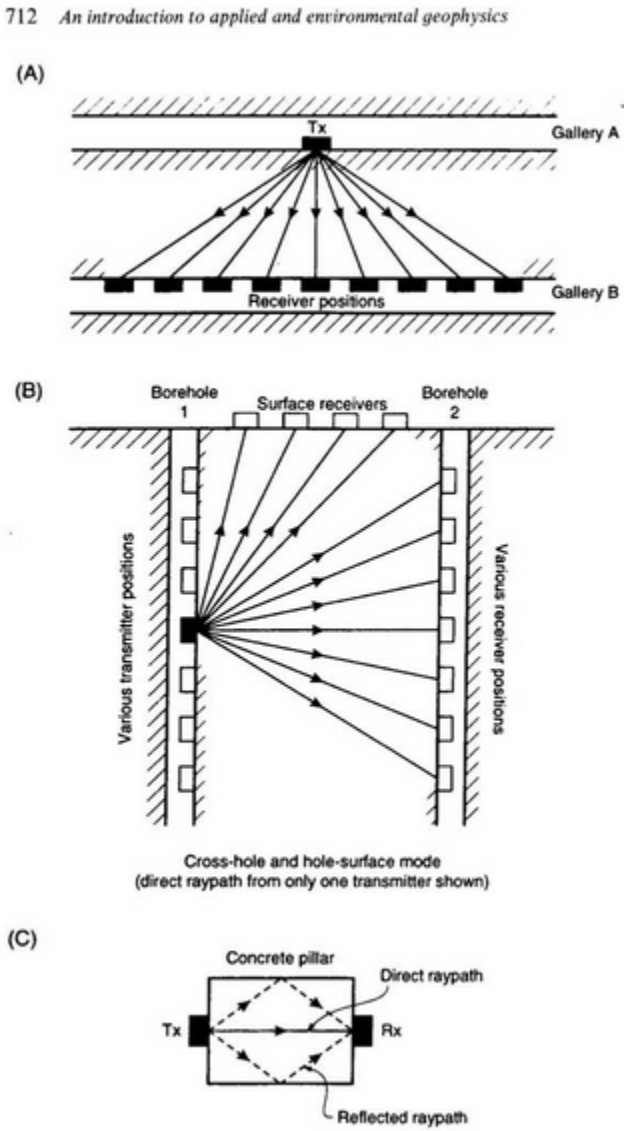
Common Offset



Common Midpoint



Transillumination



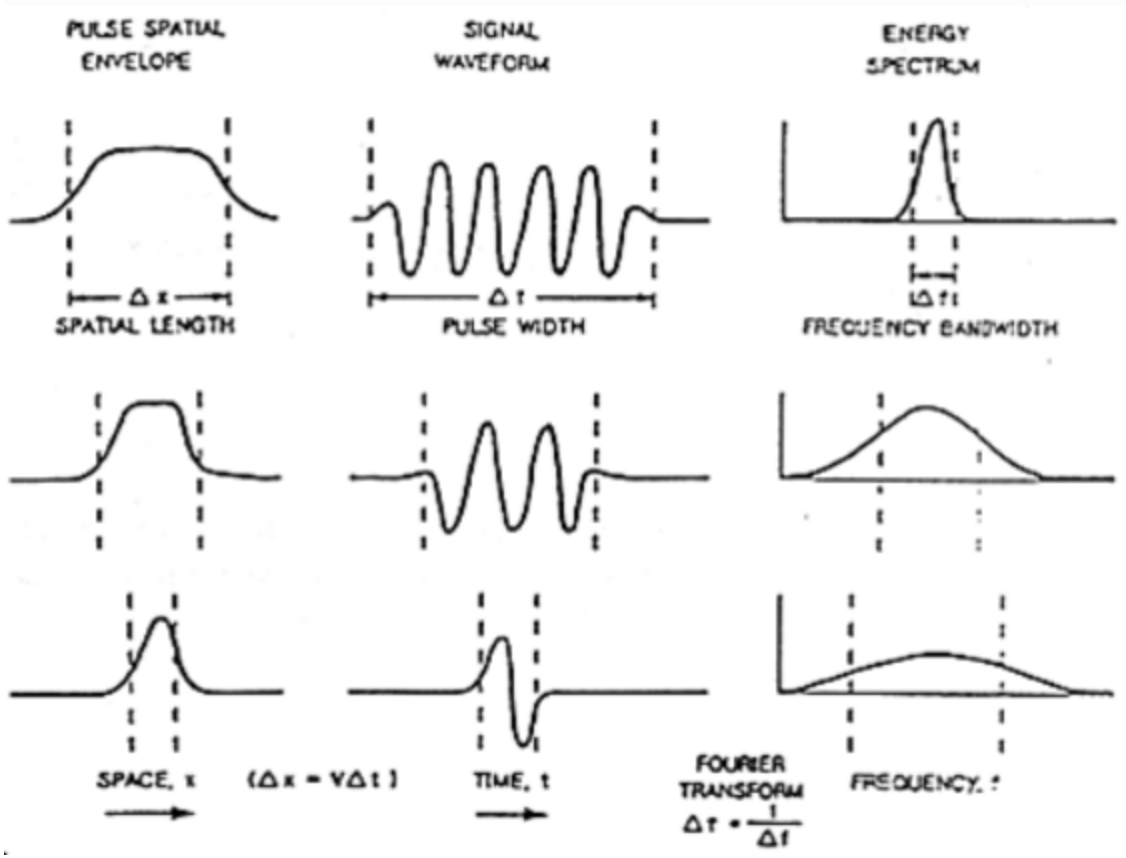
From Last Time

- Shorter pulses contain a wider range of frequencies
- Shorter pulse overall contain higher frequencies
- Spatial length increases as pulse length increases

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

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

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



From Last Time

- There is a compromise between resolution and probing distance:

Higher frequencies → Better resolution

Layers: $L > \dfrac{c}{4f_c\sqrt{\varepsilon_r}} = \dfrac{c\Delta t}{4\sqrt{\varepsilon_r}}$

Objects: $L > \sqrt{\dfrac{V\,d}{2f_c}}$

Higher frequencies → Lower probing distance

$$D = 3\delta \approx \begin{cases} 1510\sqrt{\dfrac{1}{\sigma f}} & \text{for } \omega\varepsilon \ll \sigma \\ 0.0159\dfrac{\sqrt{\varepsilon_r}}{\sigma} & \text{for } \omega\varepsilon \gg \sigma \end{cases}$$

Today's Topics

- Processing:

  - Arrival time to depth conversion

  - Reducing Noise

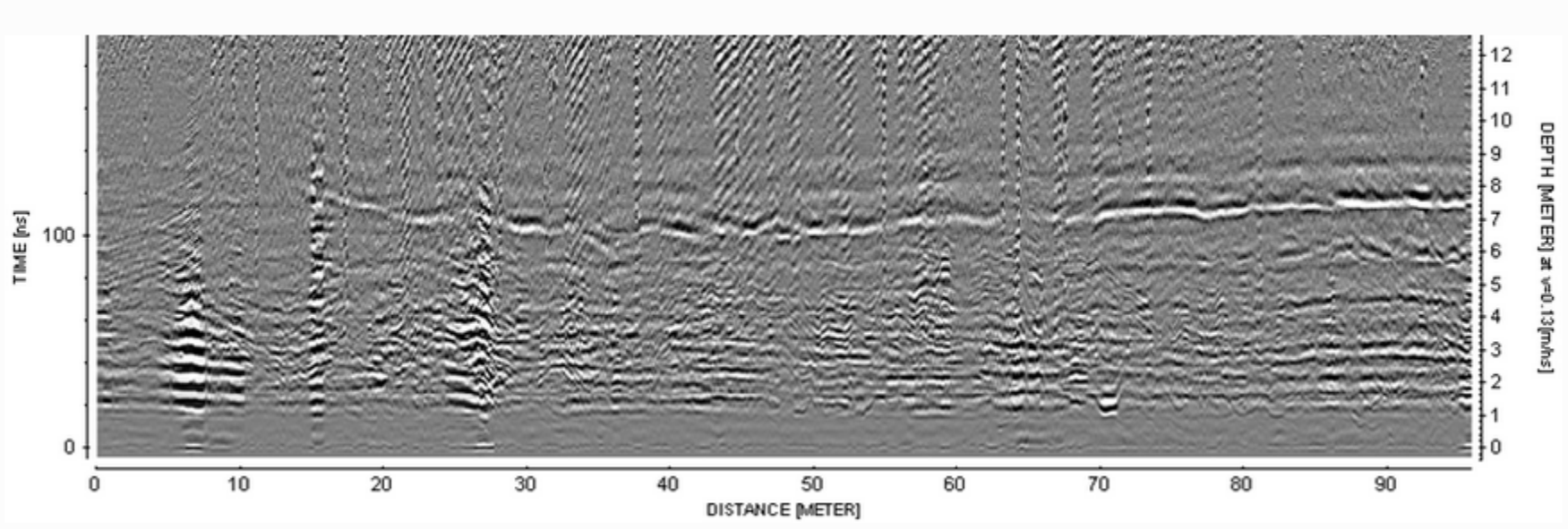
- Interpretation

- Some Examples

Arrival Time to Depth Convesion

- Vertical axis usual 2-way travel time [ns]
- If you can get velocity, you can get an apparent depth:

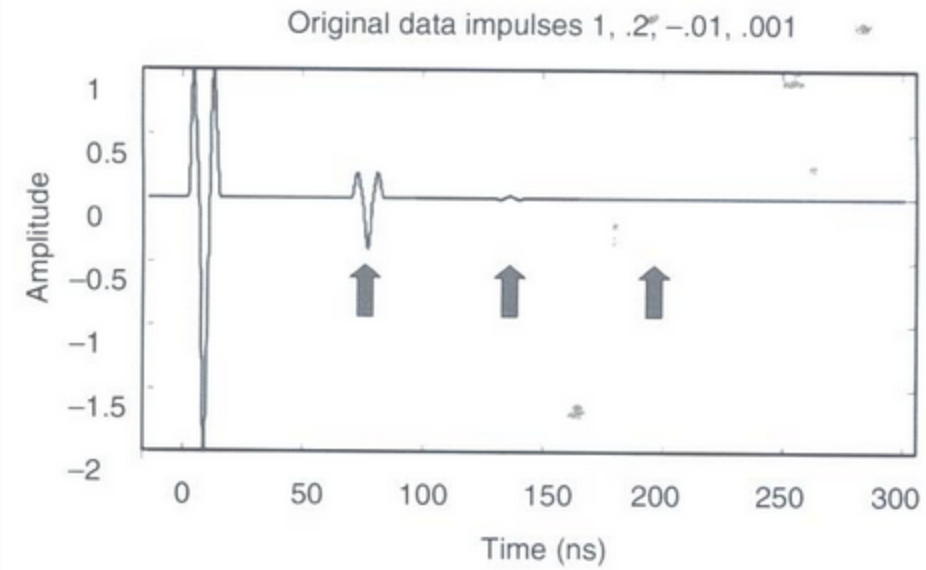
$$d_a = \frac{Vt}{2}$$



Gain Correction

- GPR signal strength decreases exponentially travel distance

Measured signal strength decreases over time

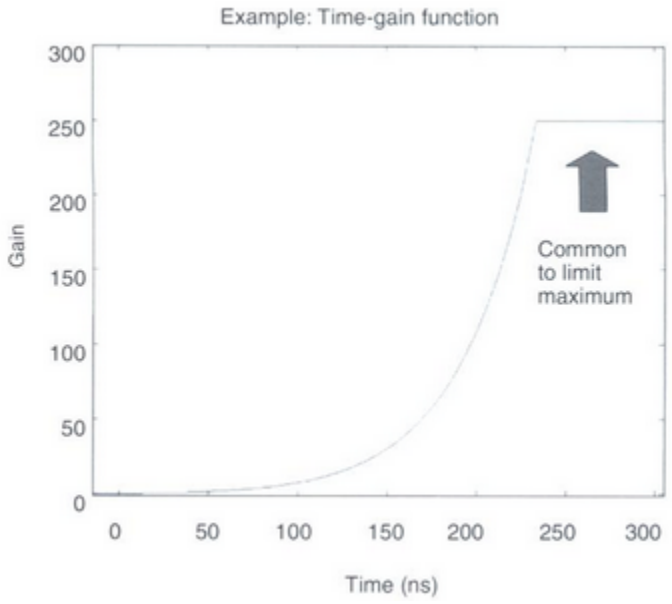


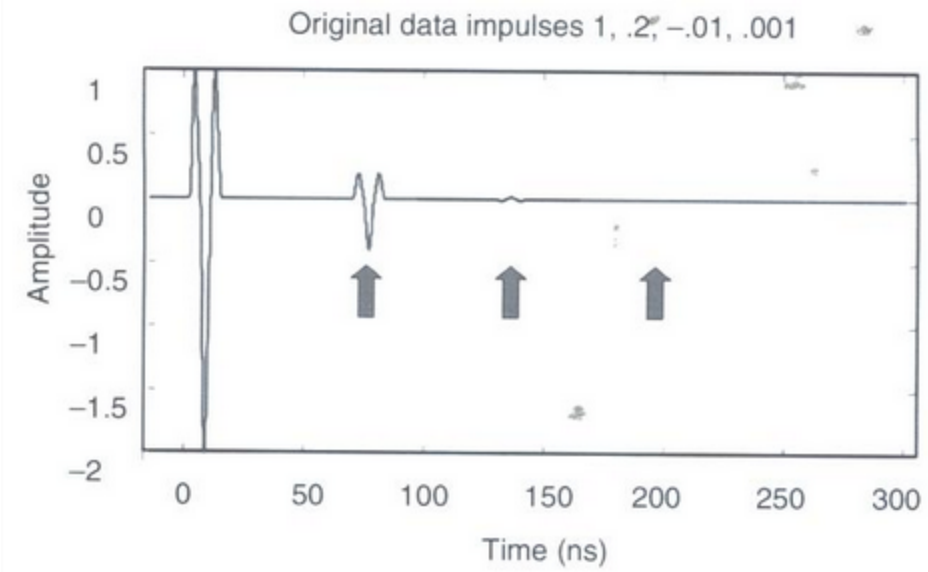
Gain Correction

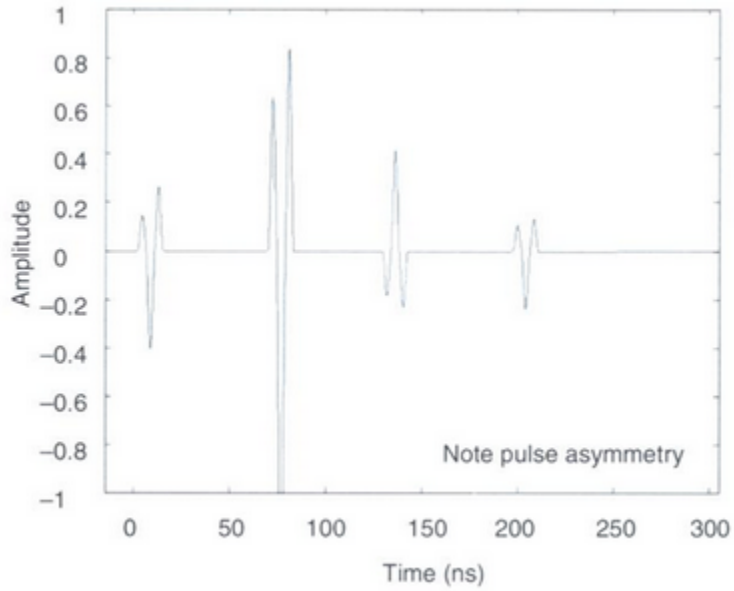
- Multiply raw data by a **gain factor** so that late signals can be recognized.

$$d(t) = g(t) \times d_{raw}(t)$$

- Gain factor generally counteracts exponential decay in amplitude







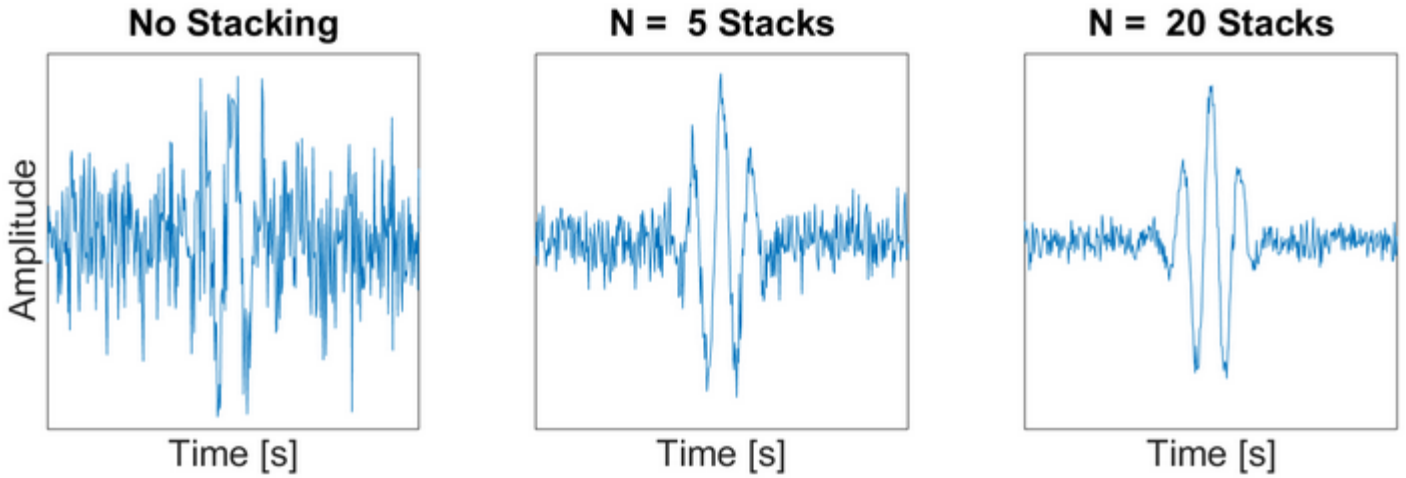
Stacking to Reduce Noise

- 2-way travel times for GPR are 100s of nanoseconds

  The same GPR shot can be repeated many times within a short period of time

- Data from repeated shots are averaged (stacked)

- Stacking reduces the amplitude of incoherent noise

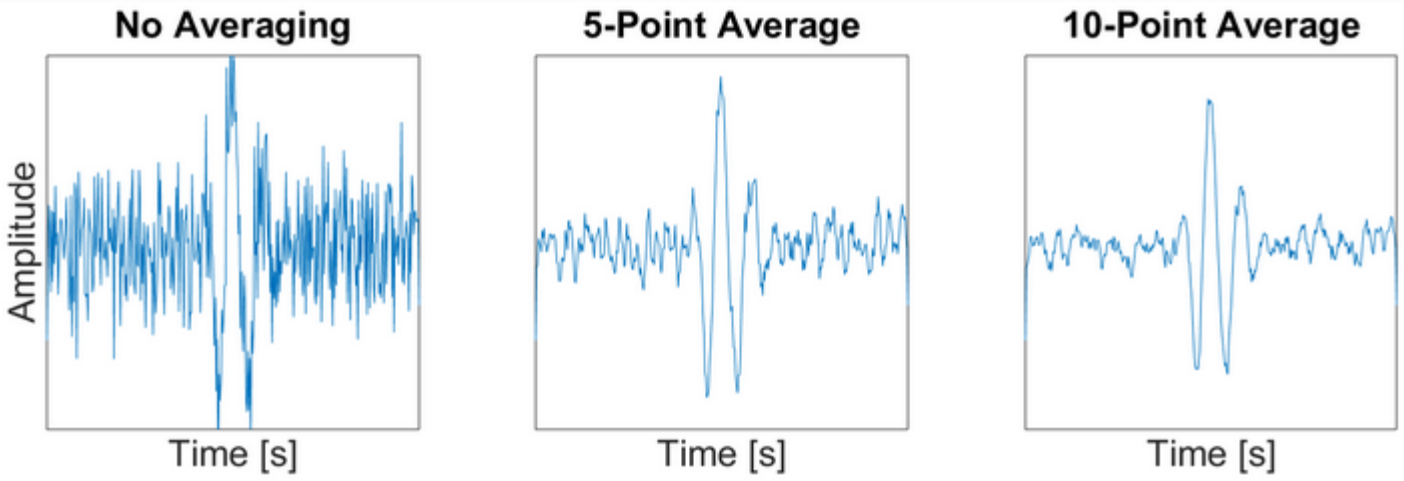


Smoothing to Reduce Noise

- Data sampling rate is very high relative to returning wavelet signal.

Wavelet signal is smooth whereas incoherent noise is random

- Smoothing decreases amplitude of random noise relative to returning signals.



Processing Recap

- Gain correction is need so late time signals are as visible as early time signals.
- Stacking is used to reduce the noise to signal ratio.
- Smoothing can be used to reduce the amplitude of incoherent noise.

Recap Questions

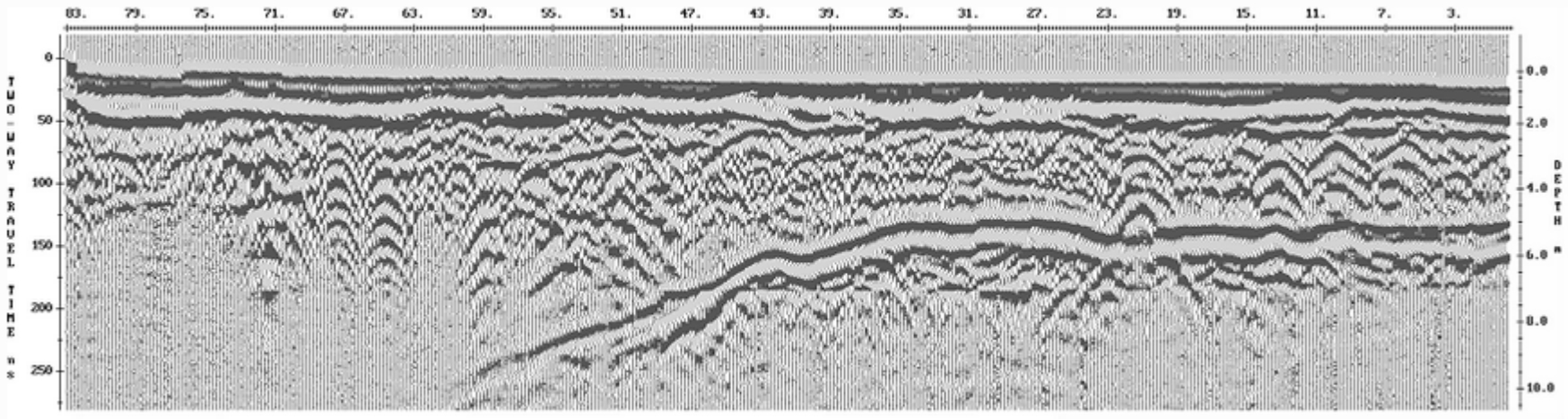
Q: Why would we do a time to depth conversion?

Q: What's a way we can reduce incoherent noise?

Interpretation

Regarding the Survey

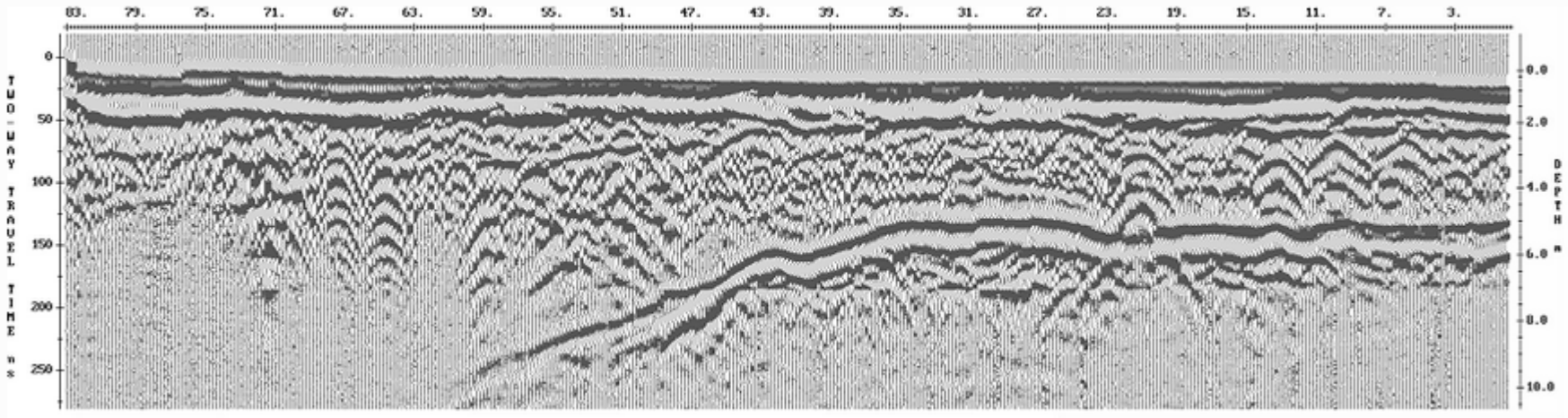
- What is the Tx-Rx separation distance?
- What is the operating frequency and wavelet pulse width?
- What do you know about the local physical properties? high/low conductivity? high/low dielectric permittivity?
- Is the ground dry or saturated (permittivity)? Does the ground contain features which may scatter the signal?
- Having considered the previous statements, what do you think the resolution and probing distance are?



Interpretation

Regarding the Data

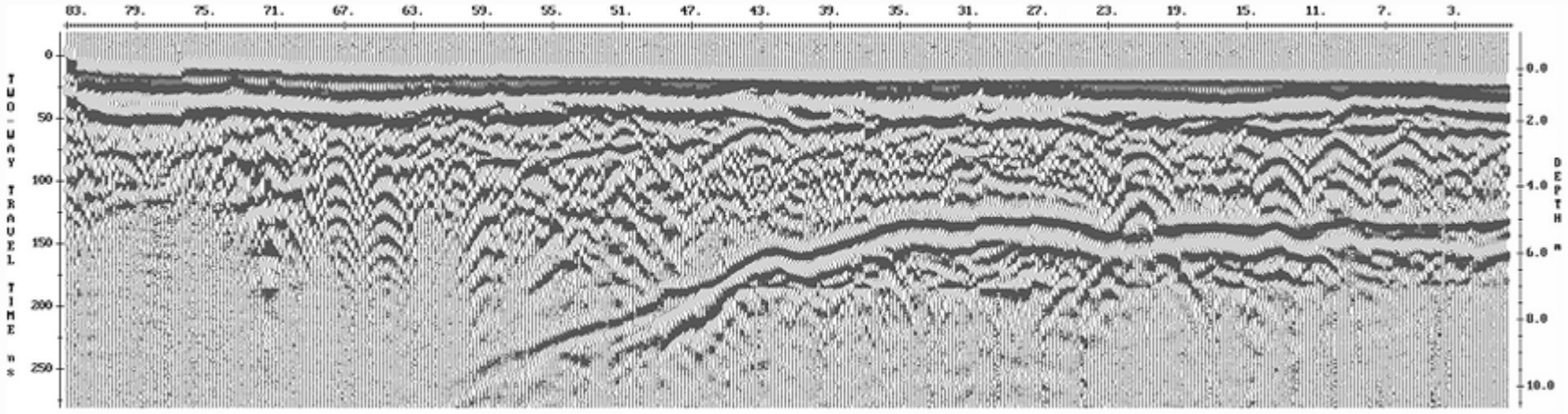
- When is the earliest useful signal you measure? When is the latest?
- Why can't you see anything after the latest signal? Attenuation? Strong reflector?
- Can you infer a layer velocity and turn the travel time axis into an apparent distance axis?
- Is there a reverse in polarity of the wavelet signal? What does that tell you about ε_1 and ε_2 for an interface?



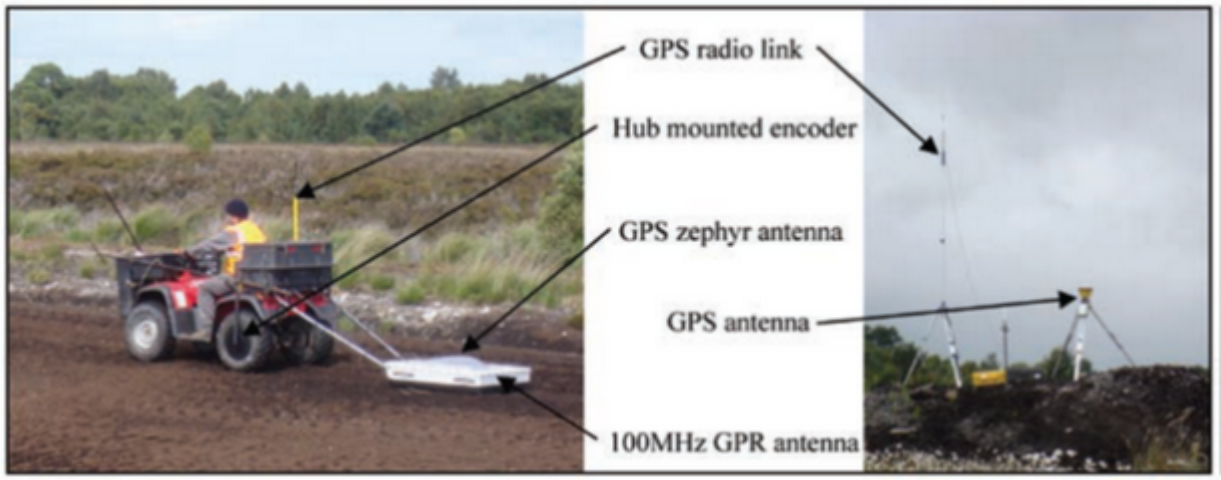
Interpretation

Recognizing Features

- Do you notice any hyperbolic features? Indicates point reflector for zero-offset. Indicates layer for common midpoint.
- For hyperbolic signatures (or signatures from other discrete shapes), what does the slope tell you about the propagation velocity of the medium it's in?
- Based on the slope, is the object above ground (noise), or below ground (potential target)?
- Are there any linear features (zero-offset)?
- Do linear features indicate a flat or dipping interface? Is the a method you can use to get the dip?
- Are you able to get signals from anything below an obvious reflector? What does that say about ε_1 and ε_2?
- Can slopes and hyperbolas be used to obtain layer velocities?



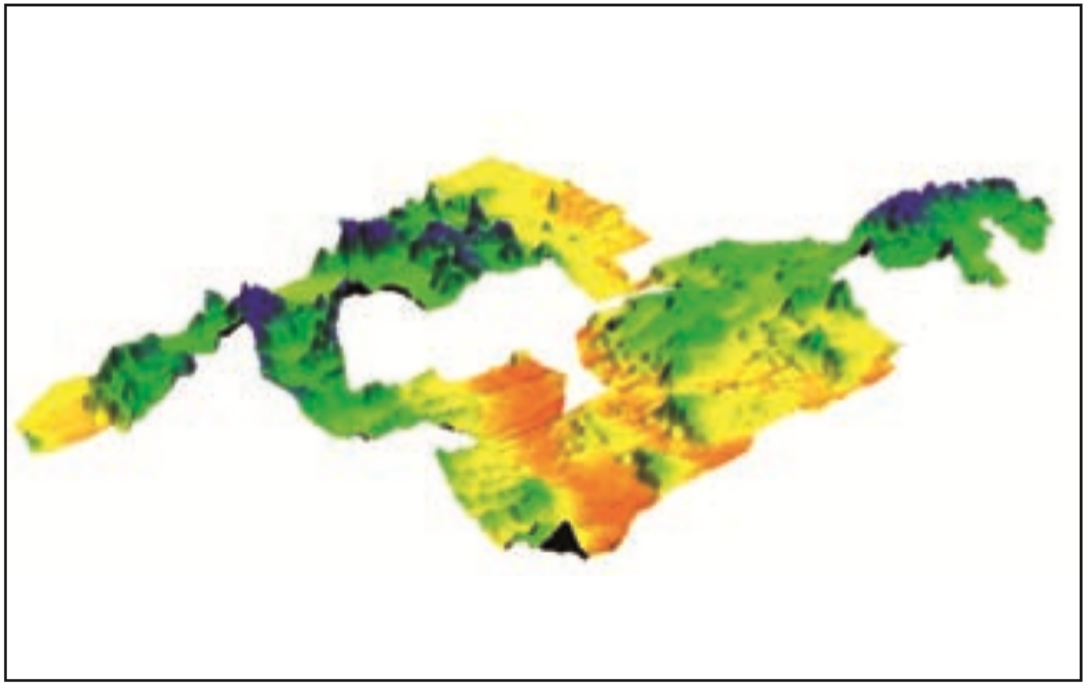
Example: Mapping Peat Thickness (Ireland)



- Common offset survey
- 100 MHz
- Arrival time to depth correction performed
- Topography correction performed (LIDAR data)

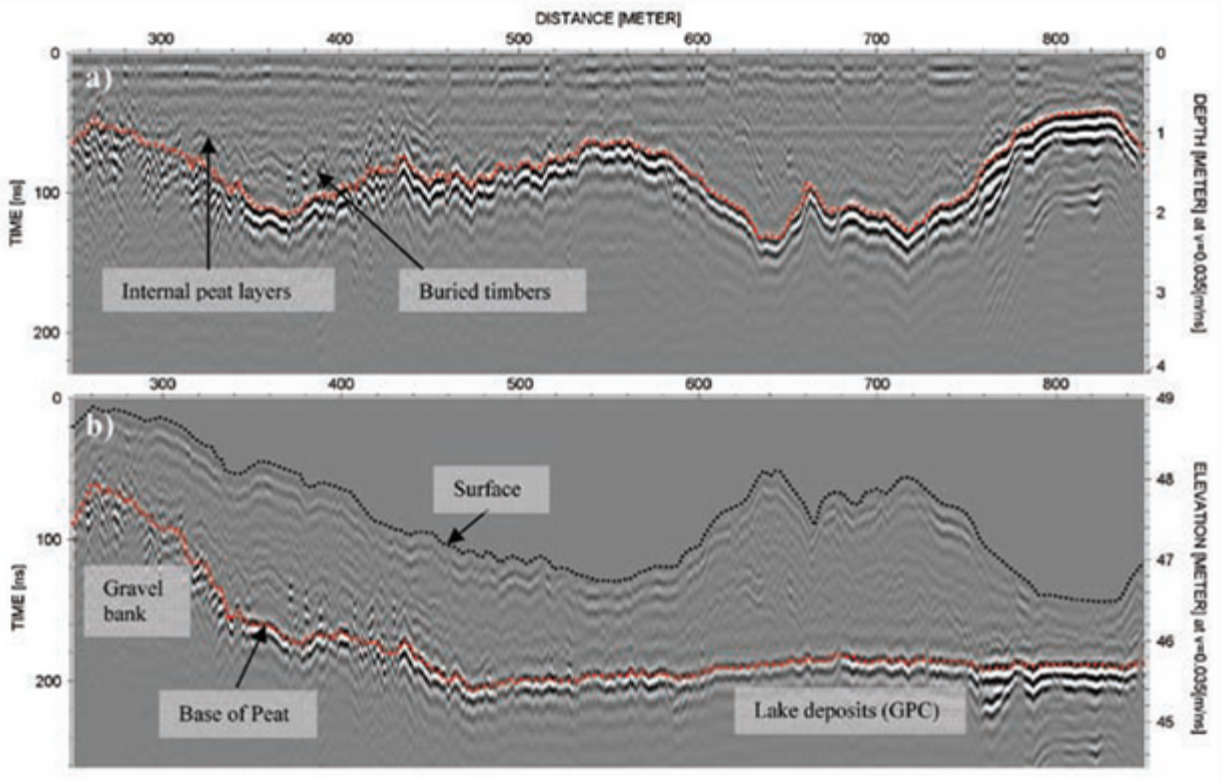
Example: Mapping Peat Thickness (Ireland)

3D LIDAR surface elevation map over peat



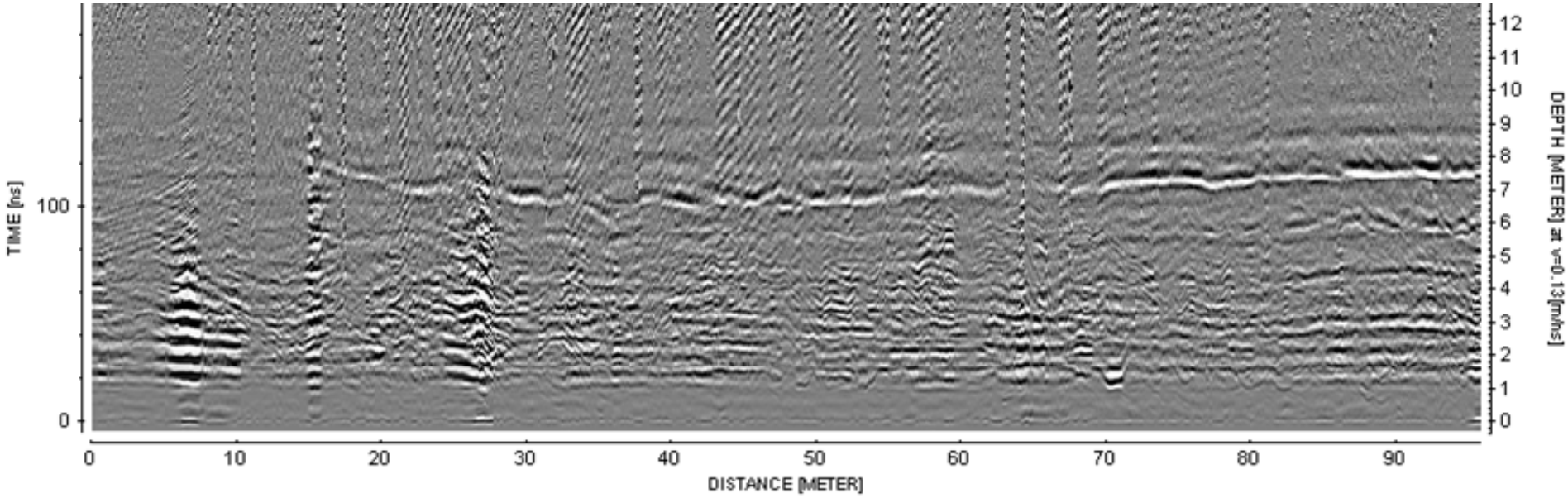
- After arrival time to depth conversion, elevation from LIDAR data used to create profile of peat layer.

Example: Mapping Peat Thickness (Ireland)



- Strong reflector at the bottom of the peat bed
- Small reflections from internal peat layers
- Gravel bank on the left

Example: Potash Mine

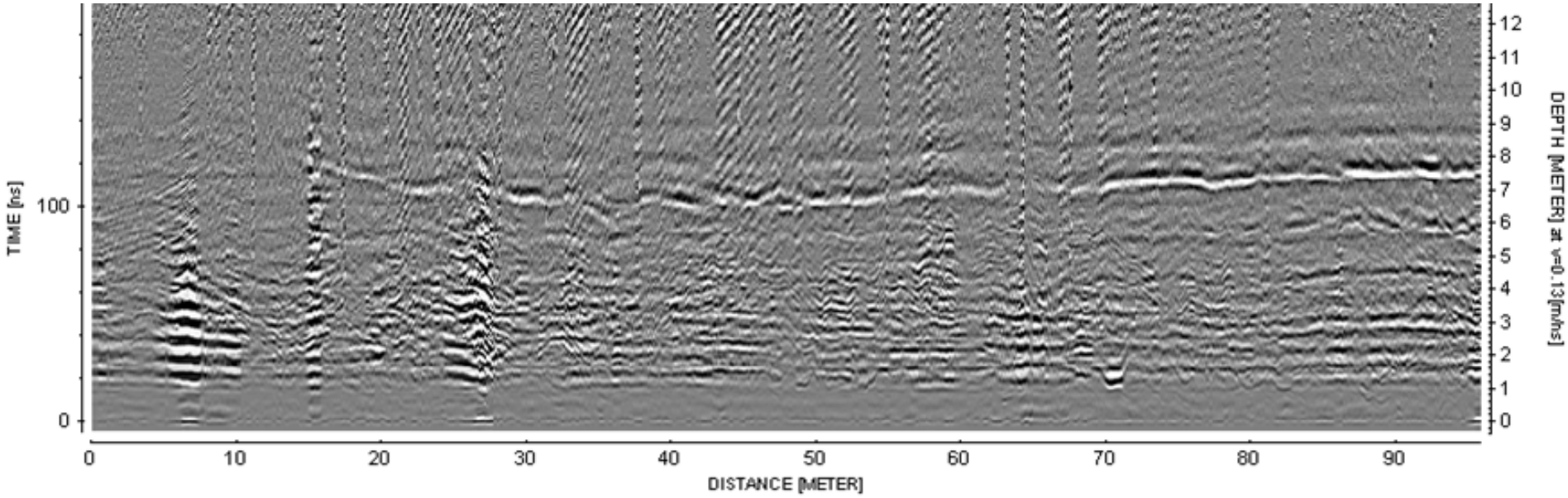


- Water was leaking into the potash mine

→ Reducing structural integrity of mine shafts

→ Want to know where water is and its source

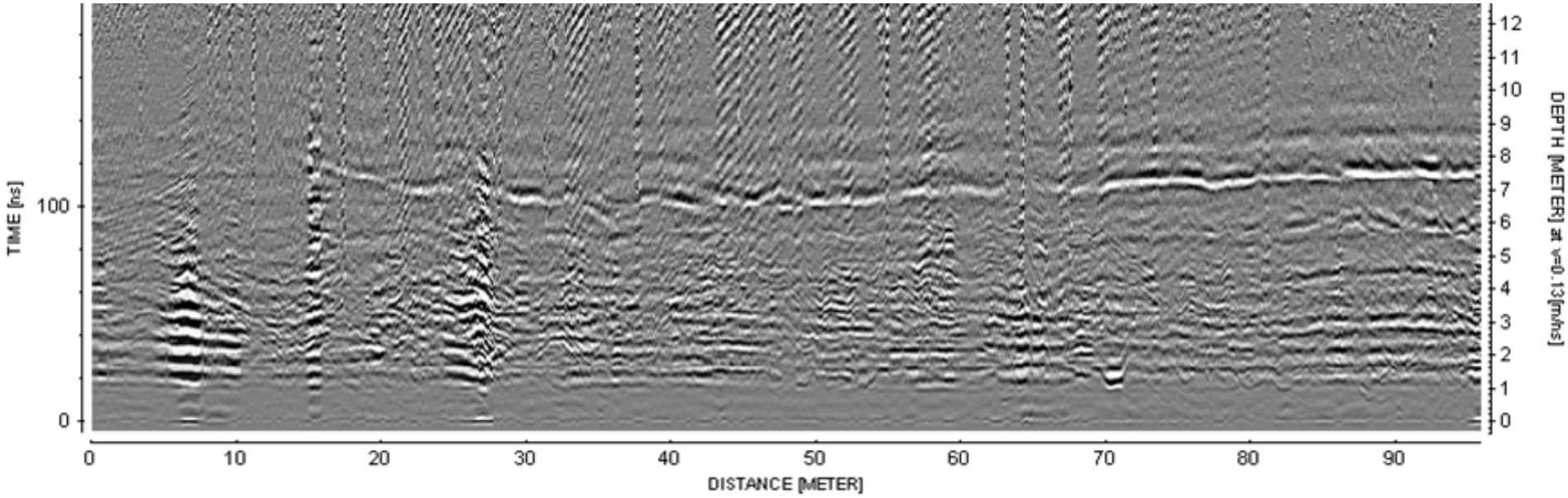
Example: Potash Mine



- Zero offset 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?

Example: Potash Mine

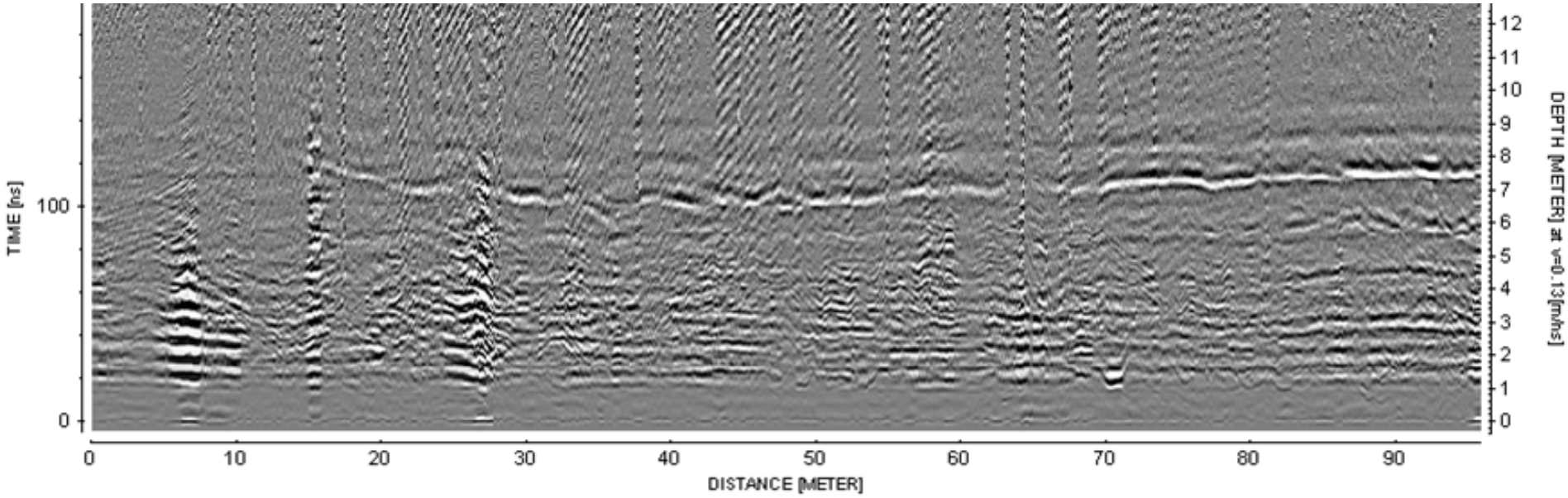


A: Potash in an **anhydrite mineral**.

From known physical properties, **V ~ 0.13 m/ns**

da = Vt/2

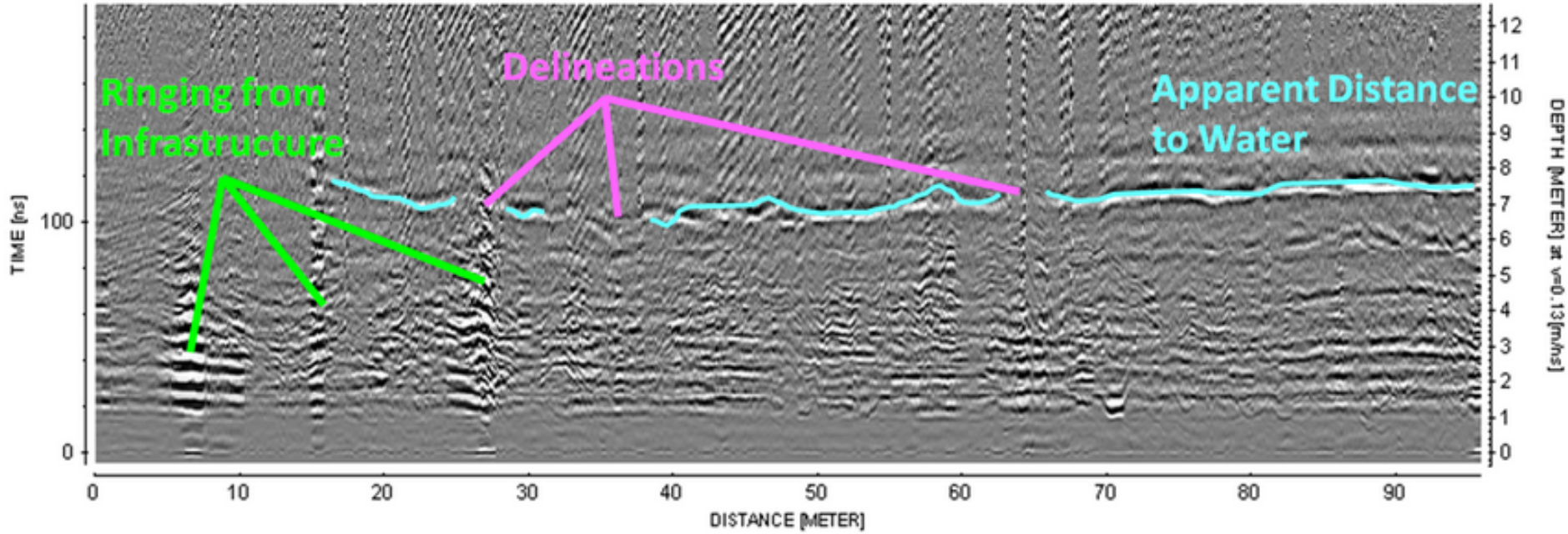
Example: Potash Mine



Q: When is the earliest return signal?

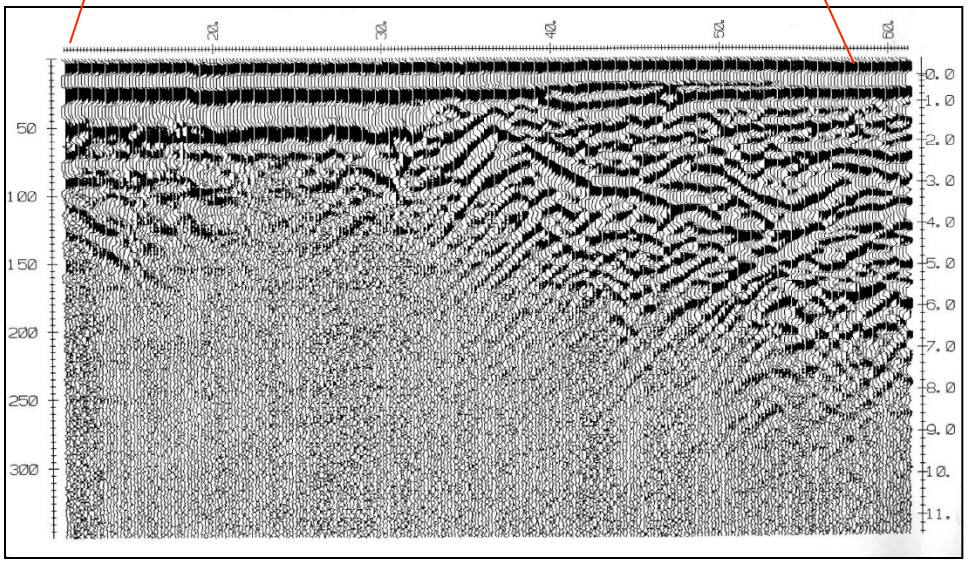
Q: What kinds of features do you see in the data?

Example: Potash Mine



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

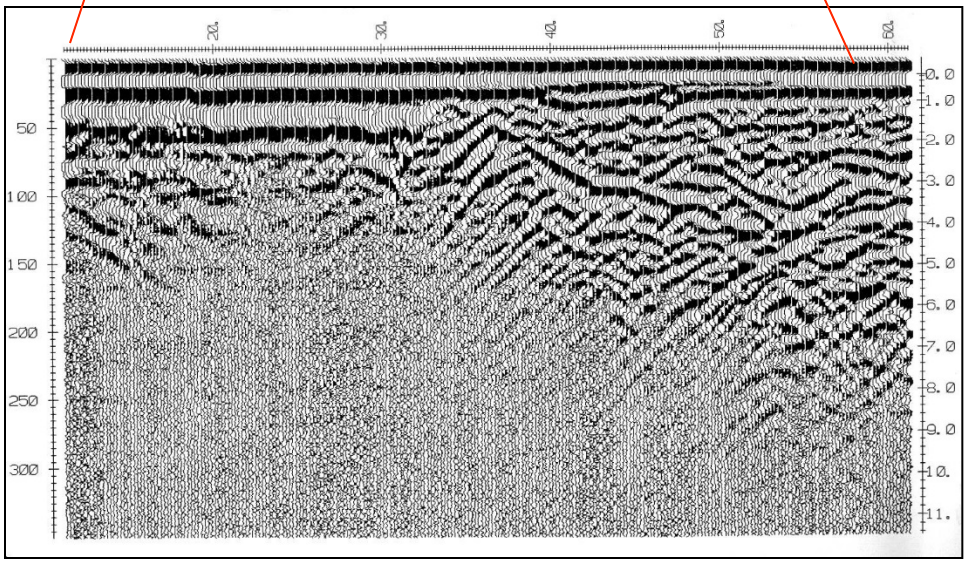
Example: UBC GPR Test Survey



Ground penetrating radar cross-section

Why is character changing?

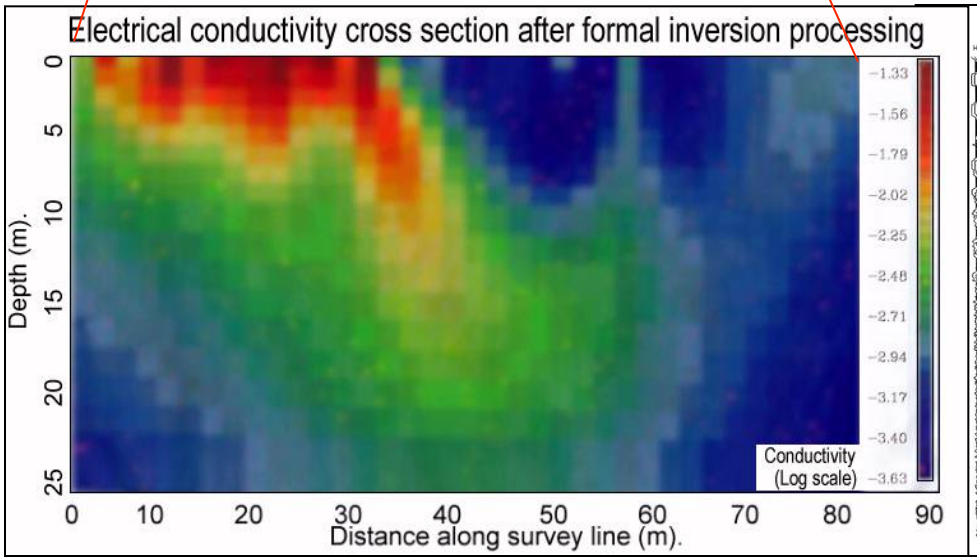
Example: UBC GPR Test Survey



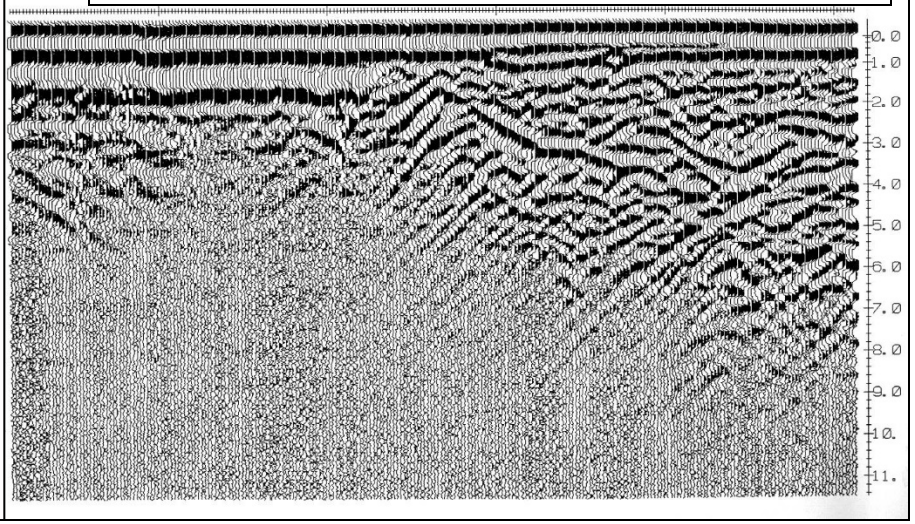
- What do the horizontal features at < 50 ns represent?
- Can you locate the boundary between the field and forest in the data?
- Why doesn't the signal penetrate as deep on the west?

Example: UBC GPR Test Survey

- Attenuation tells us the ground is more conductive under the forest.



Ground penetrating radar cross-section



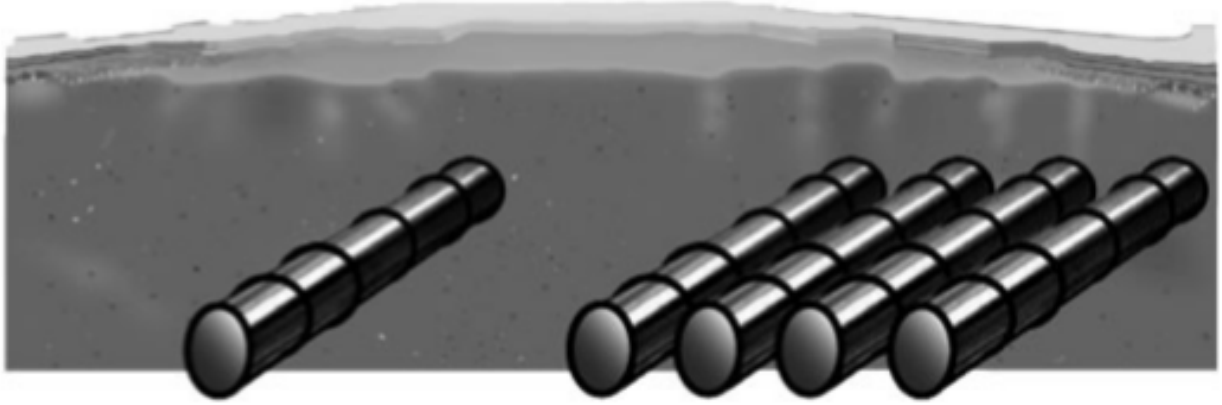
Example: Underground Storage Tanks

- Want to locate a set of underground storage tanks.

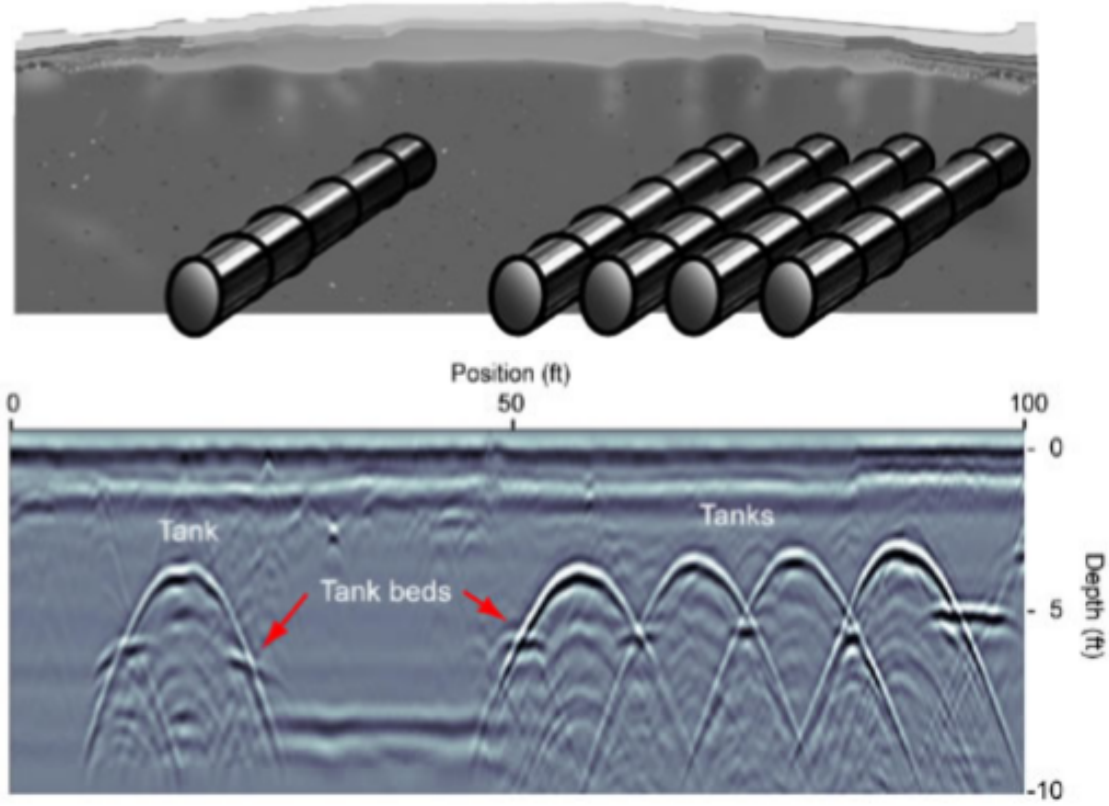
  Q: What direction would you orient your survey lines? Why?

  Q: What features do you expect in your radargram?

Diagram of problem



Example: Underground Storage Tanks



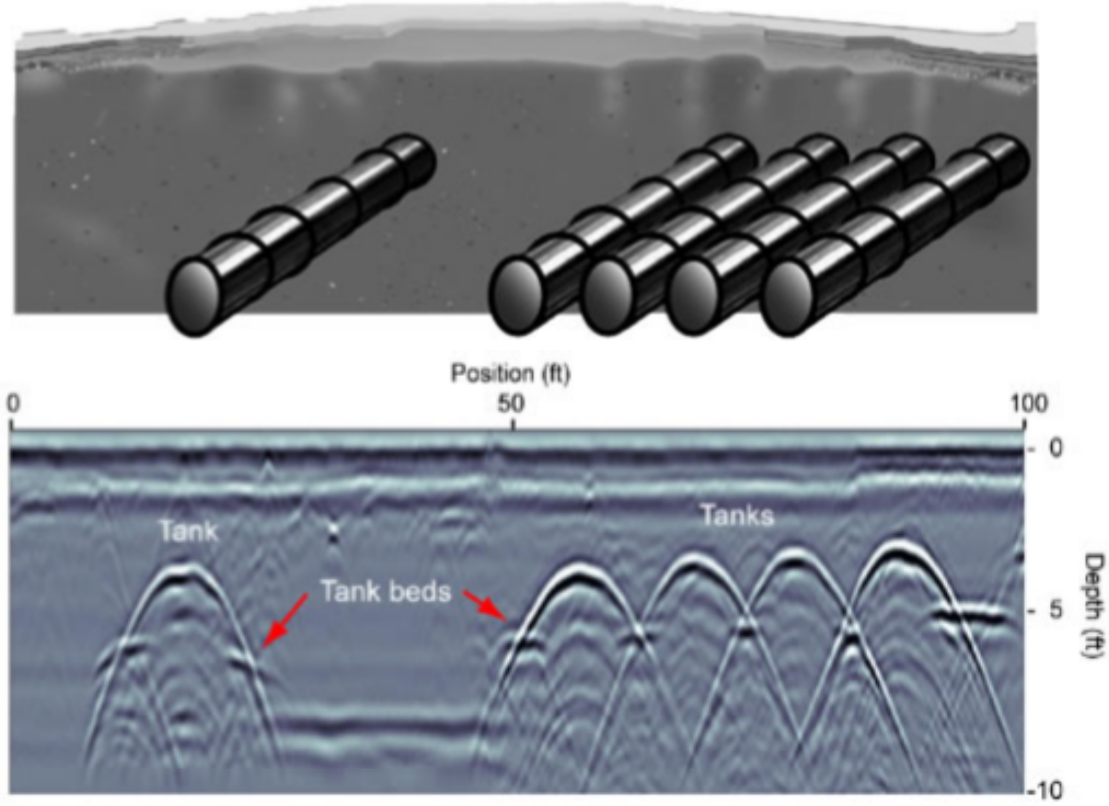
Q: If pipes too big to be point reflectors, can you still obtain layer velocity? How?

Q: If pipes act as point reflectors, is there an additional way to get velocity?

Q: How can you figure out the horizontal location and depth to each pipe? (assume you know the velocity)

Q: Why aren't signatures from tank beds entirely visible?

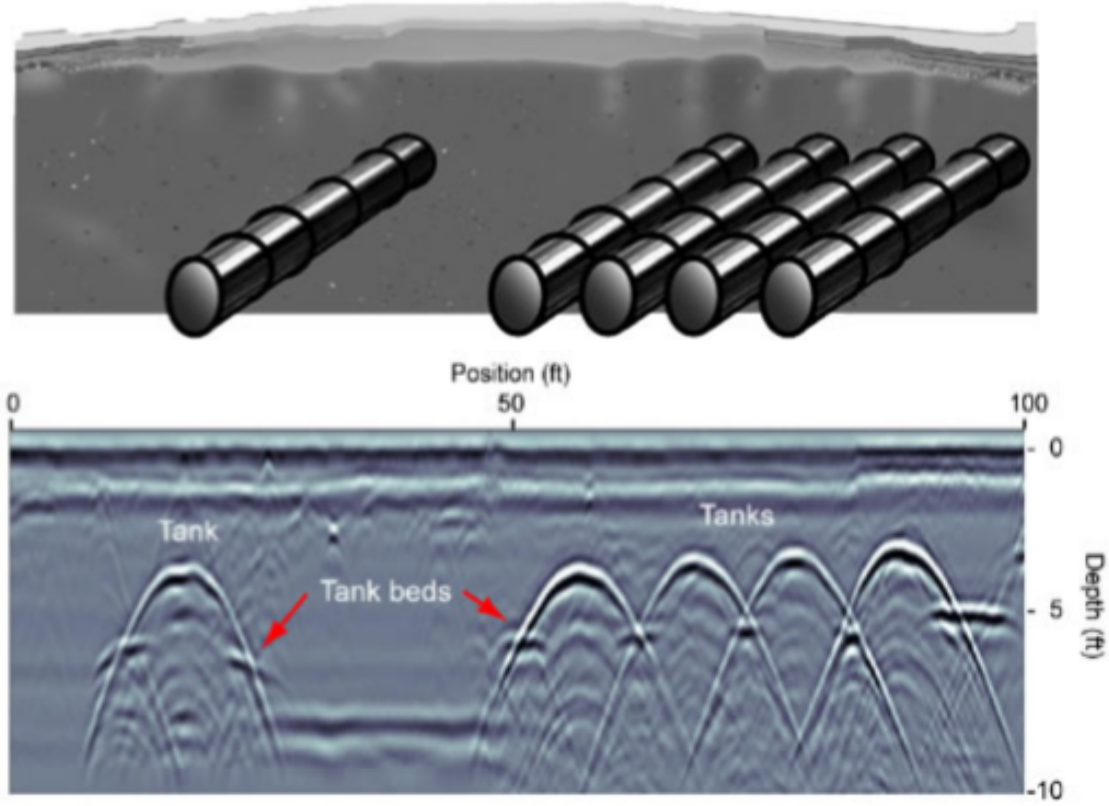
Example: Underground Storage Tanks



- Tanks approximately 3.5 ft (1 m) below surface
- Survey had 500 MHz operating frequency
- Assume V ~ 0.06 m/ns

Q: How close can storage tanks be to one another and still be recognizable?

Example: Underground Storage Tanks

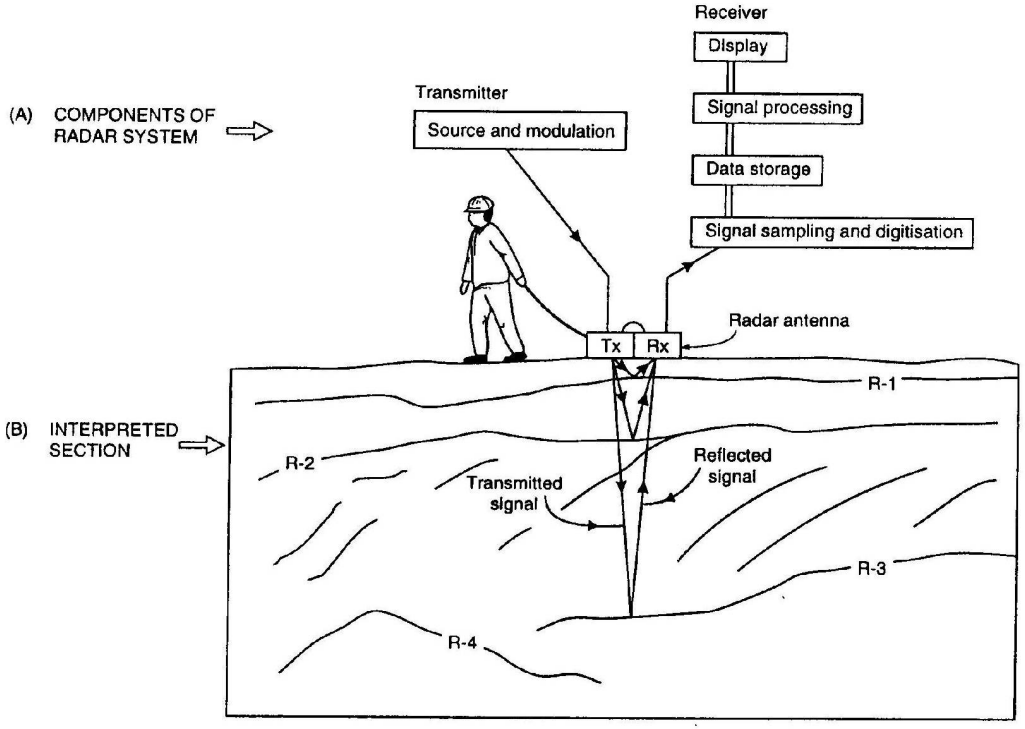


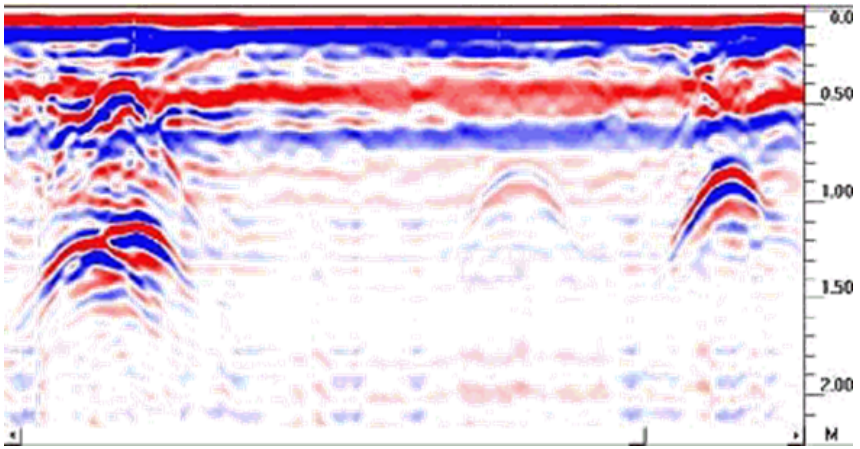
- Tanks approximately 3.5 ft (1 m) below surface
- Survey had 500 MHz operating frequency
- Assume V ~ 0.06 m/ns

Q: How close can storage tanks be to one another and still be recognizable? $D = \sqrt{Vd/2f} \downarrow c = 24\ cm$

Concluding Thoughts: GPR in a Nutshell

- Electromagnetic Method
- Exploits contrasts in **dielectric permittivity** and **conductivity**
- Sends a **pulse** of radiowaves into the ground
- Signals reflect, refract and transmit at interfaces
- Measured signals represented using radargrams





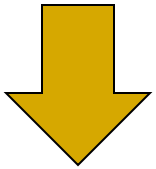
Concluding Thoughts: When to use GPR

- Generally near-surface applications (10s metres or less)
- Images the interfaces which define subsurface structures
- Examples:

  - Geotechnical problems (rock fractures, slope stability …)
  - Find buried infrastructure (pipes, wires, storage tanks …)
  - Near surface soil properties and structures
  - Forensics
  - Archaeology

Concluding Thoughts: Planning a Survey

- What do I know about the local physical properties?
- How deep do I need to image?
- What are the dimensions and separations of structures I want to image?



Allows you to pick optimum **grid spacing** and **operating frequency**

Concluding Thoughts: Optimum Frequency

- **Resolution:**

Layers

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

Objects

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

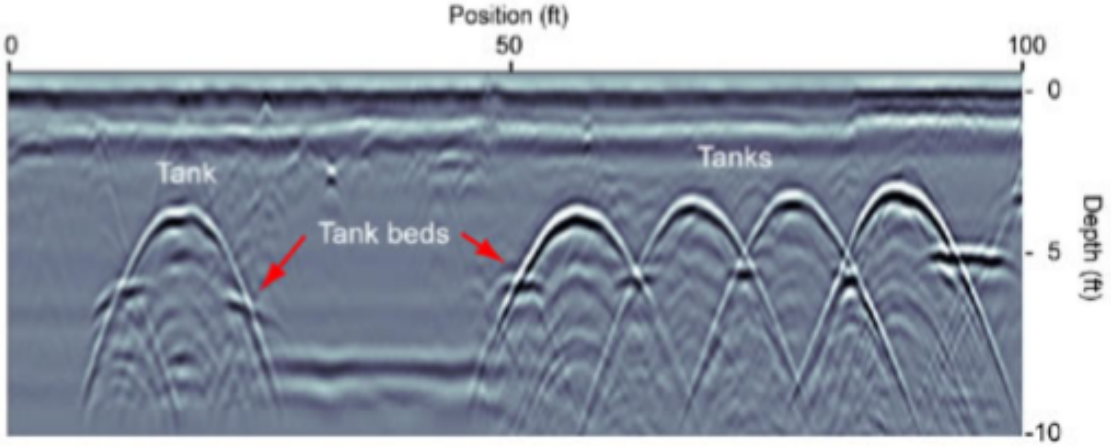
- **Probing Distance:**

$$D = 3\delta \approx \begin{cases} 1510\sqrt{\dfrac{1}{\sigma f}} & \text{for } \omega\varepsilon \ll \sigma \\ 0.0159\dfrac{\sqrt{\varepsilon_r}}{\sigma} & \text{for } \omega\varepsilon \gg \sigma \end{cases}$$

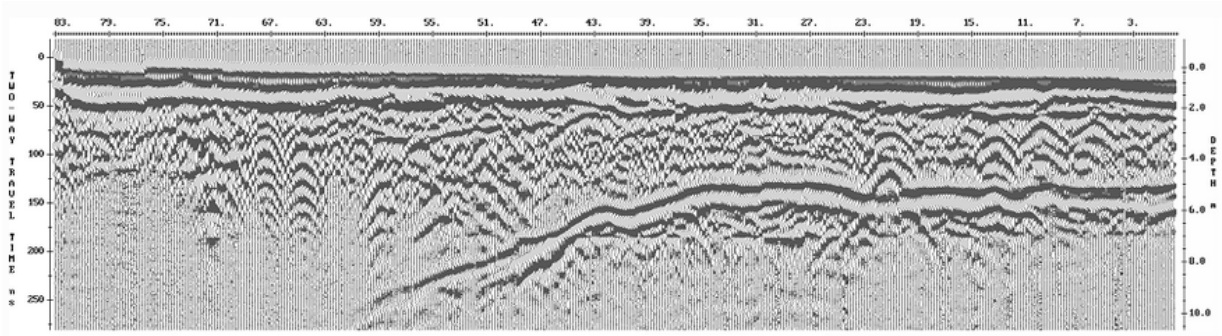
- **Choice in operating frequency is a compromise between resolution and probing distance!!!!**

Concluding Thoughts: What to Look For

Hyperbolas



Linear Features



Geometry can give us layer velocities, location of objects and depths of interfaces.

Questions About GPR?