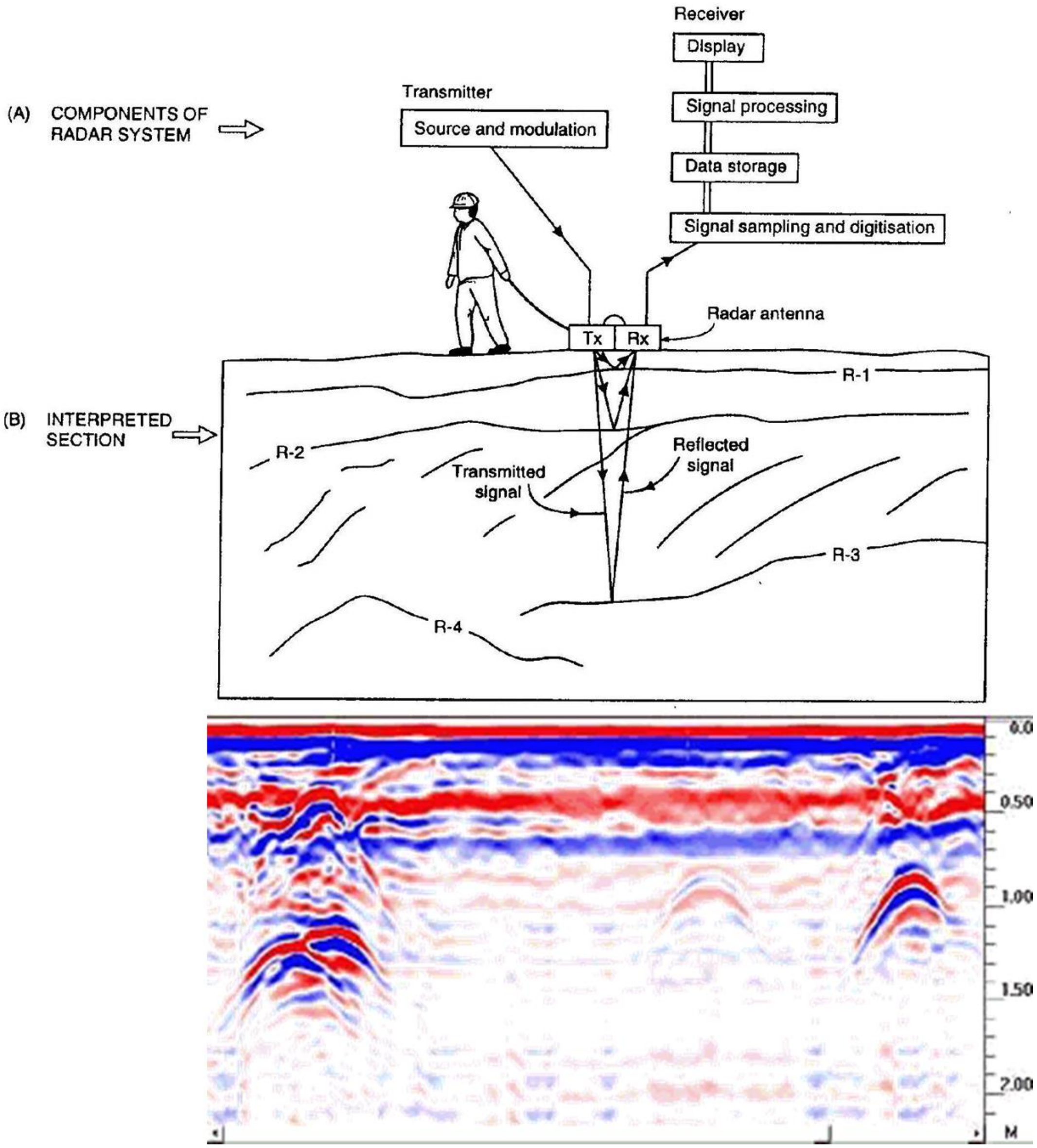
Announcements

- **Quiz:** Friday, October 20th
- **TBL:** Monday, October, 23rd
- **Office Hours:** ESB 4021 after 4:30

Ground Penetrating Radar (day 1)



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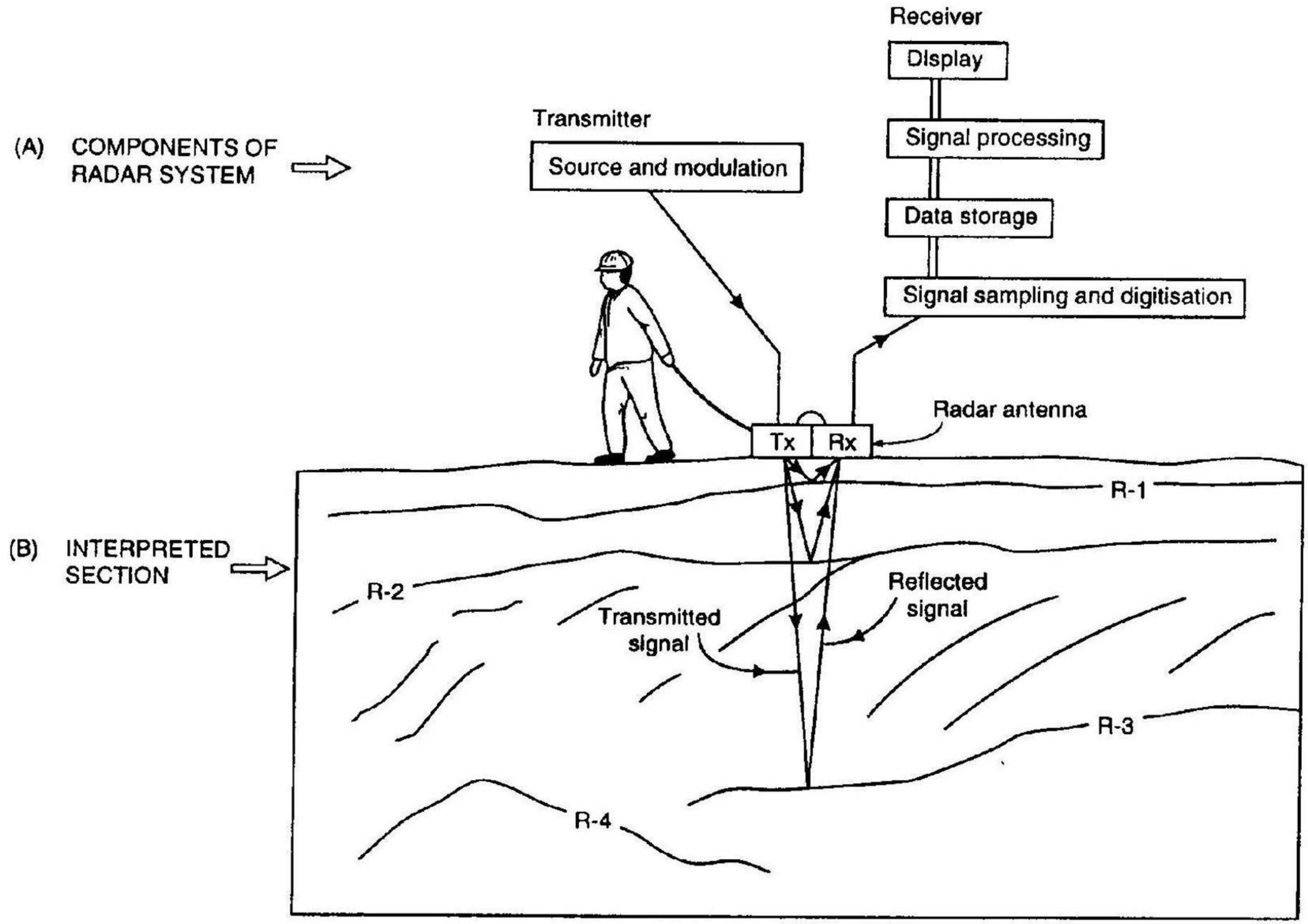
Today's Topics

- 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



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Introduction to GPR

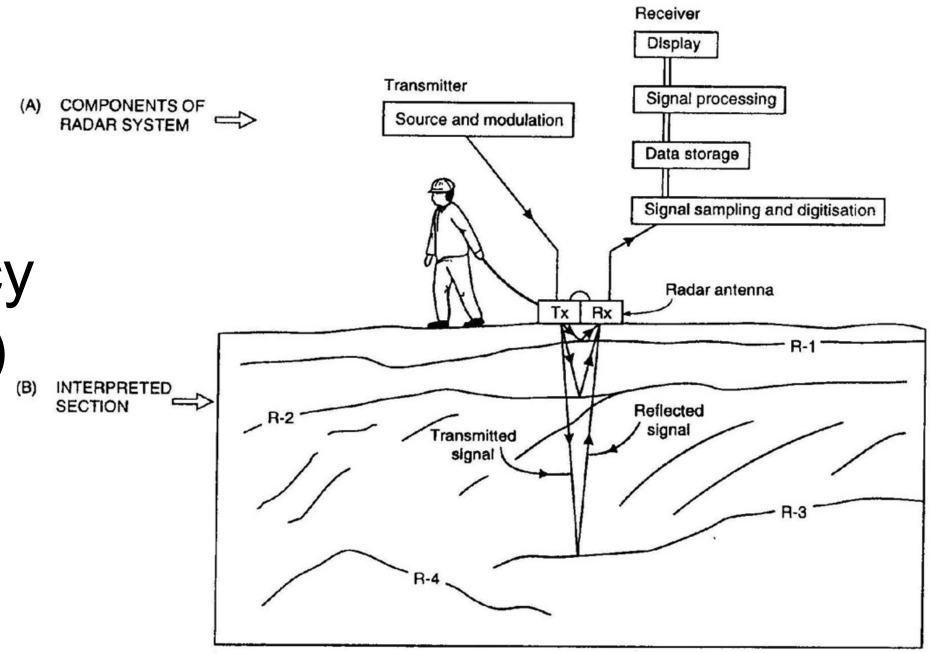
- GPR is an EM method
  (depends on ε, σ, and μ)

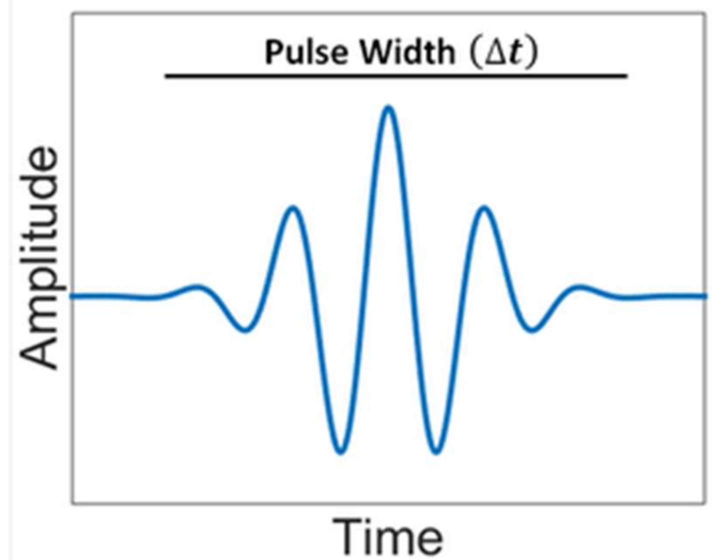
- Uses a pulse of high-frequency radiowaves (10s MHz to GHz)

- Generally shallow surveys
  (10s of metres or less)

- Radiowaves reflect and refract at boundaries
  → Theory very similar to seismic

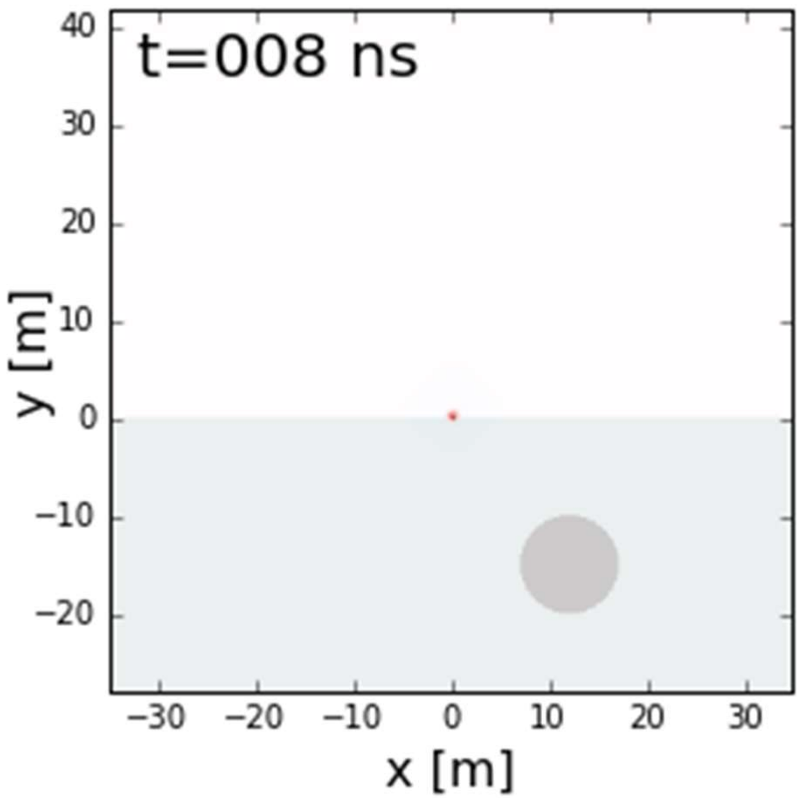
- Radiowave propagation depends on Earth’s EM properties

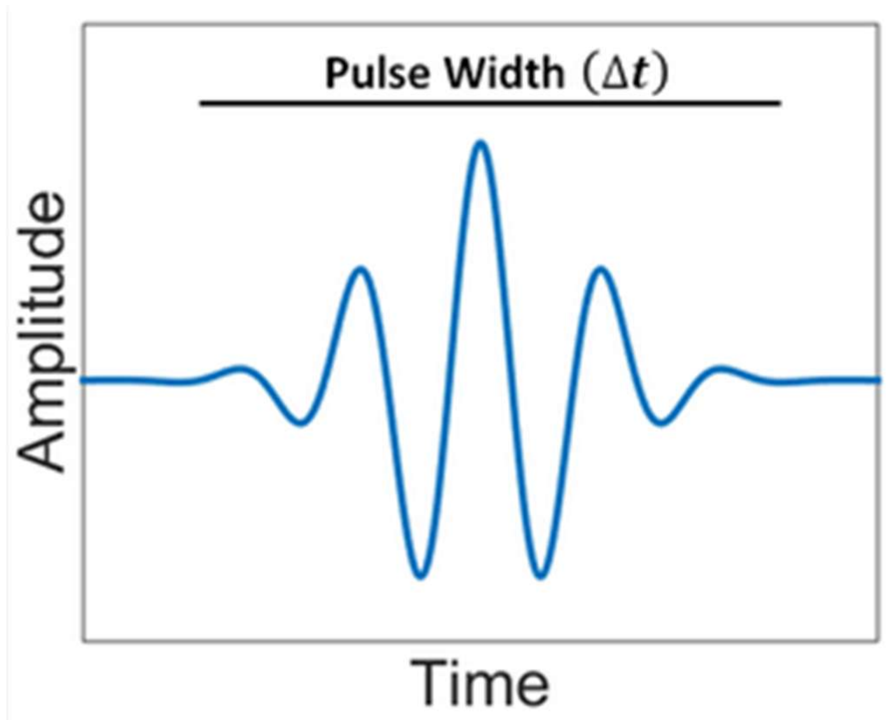




Introduction to GPR: 2D Example

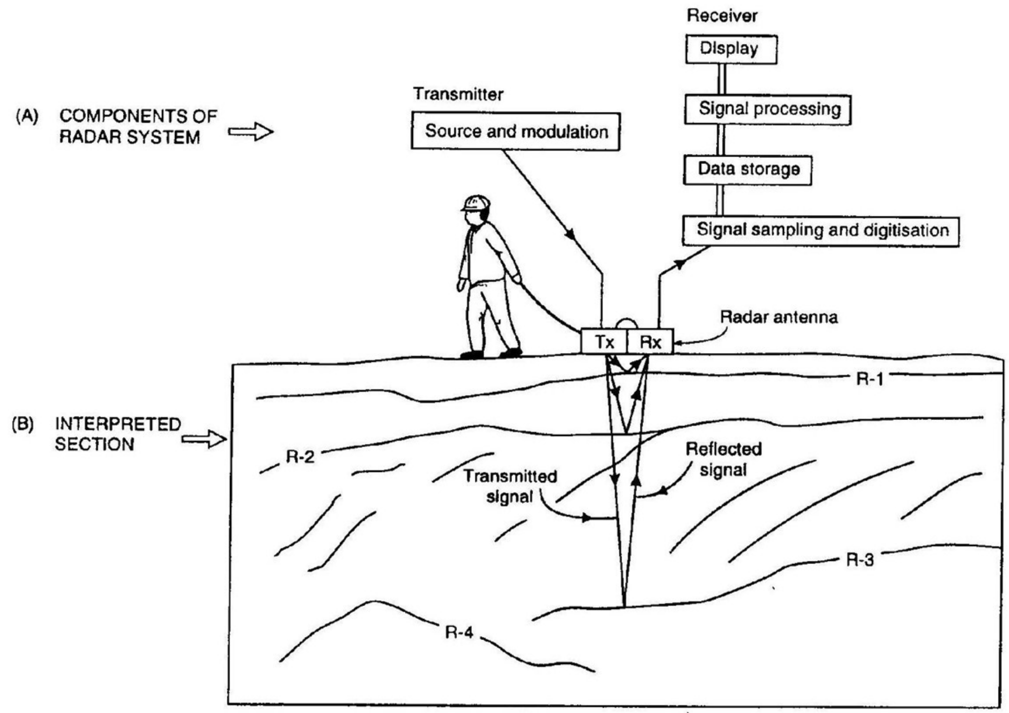
- Sends a **pulse** of waves **not** continuous waves
- What features/behaviours do you see?



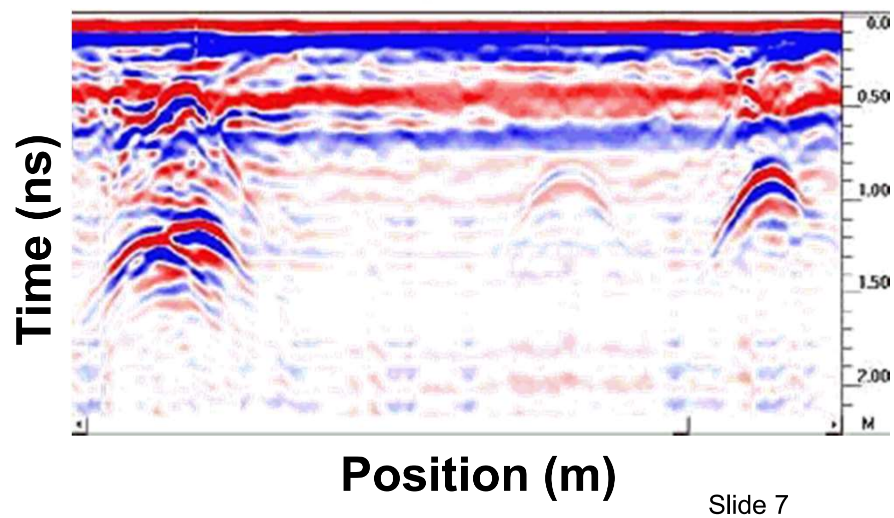


Introduction to GPR

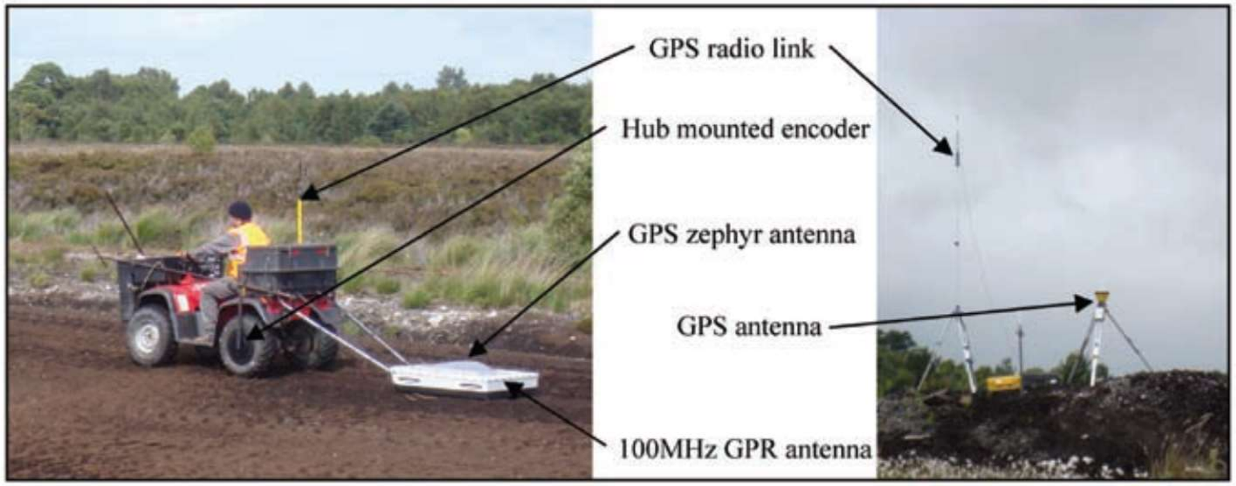
- Returning radiowave signals are measured
- These signals are represented using a **radargram**
- Radargrams essentially seismograms for GPR



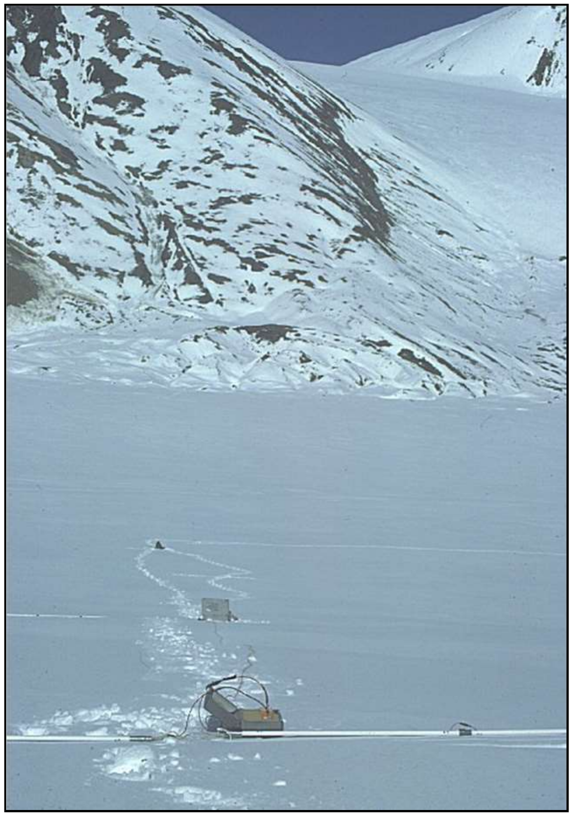
Radargram example



Some Motivational Problems

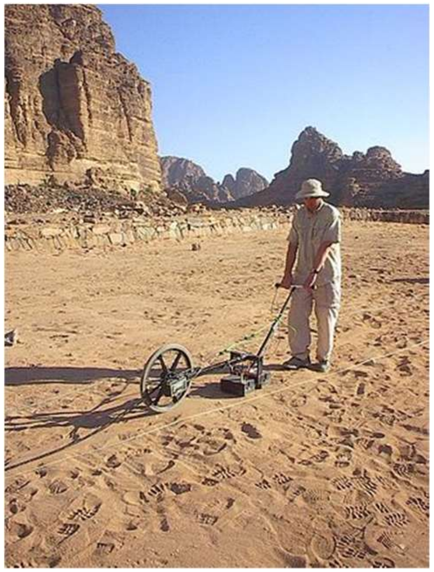


Mapping Peat Thickness (Ireland)



Mapping Ice Thickness (Antarctica)

Urban Geotechnical Problems



Archaelogy (Jordan)

Some Motivational Problems

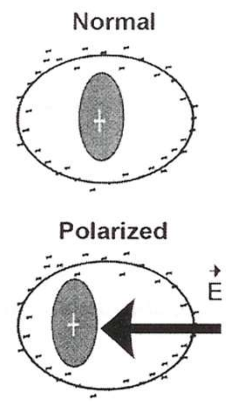
- Looking for buried pipes, objects
- Investigating concrete structures, roads
- Ice/snow: avalanche, search and rescue
- Near surface soil conditions: salinity, saturation
- Geotechnical work (tunnels)
- Forensics
- Archaeology

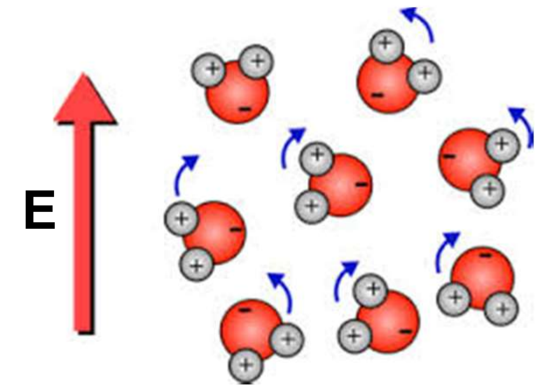
http://sensoft.ca/

Physical Properties

Dielectric Permittivity (ε):

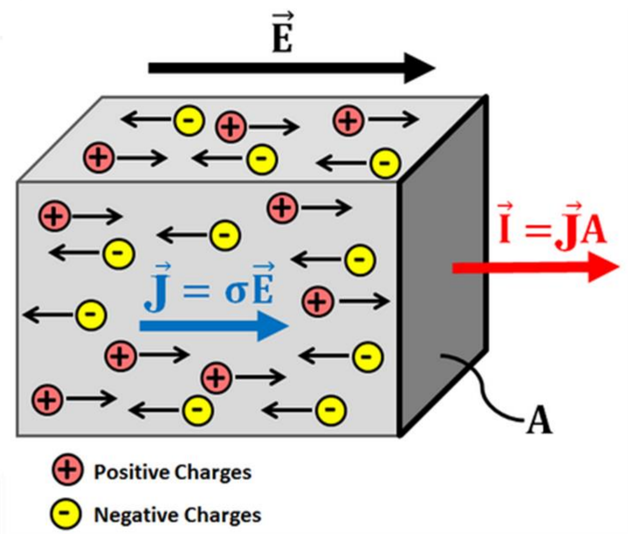
How easily a material is electrically polarized





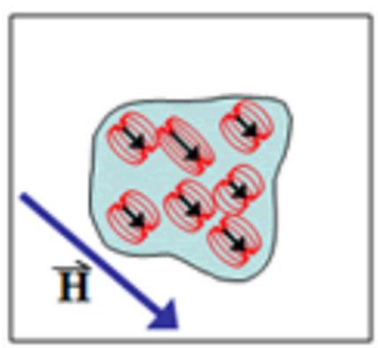
Electrical Conductivity (σ):

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: $\boldsymbol{\varepsilon}$

Relative Permittivity: $\varepsilon_{\mathbf{r}} = \dfrac{\boldsymbol{\varepsilon}}{\boldsymbol{\varepsilon}_{\mathbf{0}}}$

$$\varepsilon_{\mathbf{0}} = 8.85 \times 10^{-12}\ \mathrm{F/m}$$

$$\mathbf{1} \le \boldsymbol{\varepsilon_r} \le \mathbf{80}$$

Magnetic Permeability: $\boldsymbol{\mu}$

Relative Permeability: $\boldsymbol{\mu}_{\mathbf{r}} = \dfrac{\boldsymbol{\mu}}{\boldsymbol{\mu}_{\mathbf{0}}}$

$$\boldsymbol{\mu}_{\mathbf{0}} = 1.26 \times 10^{-6}\ \mathrm{H/m}$$

Physical Properties

Dielectric Permittivity: $\boldsymbol{\varepsilon}$

Relative Permittivity: $\boxed{\varepsilon_{\mathbf{r}} = \dfrac{\boldsymbol{\varepsilon}}{\boldsymbol{\varepsilon}_{\mathbf{0}}}}$

$$\varepsilon_{\mathbf{0}} = 8.85 \times 10^{-12}\ \mathrm{F/m}$$

$$\boxed{\mathbf{1} \le \boldsymbol{\varepsilon_r} \le \mathbf{80}}$$

Magnetic Permeability: $\boldsymbol{\mu}$

Relative Permeability: $\boldsymbol{\mu}_{\mathbf{r}} = \dfrac{\boldsymbol{\mu}}{\boldsymbol{\mu}_{\mathbf{0}}}$

$$\boldsymbol{\mu}_{\mathbf{0}} = 1.26 \times 10^{-6}\ \mathrm{H/m}$$

$$\boxed{\boldsymbol{\mu}_{\mathbf{r}} = \mathbf{1}}$$

Dielectric Permittivity and Radiowaves

- Water has strongest effect on ε in geologic materials.
- **<u>Velocity</u>** 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

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

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

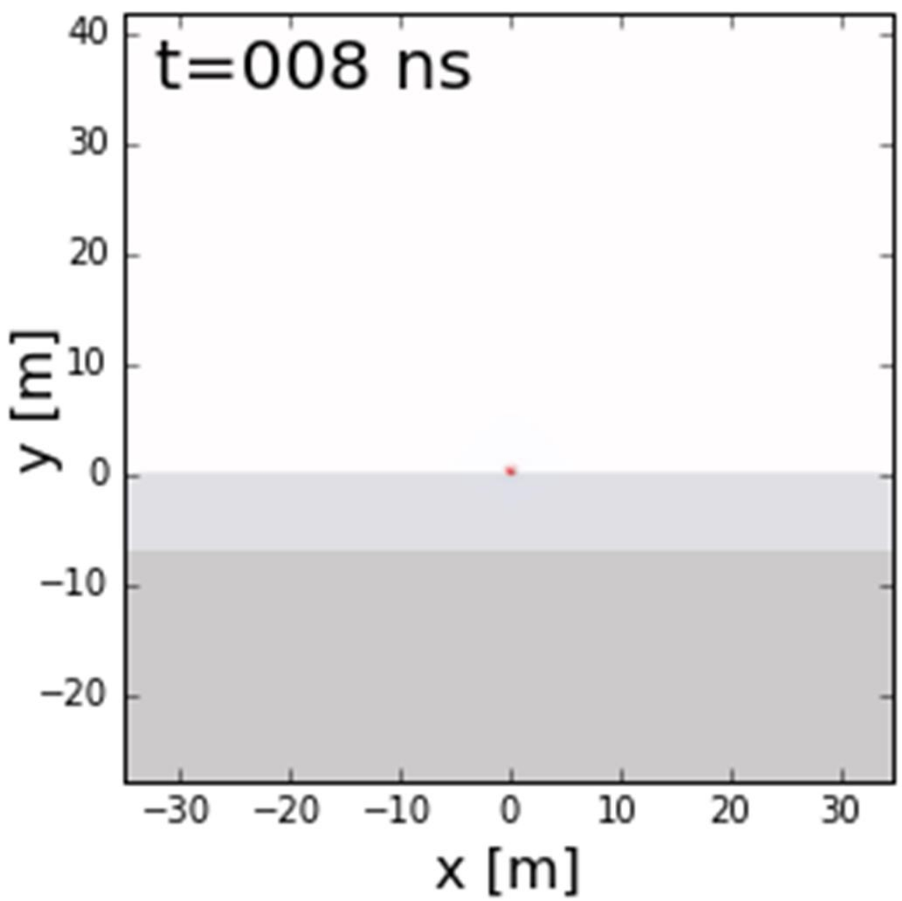
$$c = 0.3 m/ns$$

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0}$$

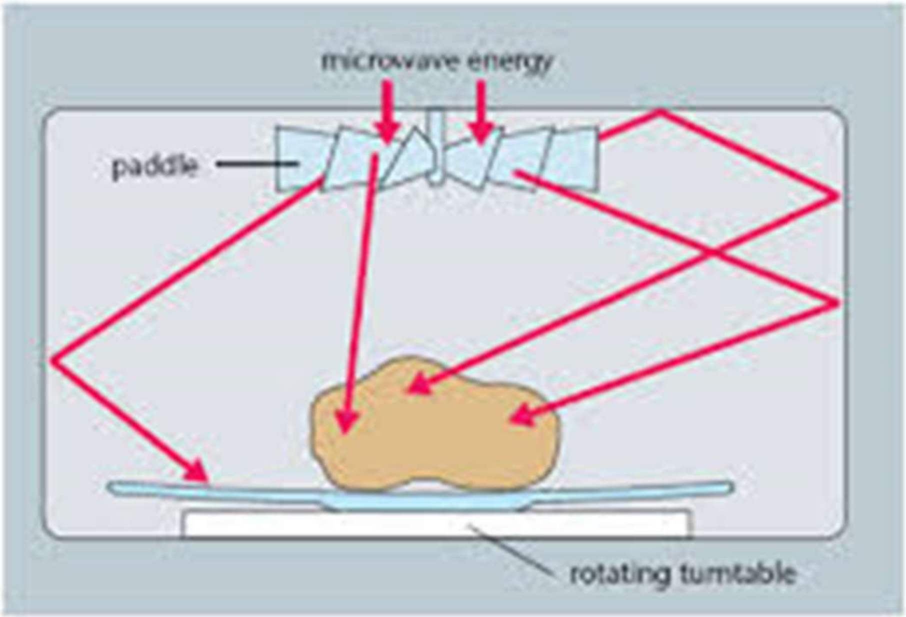
Introduction to GPR: 2D Example

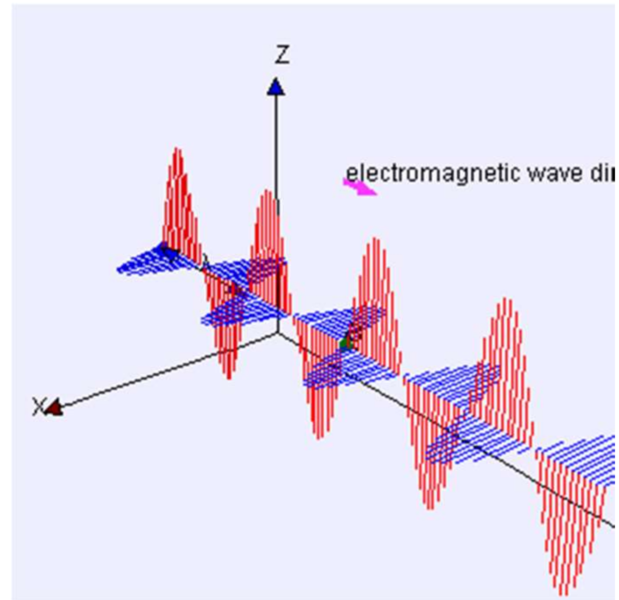
- What has faster propagation velocity?
- What has larger dielectric permittivity?

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



Microwave Oven Example



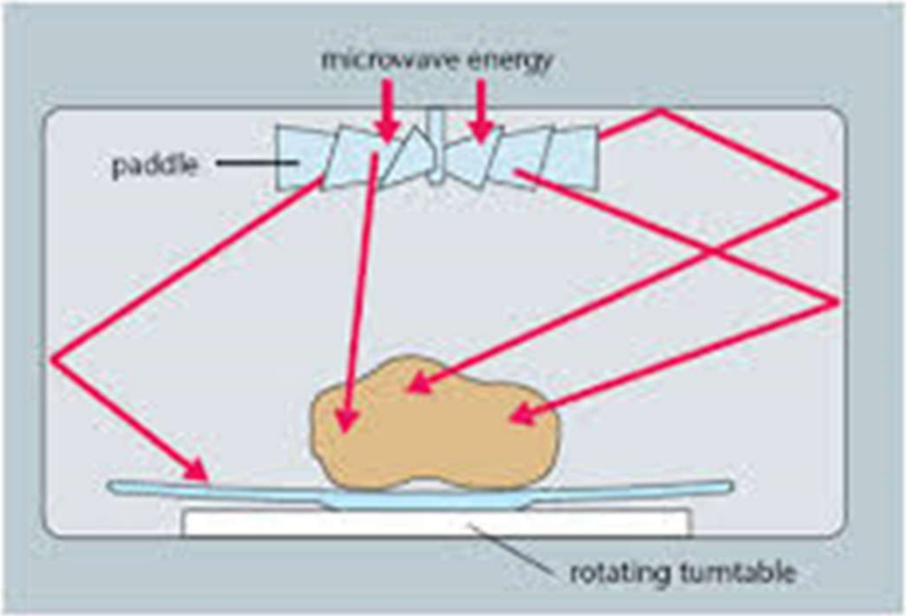


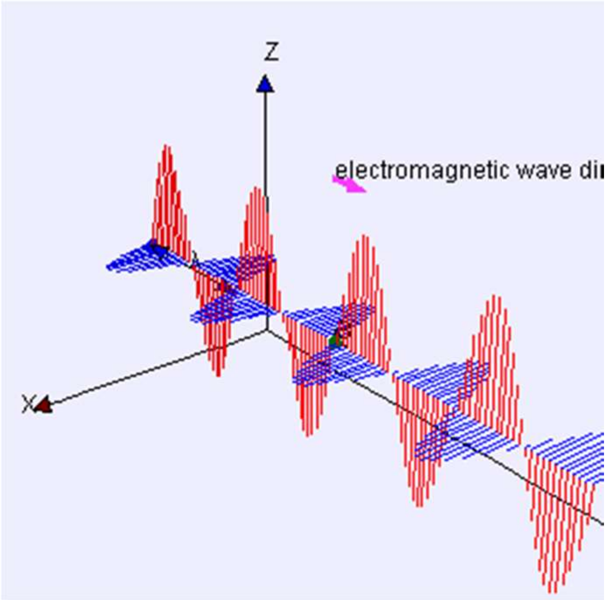
- Radiowaves and microwaves support oscillating electric and magnetic fields (why ε,σ and μ are all significant)

- Microwaves use very high frequencies (~ 2.45 GHz)

- Wavelength: $\mathbf{L} = \frac{c}{f} = \frac{3.00 \times 10^{8}\ m/s}{2.45 \times 10^{9}\ s} \approx 12\ cm$

Microwave Oven Example

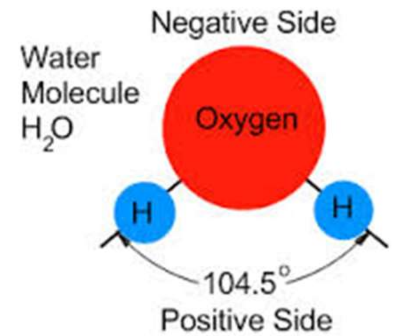




- Microwaves (and radiowaves) reflect off conductive walls
- Microwaves (and radiowaves) don't interact with plastic turntable
- Microwaves energy absorbed by water in food

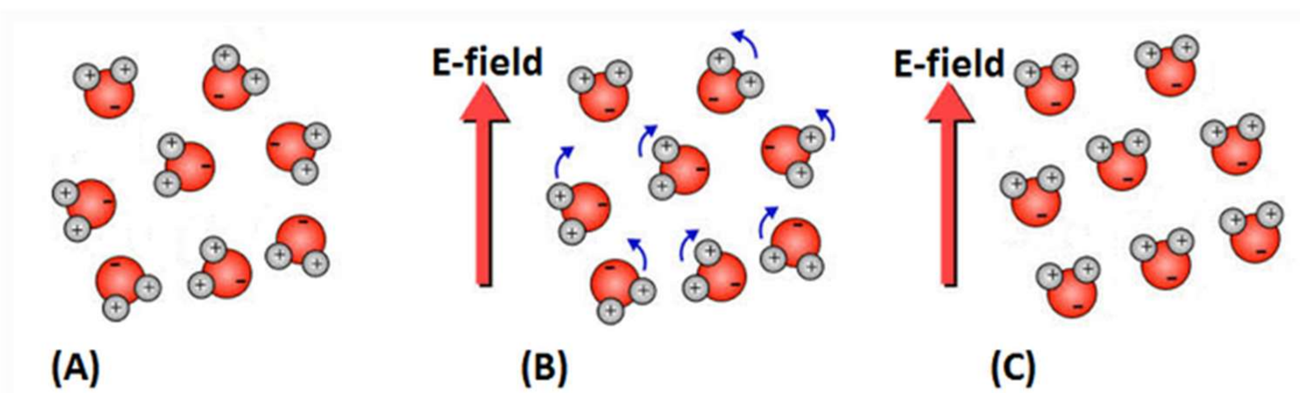
Microwave Oven Example

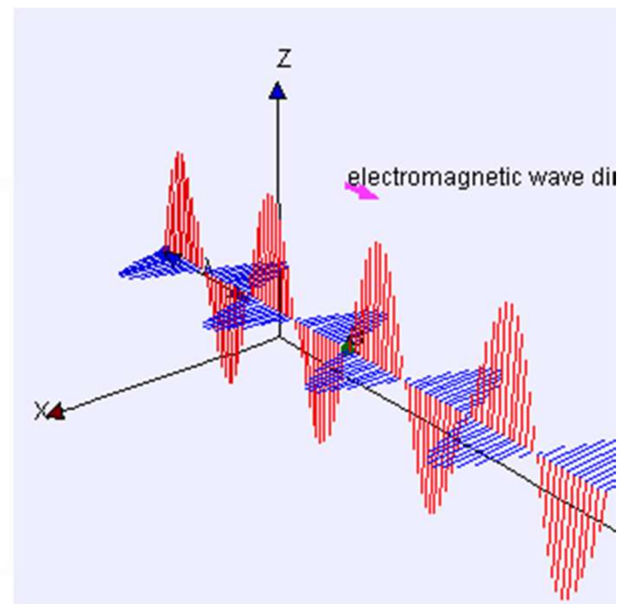
- Water molecules are naturally polarized



- 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!!!)





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The Magic of Microwave Ovens

1. Microwaves reach food

2. Microwaves cause rapid re-orientation of water molecules in food (because of ε_r)

3. 2.45 GHz is the resonance frequency for water
   $\rightarrow$ 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?

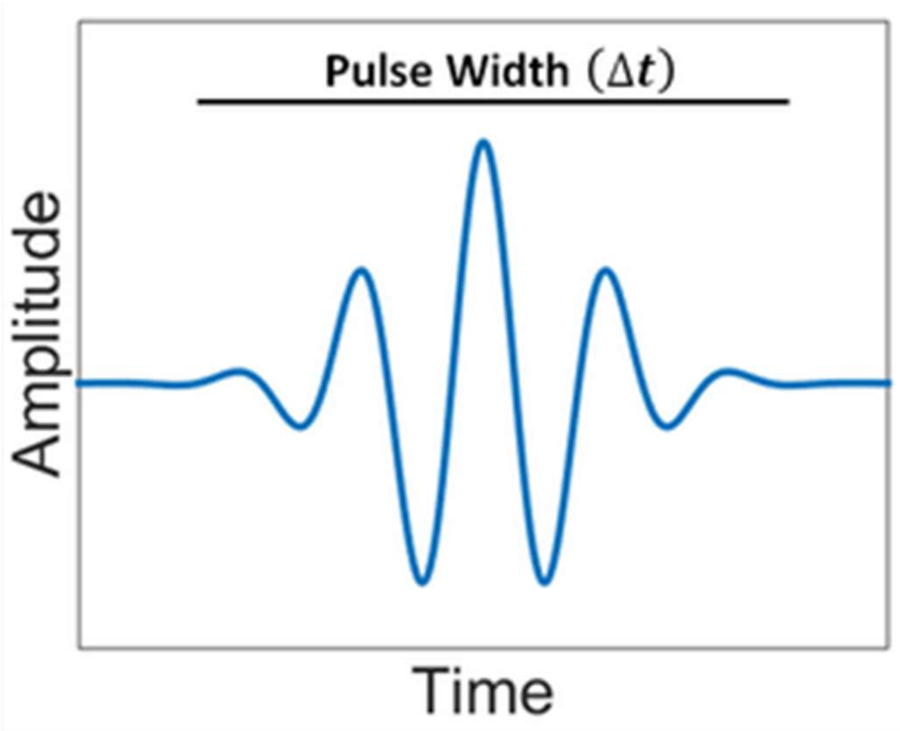
Q: What is the diagnostic physical property for GPR?

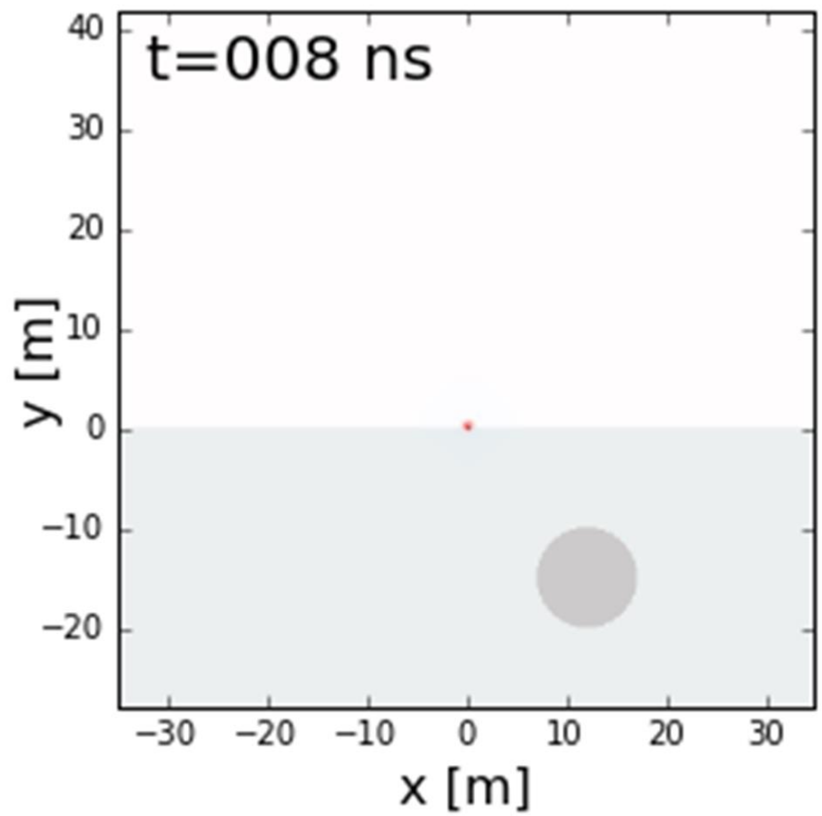
Q: What impacts this physical property the most?

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

Radiowave Propagation

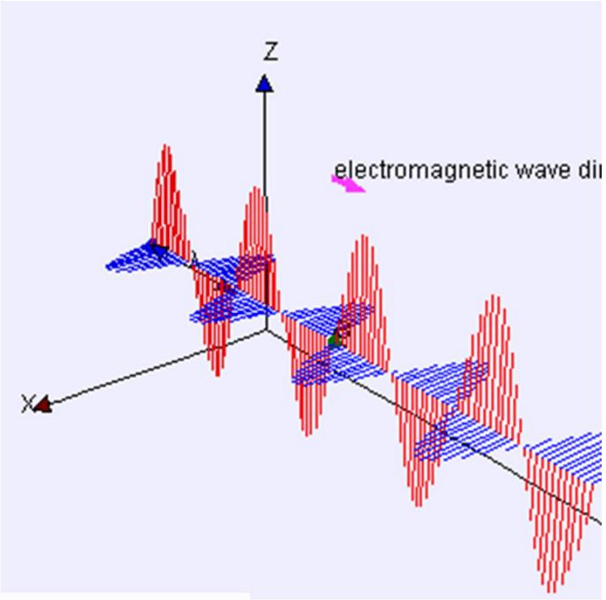
- GPR sends a **pulse** of EM waves. **Not continuous!**





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

Radiowave Propagation



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

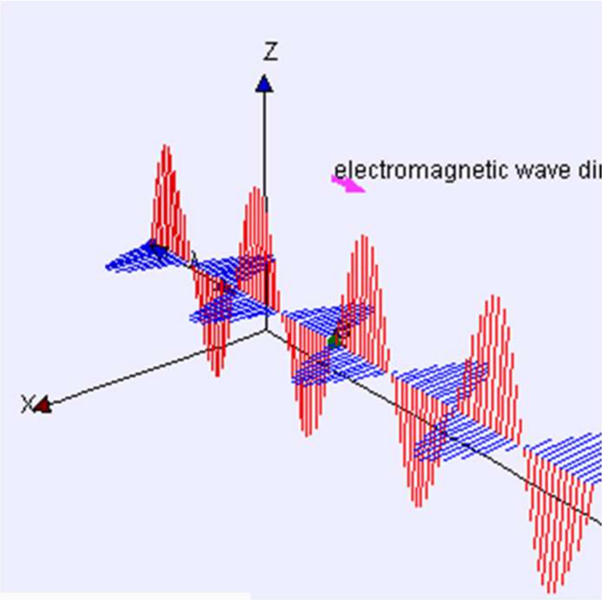
- EM waves move through
  different materials at different speeds

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

Radiowave Propagation



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Radiowave Propagation

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Fresh water	80	0.5	0.033
Sea water	80	**3000**	**0.01**
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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**

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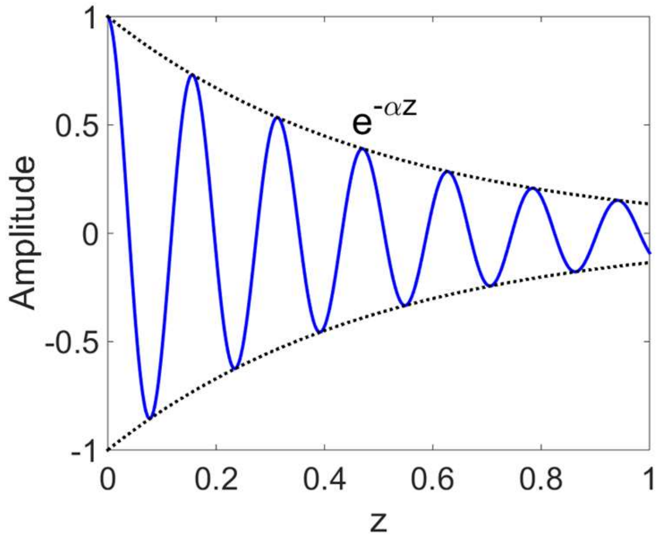
Radiowave Propagation

- 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

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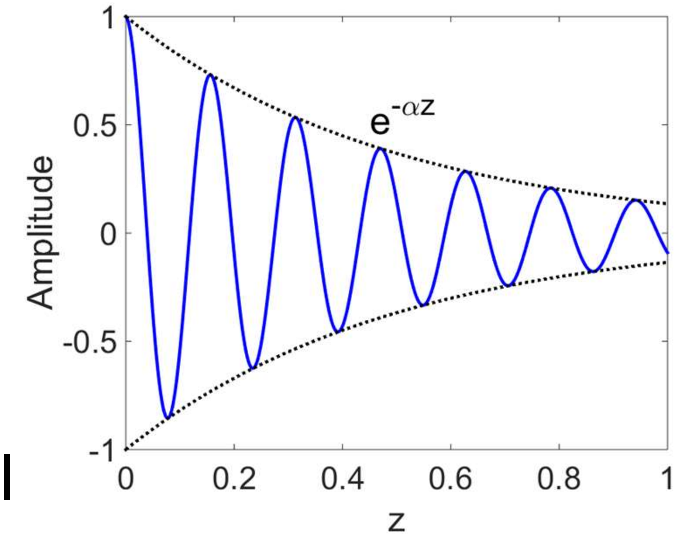

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Radiowave Attenuation

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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

- Radiowaves attenuate quickly if conductivity is large

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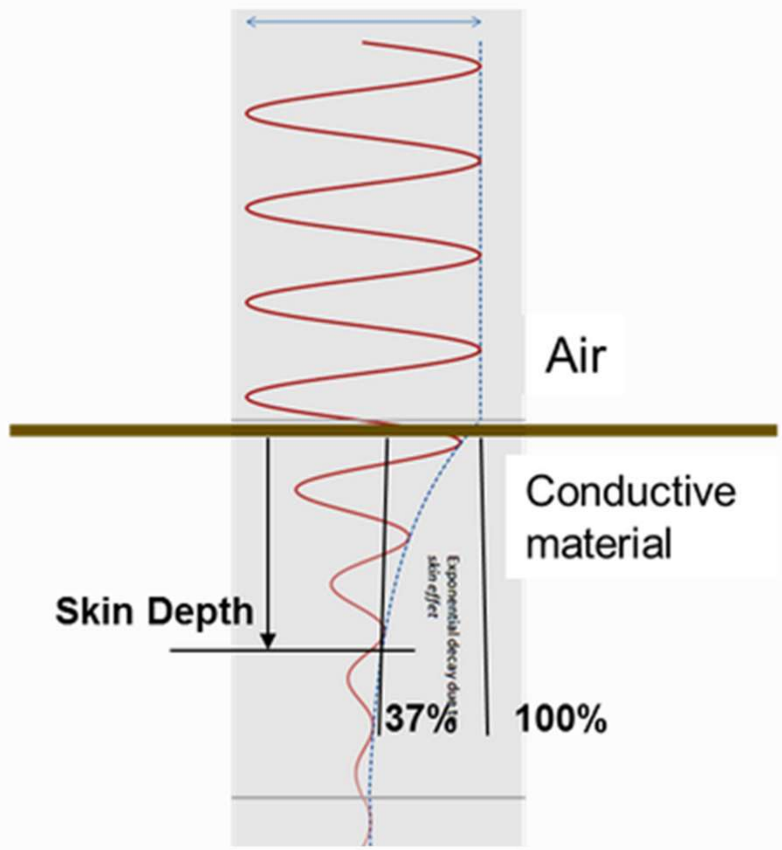
Radiowave Attenuation: Skin Depth

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

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

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



- 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

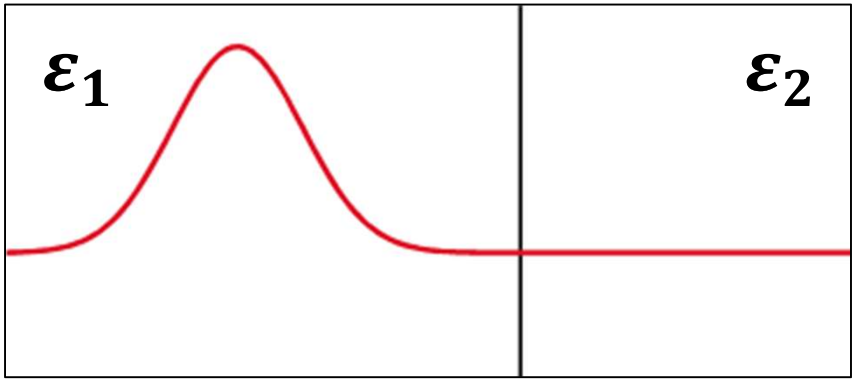
Q: What happens to wave amplitude as it propagates?

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

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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

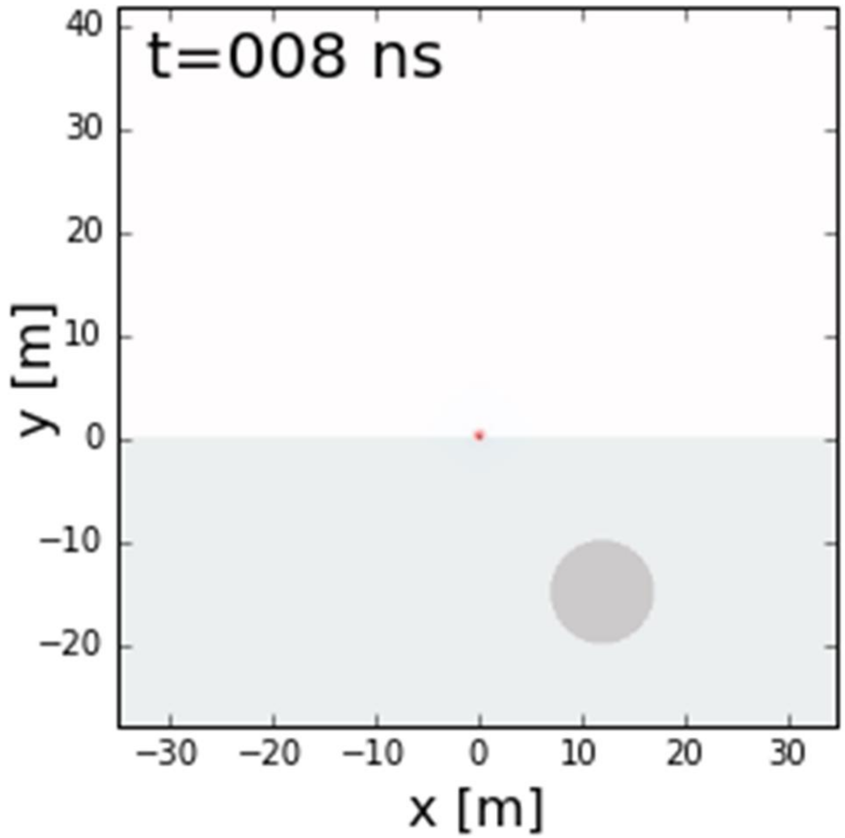
Reflection from Conductors

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

- 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?



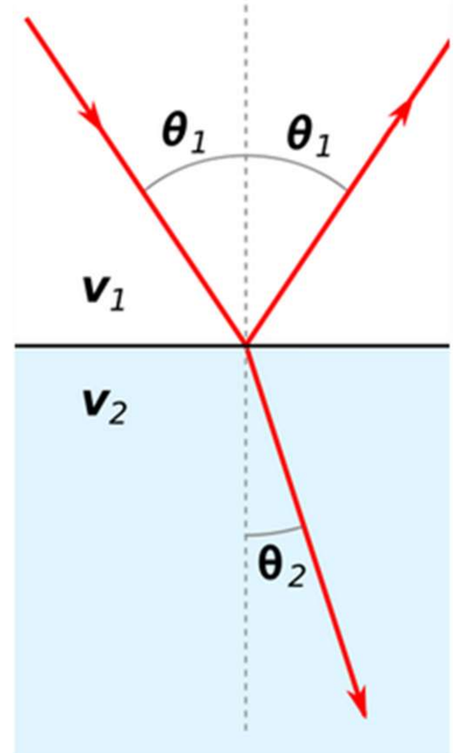
Refraction

- Snell's Law:

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

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

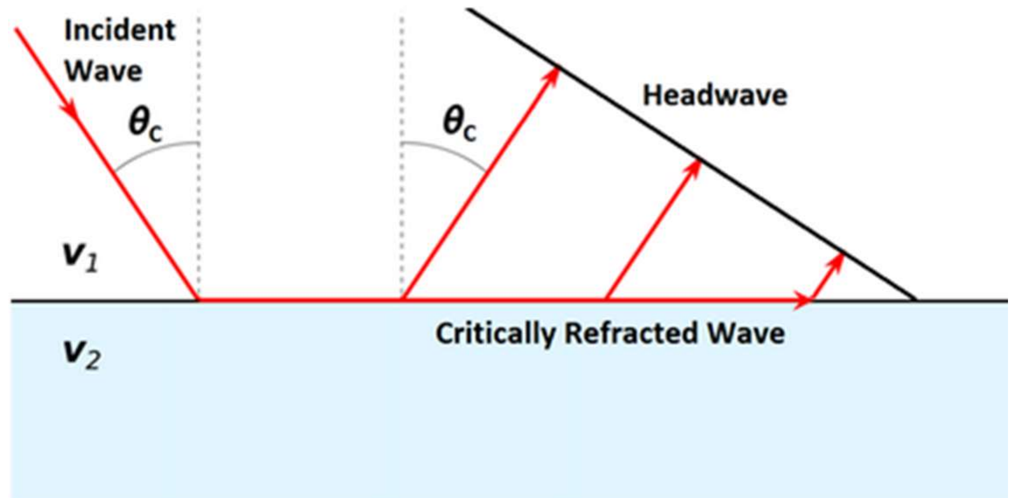
$$\sqrt{\varepsilon_1}\,\sin\theta_1 = \sqrt{\varepsilon_2}\,\sin\theta_2$$



Critical Refraction

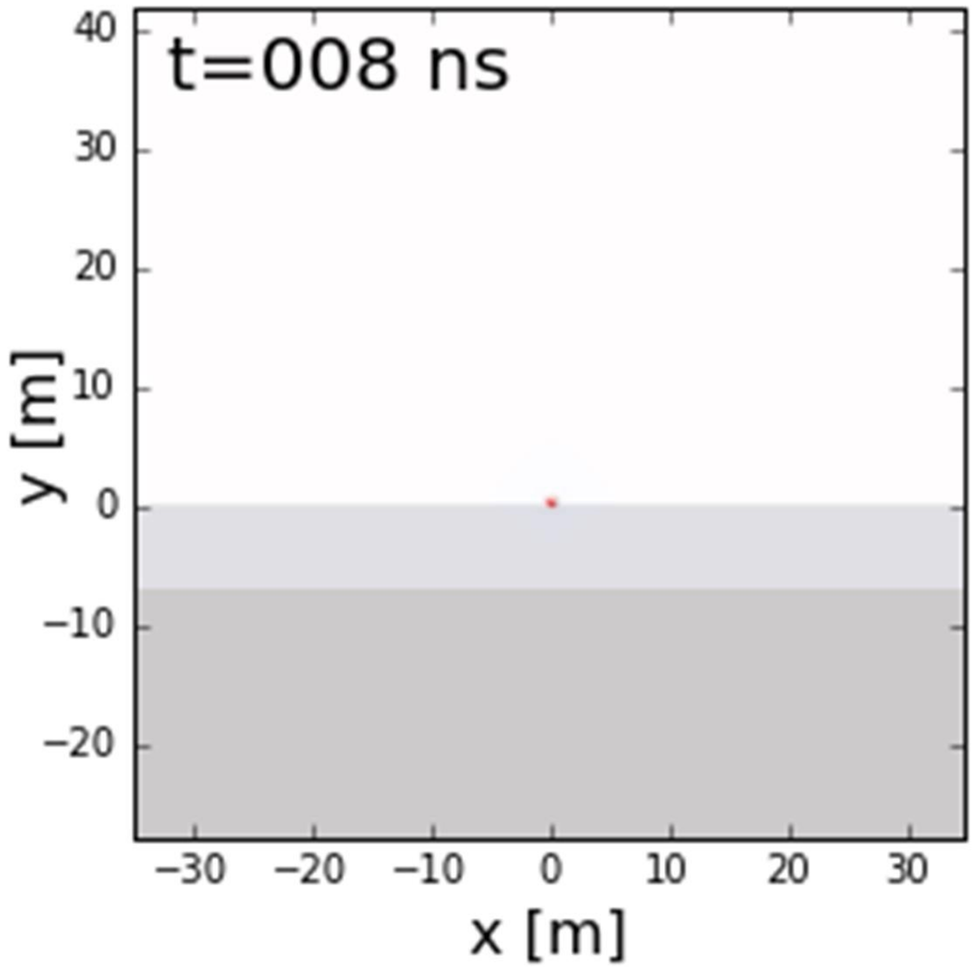
$$\sin\theta_c = \frac{V_1}{V_2}$$

Requires $V_1 < V_2$.



Refraction

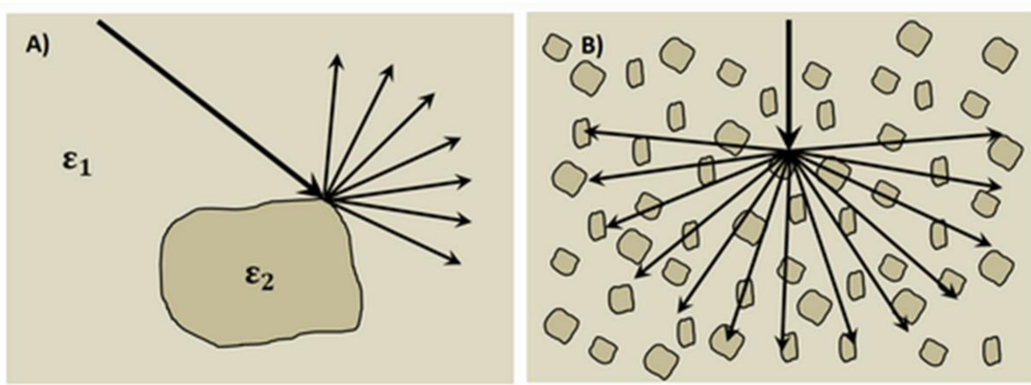
- Can we see any refraction?

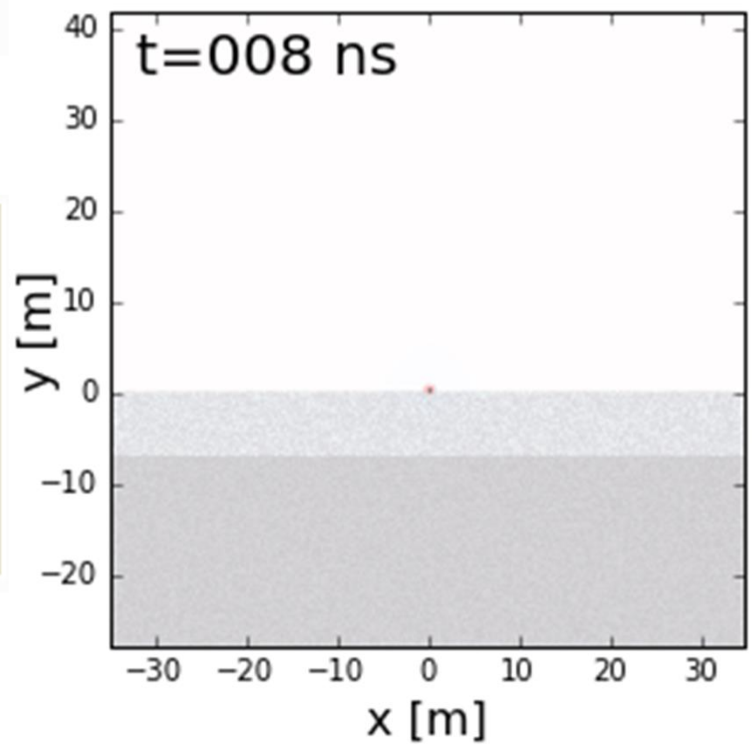


Scattering

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





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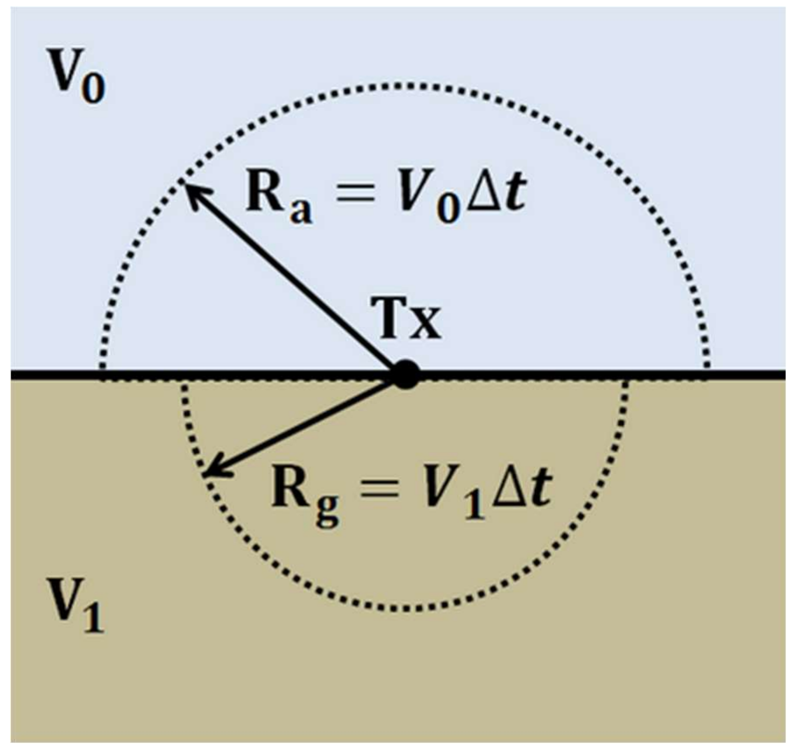
Geometrical Spreading

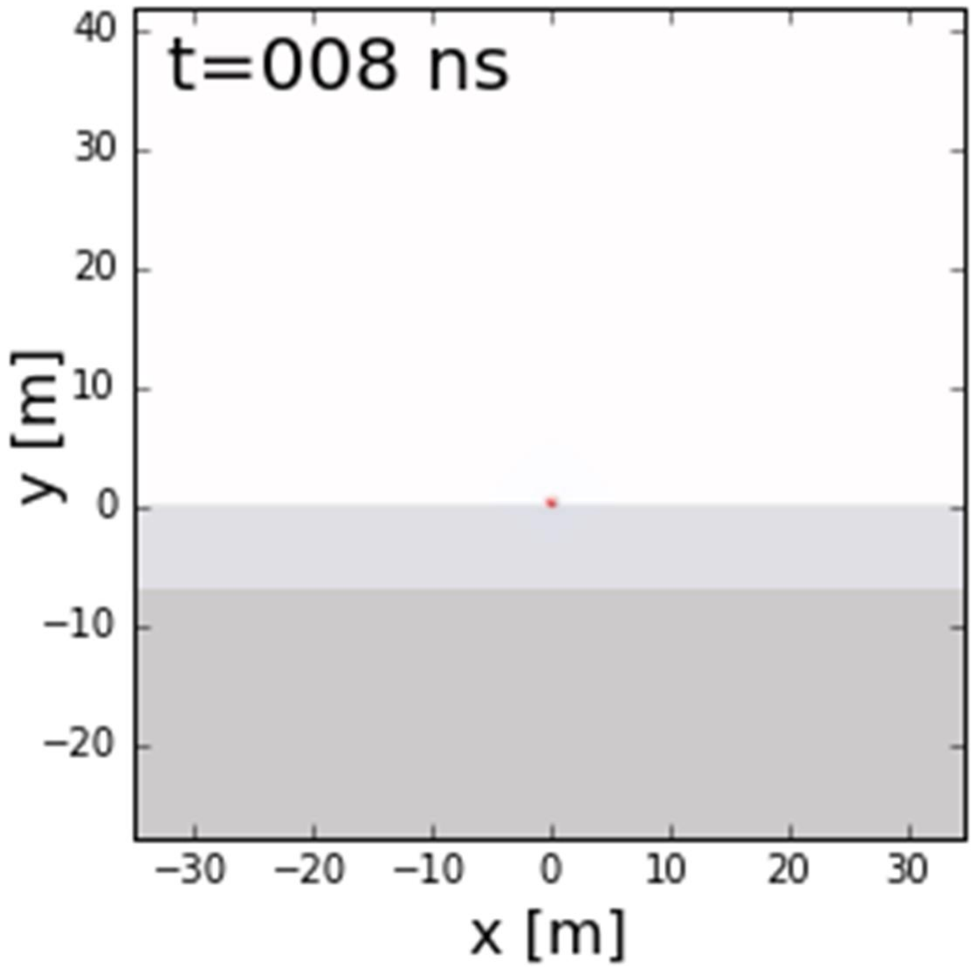
- As the wave front travels, it spreads geometrically
- The rate of geometrical spreading depends on the velocity
- Spreading causes the radiowave to lose amplitude

$$\frac{|\mathbf{A}|}{|\mathbf{A}_0|} \propto \frac{1}{R}$$



Geometrical Spreading

- Can we see geometrical spreading?



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:

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

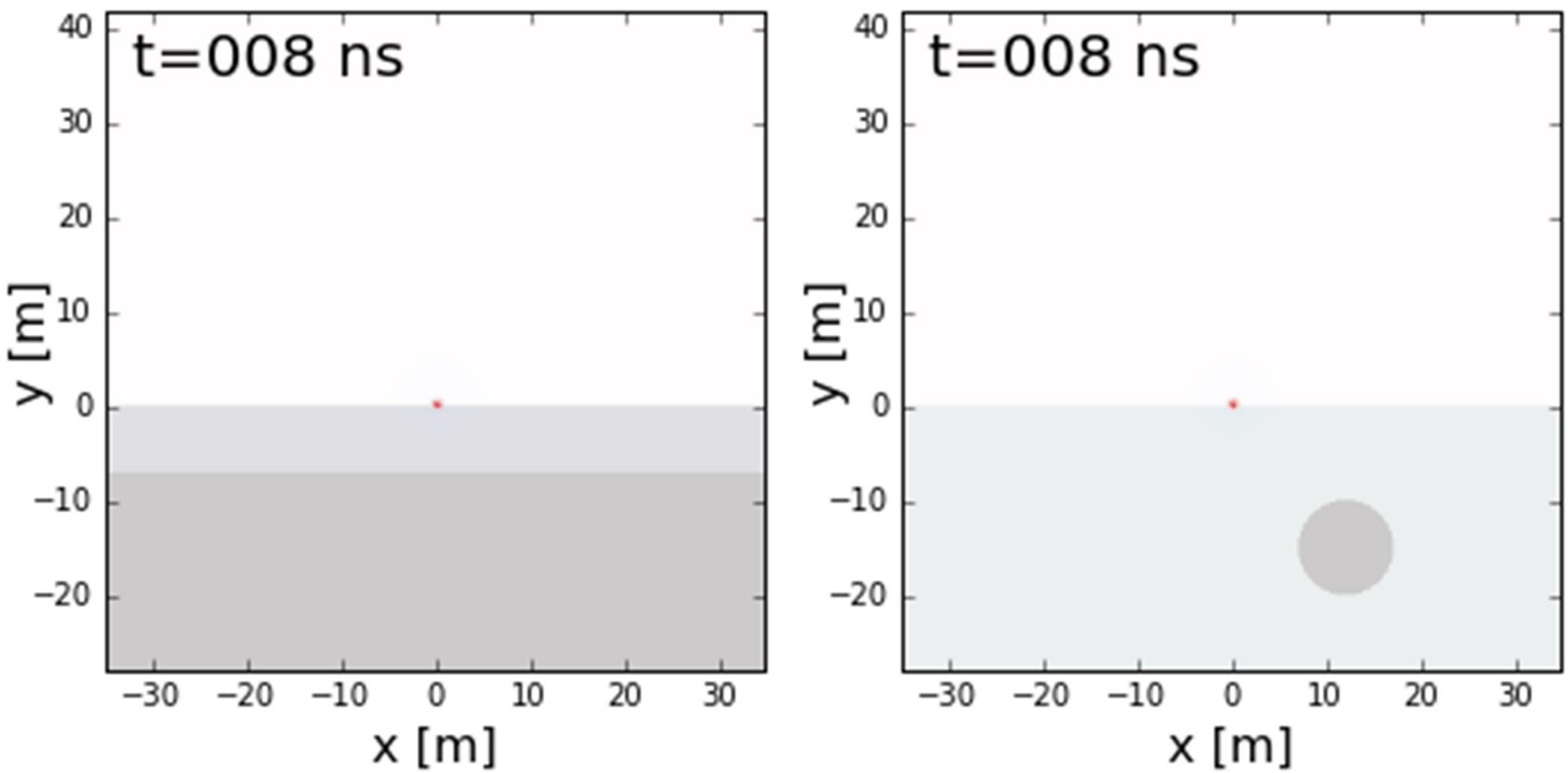
$$\sqrt{\varepsilon_1}\sin\theta_1 = \sqrt{\varepsilon_2}\sin\theta_2$$

Questions Recap

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

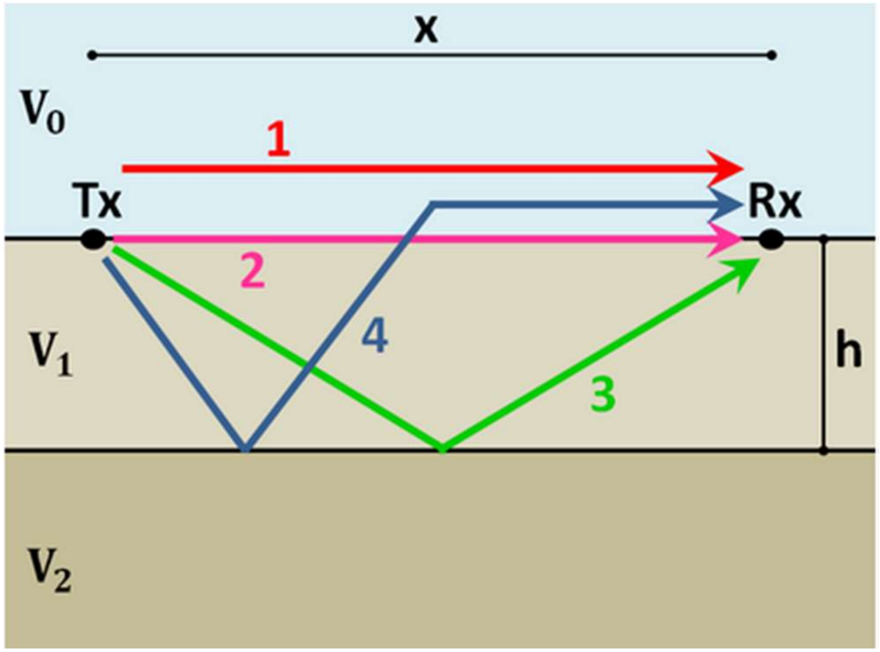
Q: Why is scattering an issue?

Ray Path vs. Wavefront

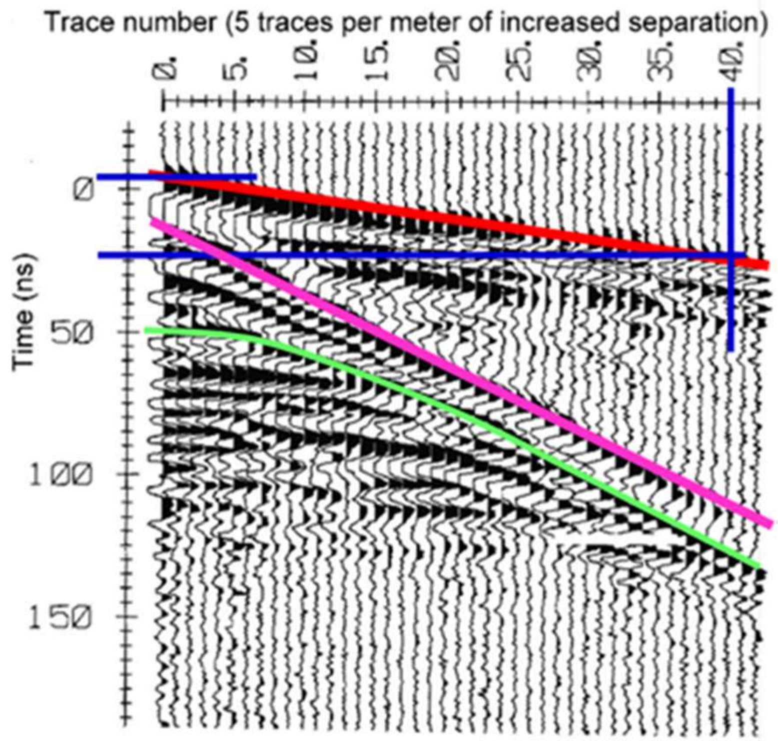


2-Layer Example

Model

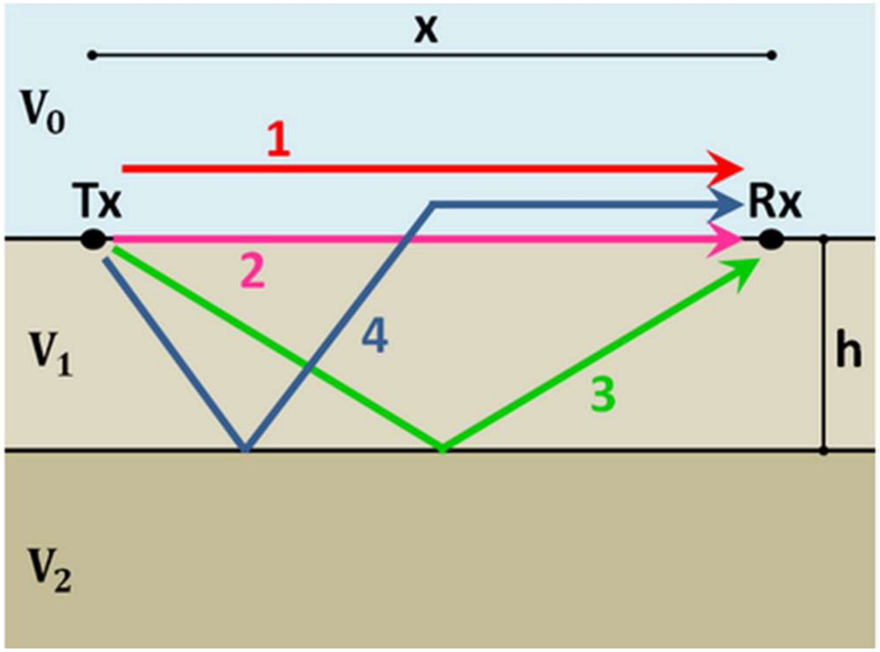


Radargram

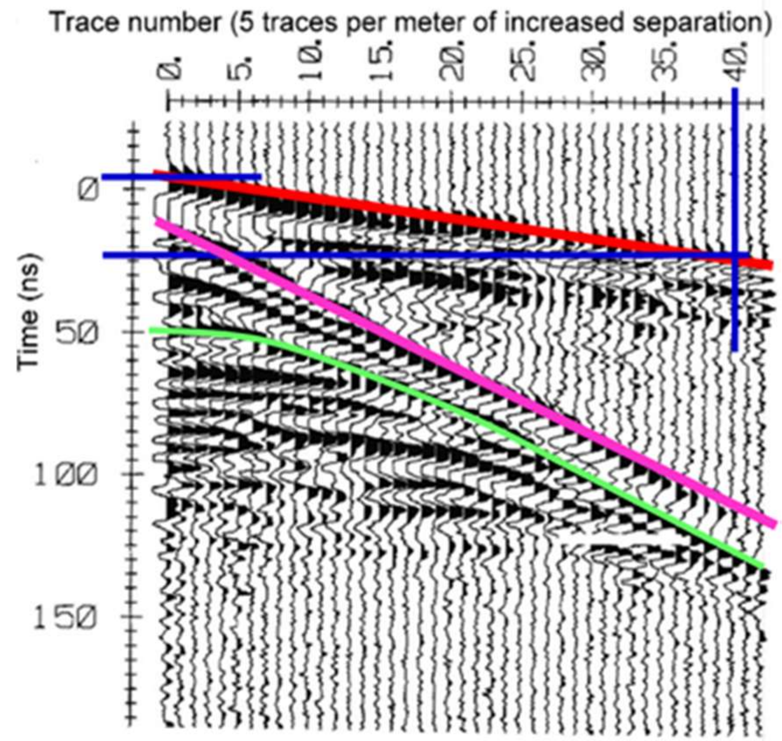


2-Layer Example

Model



Radargram



1) Direct Air Wave

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

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

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

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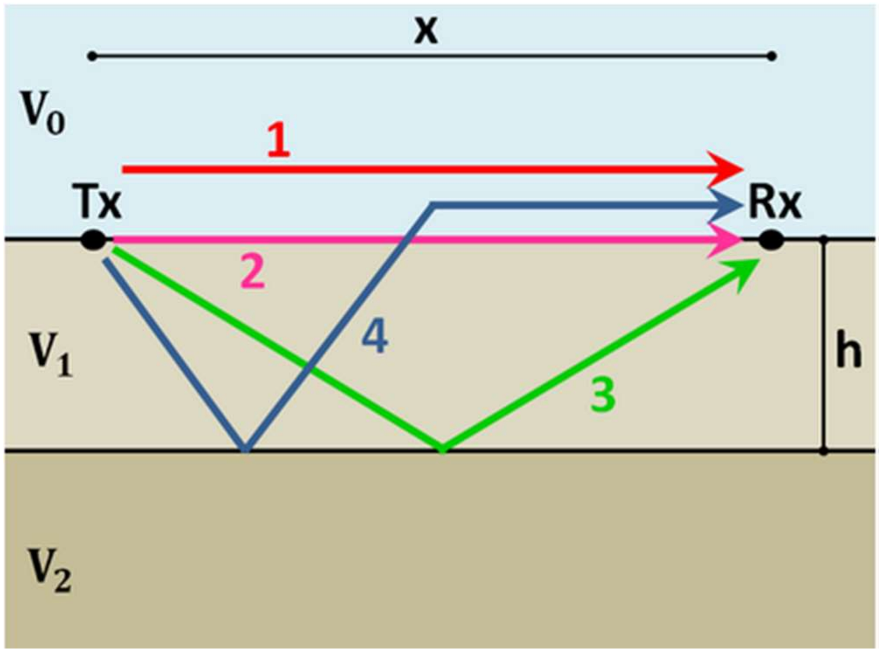
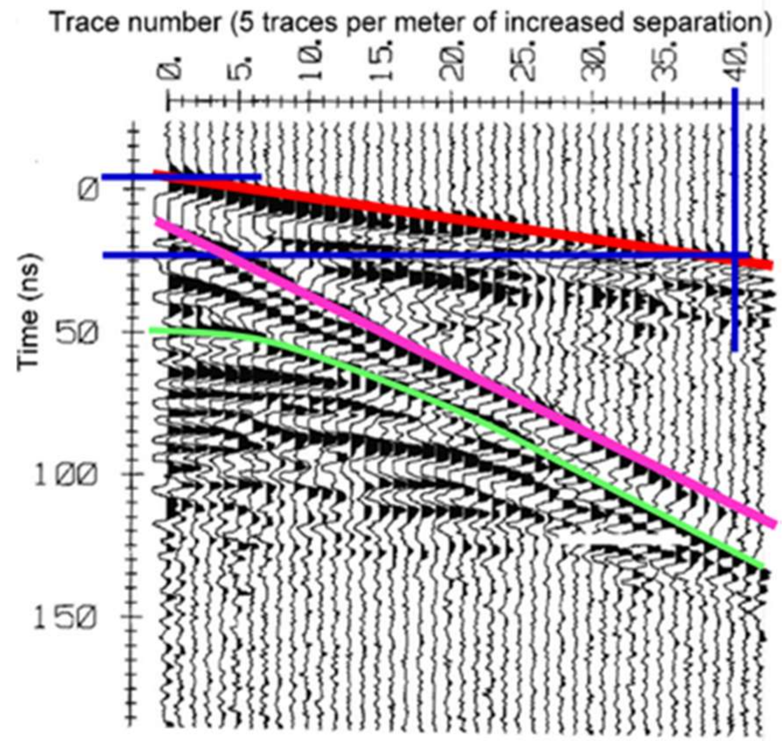
2-Layer Example

Model



Radargram



2) Direct Ground Wave

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

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

$$V_1 < c,$$

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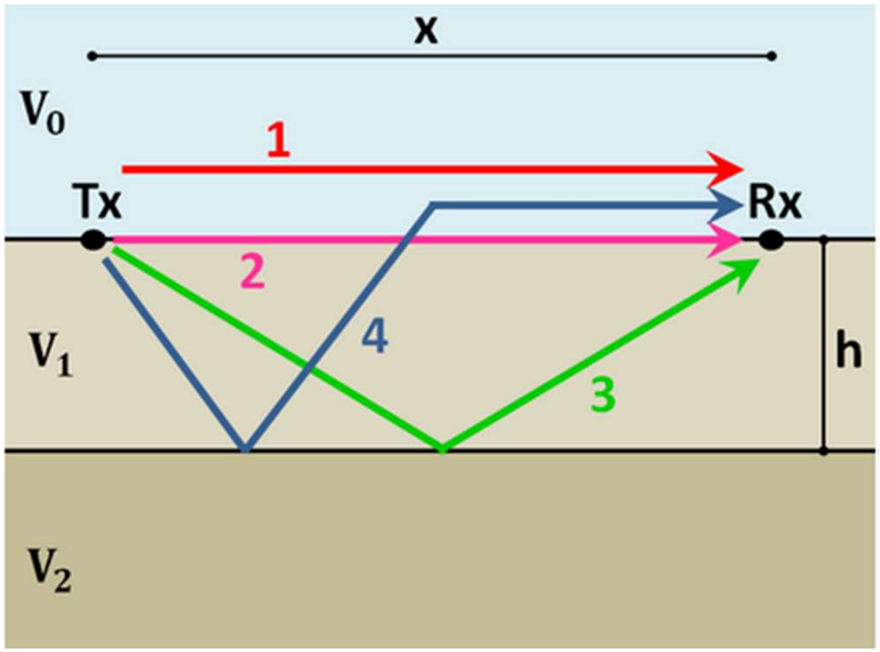
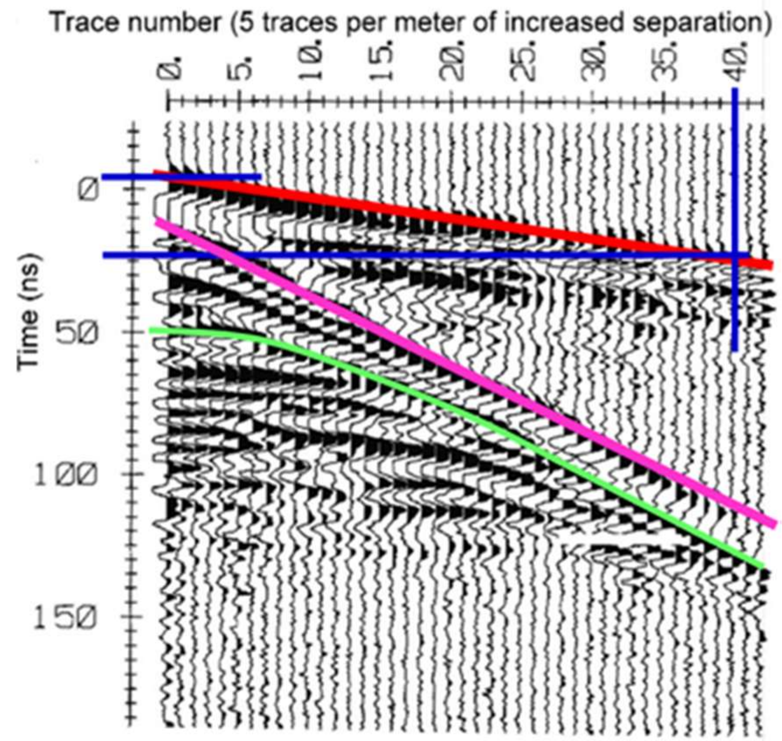
2-Layer Example

Model



Radargram



3) Reflected Wave

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

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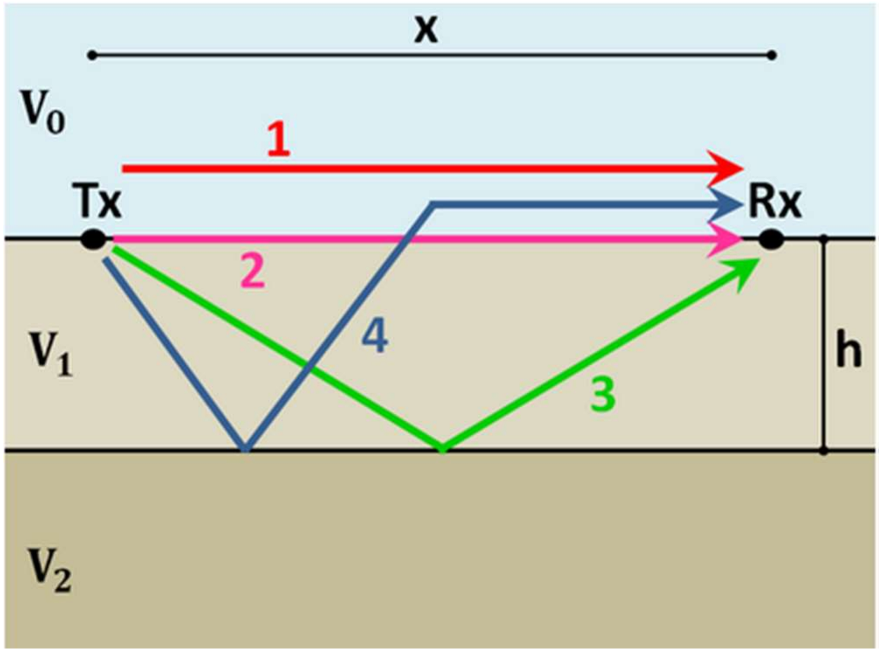
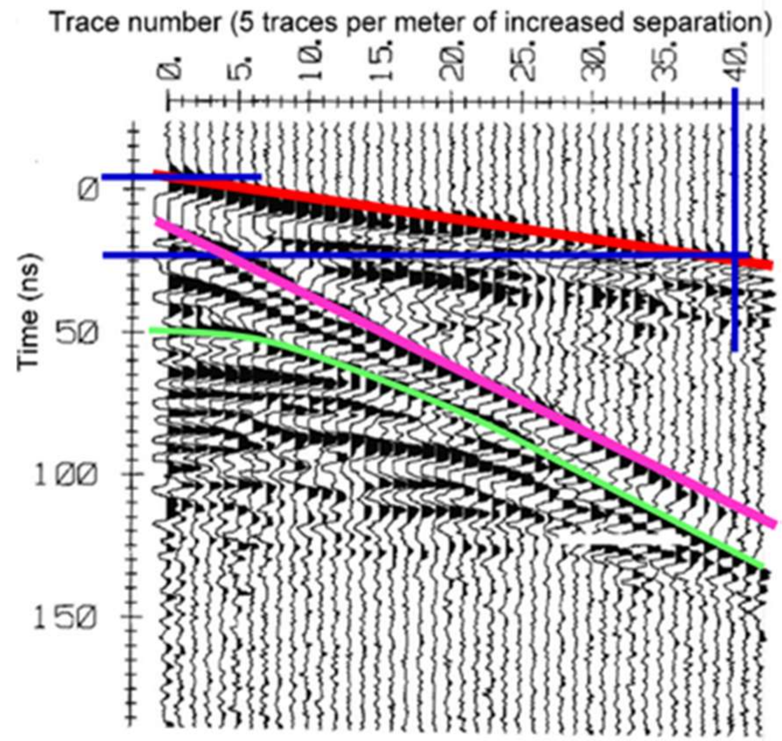
2-Layer Example

Model



Radargram



4) Refracted Wave

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

$V_1 < V_0$

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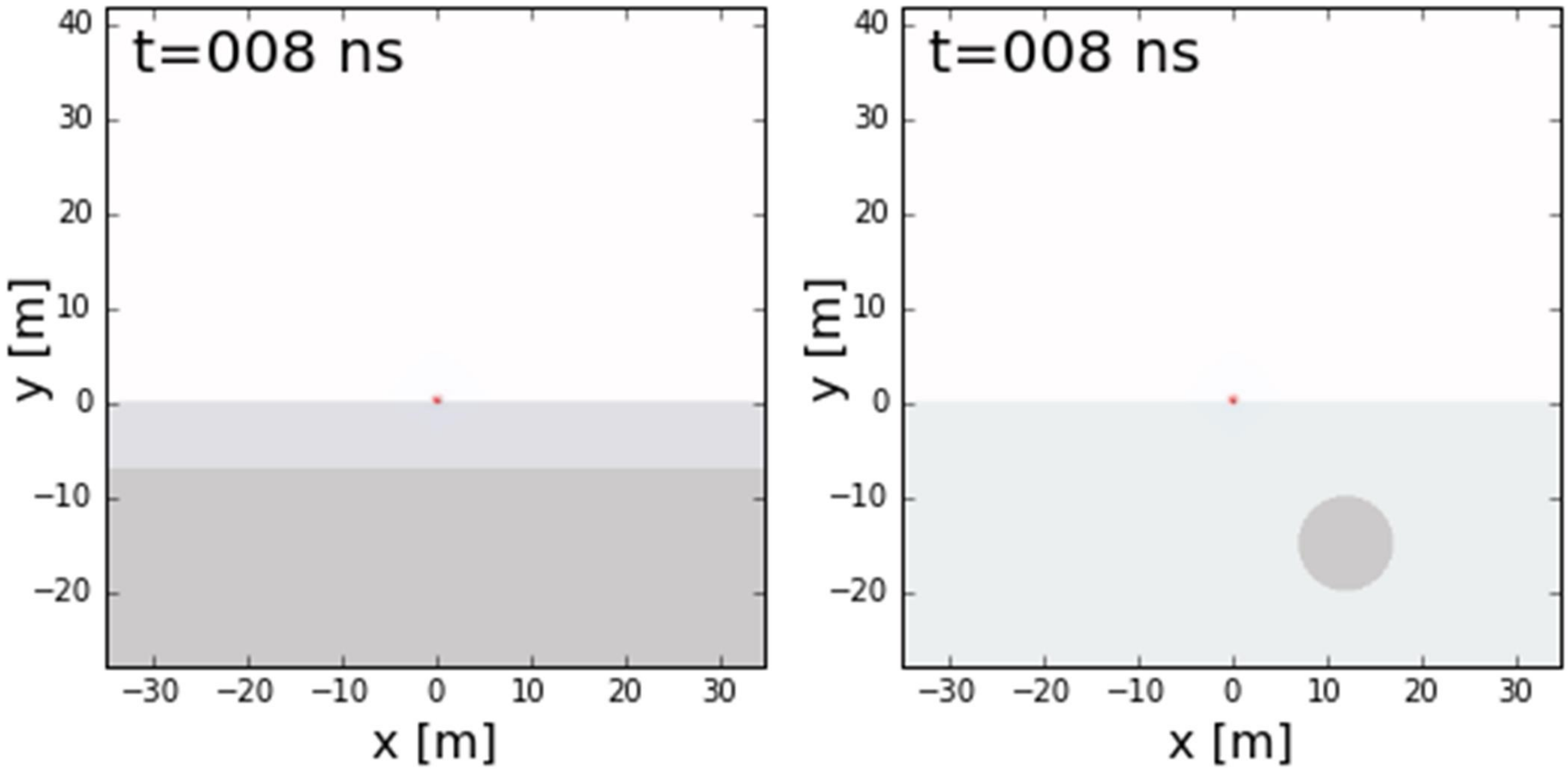
Identifying Ray Paths



Recap Questions

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

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

Questions About Material?