Ground Penetrating Radar

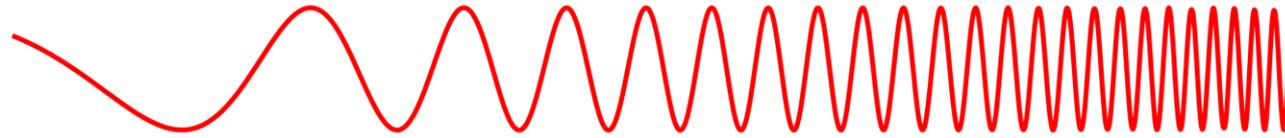# Birth of Radar

Timeline: The Evolution of Radar

- **1887–1904 (Discovery):** Hertz proves EM waves reflect off metal; Hülsmeyer patents the "Telemobiloscope" for ship safety.
- **1935 (The Pivot):** Watson-Watt shifts from "Death Rays" to **Radio Detection and Ranging** (Chain Home system).
- **1940 (Miniaturization):** Invention of the **Cavity Magnetron** shrinks radar from buildings to portable aircraft units.
- **1970s–Present (The Earth Shift):** Technology adapted for **Near-Surface Geophysics** (Archaeology, Forensics, and Engineering).

BIRTH OF RADAR MEMORIAL
ON 26th FEBRUARY 1935, IN THE FIELD OPPOSITE
ROBERT WATSON WATT AND ARNOLD WILKINS
SHOWED FOR THE FIRST TIME IN BRITAIN THAT AIRCRAFT COULD BE DETECTED BY BOUNCING RADIO WAVES OFF THEM. BY 1939 THERE WERE 20 STATIONS TRACKING AIRCRAFT AT DISTANCES UP TO MORE THAN 100 MILES. LATER KNOWN AS RADAR, IT WAS THIS INVENTION, MORE THAN ANY OTHER, THAT SAVED THE RAF FROM DEFEAT IN THE 1940 BATTLE OF BRITAIN.

Refresher on Electromagnetic spectrum

Penetrates Earth's Atmosphere?	Y	N	Y	N

Radiation Type	Radio	Microwave	Infrared	Visible	Ultraviolet	X-ray	Gamma ray
Wavelength (m)	10^3	10^{-2}	10^{-5}	0.5×10^{-6}	10^{-8}	10^{-10}	10^{-12}

Approximate Scale of Wavelength
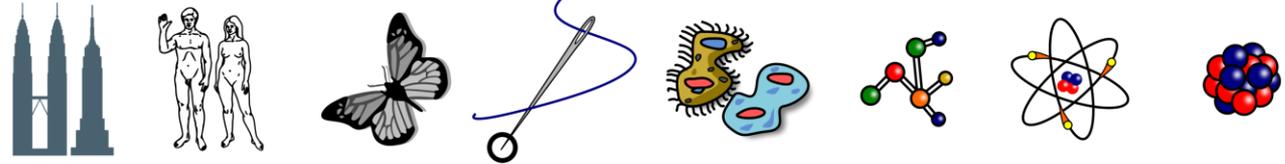
Buildings	Humans	Butterflies	Needle Point	Protozoans	Molecules	Atoms	Atomic Nuclei

Frequency (Hz)
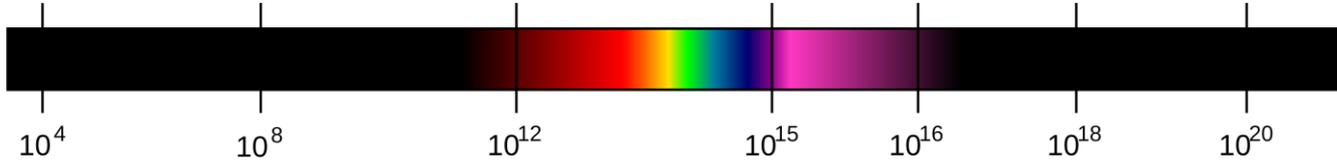
10^4 10^8 10^{12} 10^{15} 10^{16} 10^{18} 10^{20}

Temperature of objects at which this radiation is the most intense wavelength emitted

| 1 K	100 K	10,000 K	10,000,000 K
−272 °C	−173 °C	9,727 °C	~10,000,000 °C
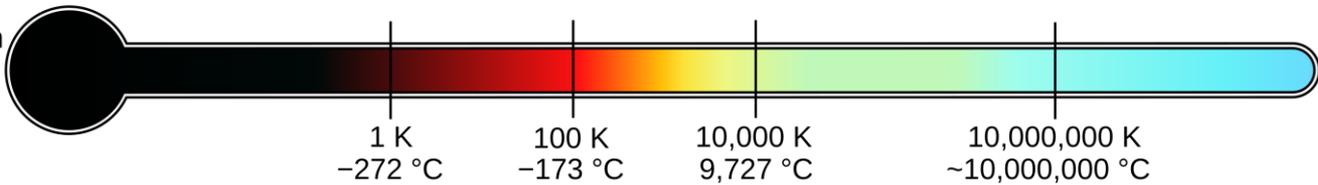
Radio Detection and Ranging (Radar)
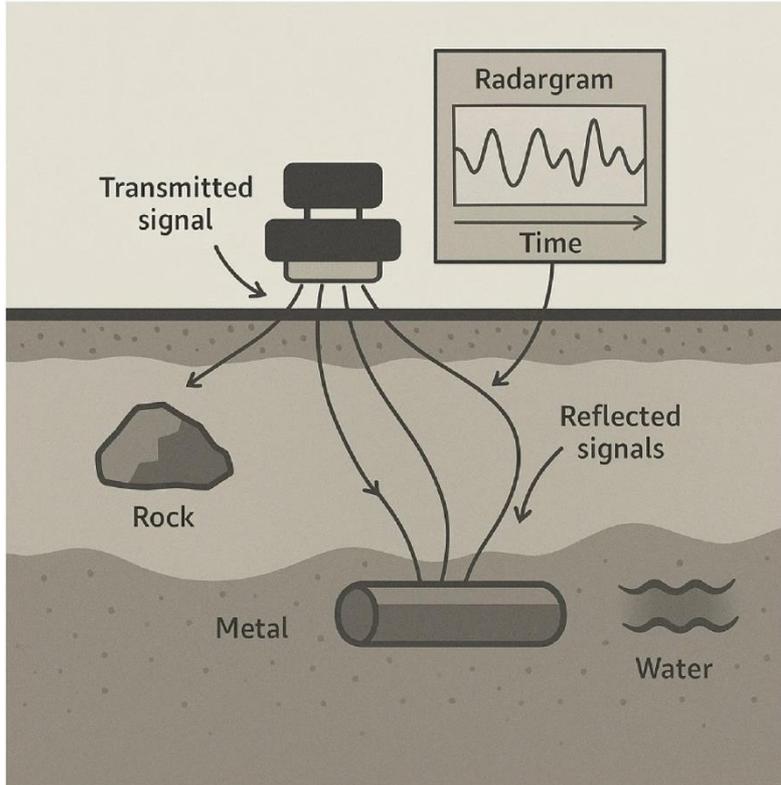
- Near-surface geophysical imaging method
- Uses high-frequency **electromagnetic (EM) waves**
- Transmitter emits **radio waves,** waves reflect off objects, receiver records return signal
- Non-destructive and high resolution
- Produces images of the shallow subsurface

Where Does GPR Sit in the EM Spectrum?

Penetrates Earth's Atmosphere?	Y
Radiation Type	**Radio**
Wavelength (m)	10^3
Approximate Scale of Wavelength	Buildings
Frequency (Hz)	10^4
Temperature of objects at which this radiation is the most intense wavelength emitted	
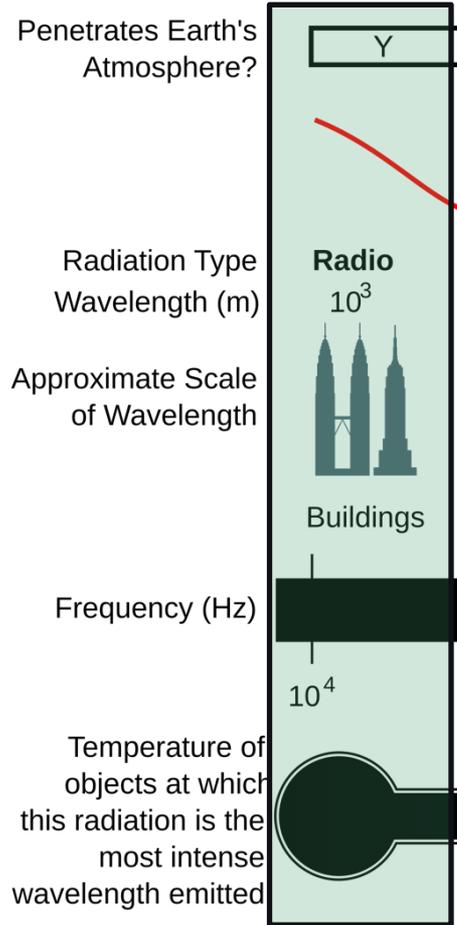
- Uses frequency of ~ 25 MHz to 1 GHz
- **Higher** frequency **= better resolution, less penetration**
- **Lower** frequency = **coarse resolution, greater depth penetration**

Compared with
Metal detectors use: 1-10 Khz
Seismic uses: ~10-200 Hz

How does GPR work? The basic setup:
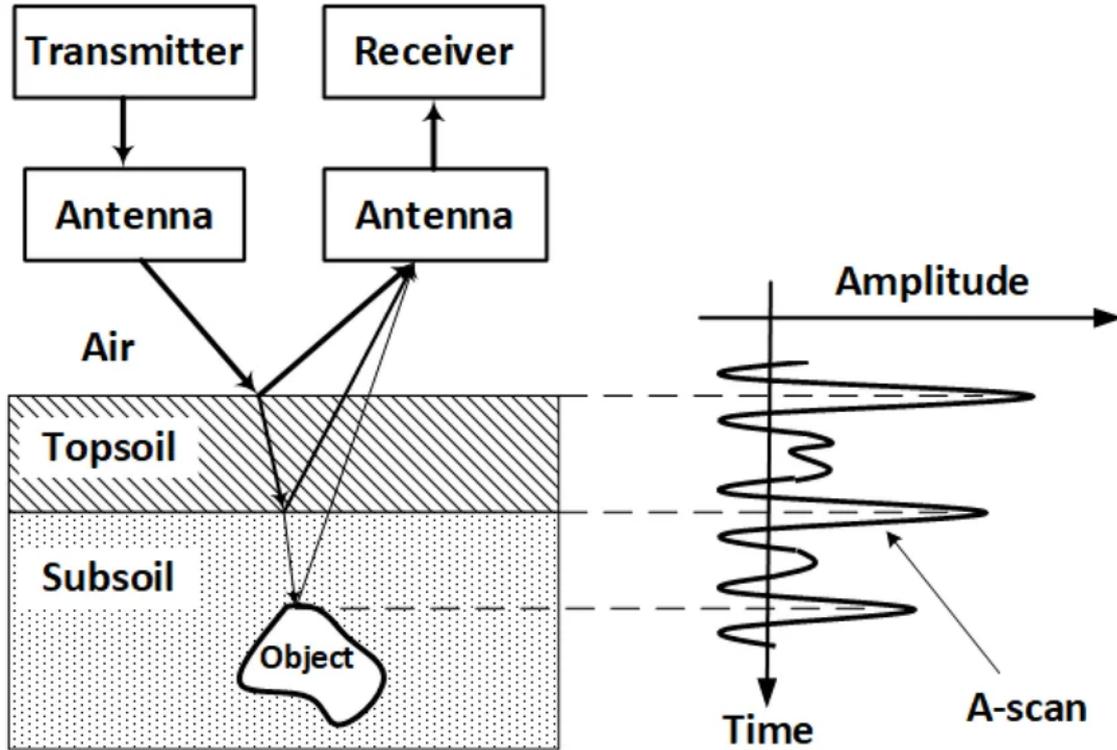
- Transmitter antenna emits a short radio pulse into the ground
- Wave travel downward through subsurface
- At boundaries where electrical properties change, wave partially reflects
- Receiver antenna records reflected signal
- Two-way travel time is recorded at each position
- Process repeated along a profile that builds a cross-section image.

Radar velocity in Earth Materials

- Radar waves travel with the speed of light (3×10^8 m/s) in vacuum.
- In other medium, velocity is less than c.

$$V \approx \frac{c}{\sqrt{\mu_r \, \varepsilon_r}}$$

where ε_r is the relative dielectric permittivity and μ_r is the relative magnetic permeability (usually ~ 1 for most geological materials)

Material	ε_r	Velocity (m/ns)
Air	1	0.30
Ice	3–4	0.16
Dry sand	3–10	0.15
Wet sand	20–30	0.06
Limestone	4–8	0.12
Clay	5–40	0.06–0.17
Freshwater	80	0.033
Salt water	81–88	0.01

What is Dielectric Permittivity?

In **Conductors** (Metals, Clays), electrons are not bound to nuclei. An external field induces a continuous current flow, converting EM energy into heat (Ohmic loss). This results in high attenuation of the GPR signal.

Ideal **insulators** lack both free charges and significant polarizability. The EM wave passes through with minimal velocity change or energy loss.
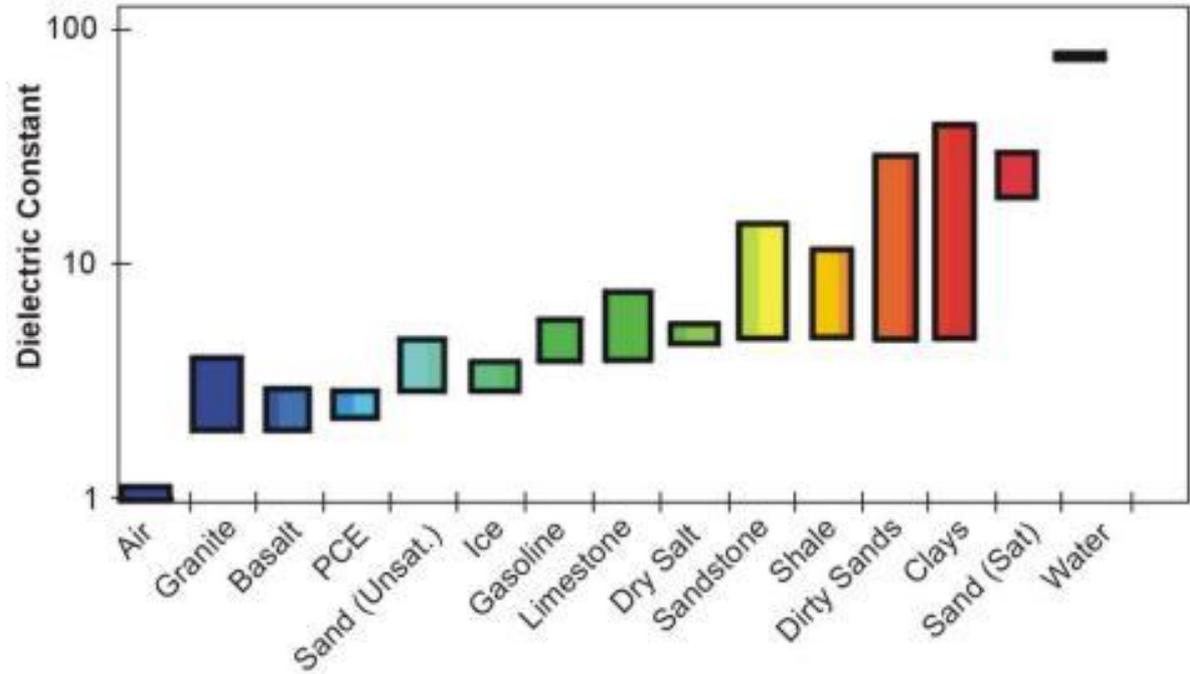
What is Dielectric Permittivity?

Dielectrics: Bound Charge Polarization
- Dielectrics are insulators that possess **Electrical Polarizability**. Charges are structurally bound but can undergo microscopic displacement under an external electric field.
- **GPR Application:** This interaction dictates the **Relative Permittivity** which governs wave velocity and the reflection coefficient at material interfaces.

Dielectric Permittivity

- **Dielectric permittivity (ε_r):** Materials that can be polarized by an electric field
- Measures how easily a material polarizes
- Strongly influenced by water content
- Most Earth materials are lossy dielectrics

What controls reflection?

- Reflections occur at contrasts in electrical properties
- Largest reflections from greatest velocity contrast
- Water dominates permittivity in most geologic materials
- Key property is dielectric permittivity **(ε_r):** Materials that can be polarized by an electric field
- Most Earth materials are lossy dielectrics

$$R = \frac{\sqrt{\epsilon_1} - \sqrt{\epsilon_2}}{\sqrt{\epsilon_1} + \sqrt{\epsilon_2}} \qquad\qquad R = \frac{V_2 - V_1}{V_2 + V_1}$$

What controls reflection?

- Every GPR reflection has a **polarity** denoted by the pattern of colors in the wavelet
- Two possible patterns for a single reflector:

  Black — White — Black → positive reflection coefficient (R > 0)
  White — Black — White → negative reflection coefficient (R < 0)
- Polarity tells you whether radar wave is going from **slow to fast** or **fast to slow** material
- Same information as seismic polarity but different property being measured
- **Positive R (BWB):** wave going from low ε_r into high ε_r → **slower material below**
- **Negative R (WBW):** wave going from high ε_r into low ε_r → **faster material below**

$$R = \frac{\sqrt{\epsilon_1} - \sqrt{\epsilon_2}}{\sqrt{\epsilon_1} + \sqrt{\epsilon_2}} \qquad R = \frac{V_2 - V_1}{V_2 + V_1}$$

How does Electrical Conductivity impact Radio waves?

- **Electrical Conductivity (σ):**
  Measure ability to conduct electric current
- Controls energy loss (attenuation)
- High conductivity – strong signal loss
- Common in clays and saline water
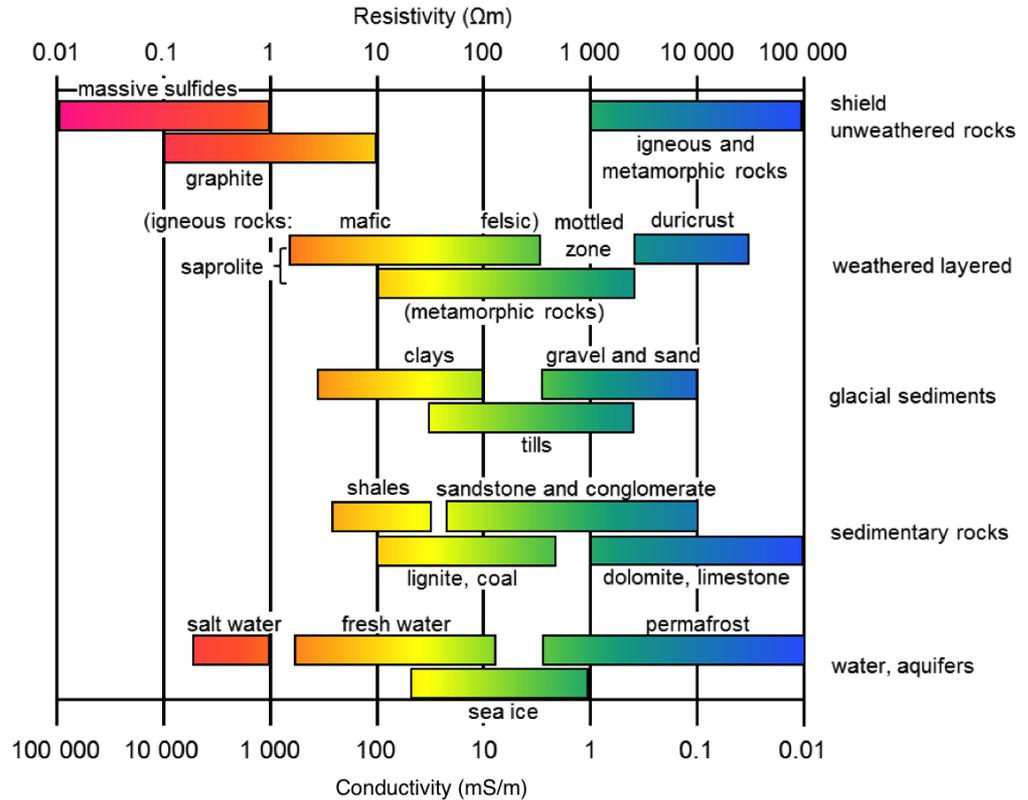
Resolution-Depth trade off

- Resolution is proportional to wavelength

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

- Higher frequency = shorter wavelength = better resolution but more attenuation
- Lower frequency = longer wavelength = worse resolution but deeper penetration
- Attenuation is controlled by electrical conductivity
- Wet clays, salt water = high attenuation = GPR fails
- Dry sand, ice, concrete = low attenuation = GPR excels

Why GPR has better resolution than seismics?

- Resolution is proportional to wavelength

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

- **GPR wavelengths are about ~ 100 times shorter than seismic**
- **Minimum resolvable layer thickness is $\frac{\lambda}{4}$**

- Seismic example: 100 Hz in granite $\qquad \lambda = \dfrac{5000}{100} \quad = \quad 50\text{ m}$

- GPR example: 200 MHz in granite $\qquad \lambda = \dfrac{1.3e^8}{2e^8} \quad = \quad 0.65\text{ m}$

GPR vs Seismic

	Seismic	GPR
Measures	Acoustic impedance $Z = \rho V$	Dielectric permittivity ε_r
Controlled by	Density × elastic stiffness	Water content
Wave type	Mechanical	Electromagnetic
Frequencies	10–200 Hz	10 MHz–1 GHz
Wavelengths	10–50 m	0.01–1 m
Resolution	~5–15 m	~0.01–0.25 m
Depth	10s–1000s m	0.5–30 m (soil)
Travel time	Milliseconds	Nanoseconds
Velocity (soil)	500–2000 m/s	60,000–150,000 m/s
Positive R means	Entering stiffer material	Entering wetter material

GPR vs Seismic

	Seismic	GPR
Best conditions	Wet clay, soft sediments	Dry sand, ice, concrete
Worst conditions	Dry loose sand	Wet clay, saltwater
Ground contact	Required	Not required
Survey speed	Moderate	Fast — walking pace
Invasiveness	Low	None
Water table	Moderate reflection	Strong reflection
Air void	Good reflection	Good — negative R
Water void	Moderate	Strong — positive R
Metal	Poor	Excellent
Clay	Good target	GPR fails

Applications for GPR

Mapping out cracks in roads or bridges

Mapping buried utilities

Data Acquisition:
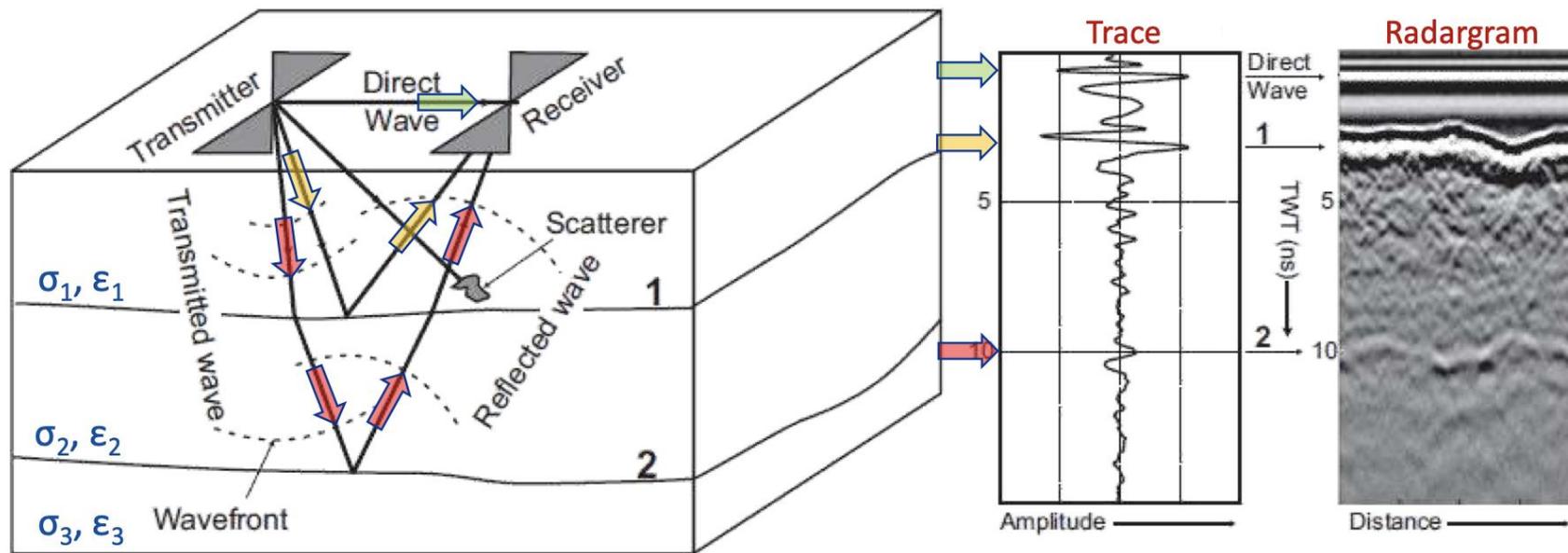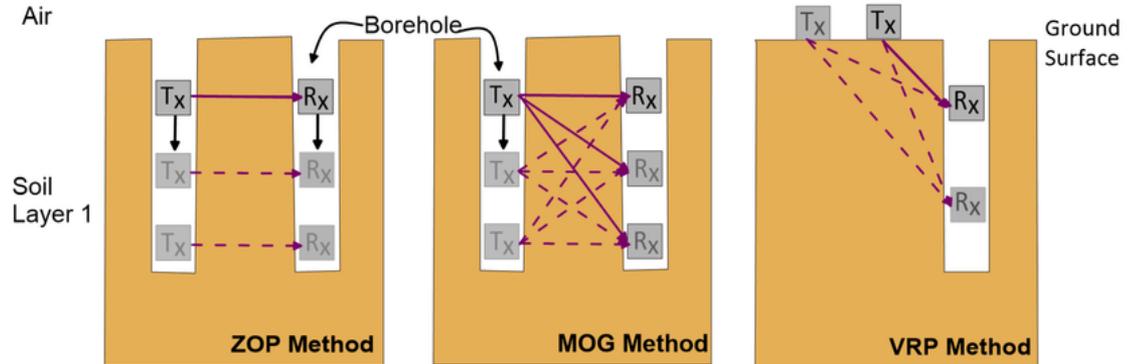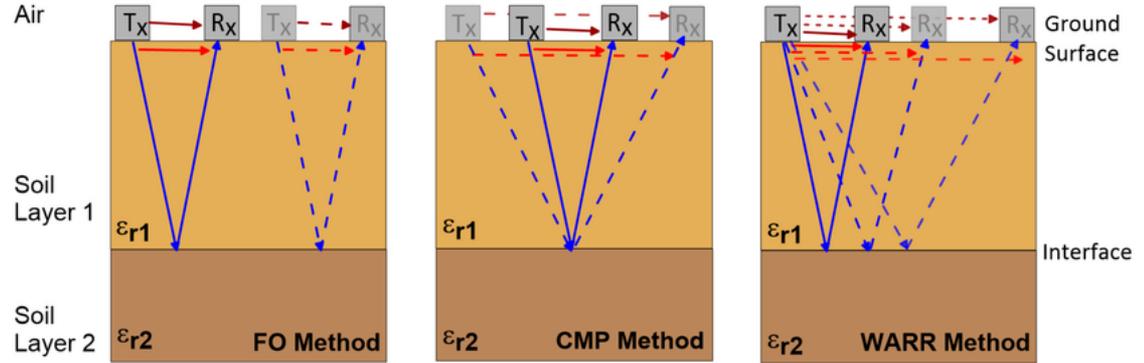
Field data collection: Equipment

Acquisition is similar to reflection seismology

- Transmitter antenna + Receiver antenna : Combined unit (**geophones**)
- Control unit records the two-way travel time vs distance
- Often integrated with GPS for spatial positioning
- Surveys are non-invasive, no ground disturbance (**no hammering or explosives**)
- Data collected at walking pace along profile lines
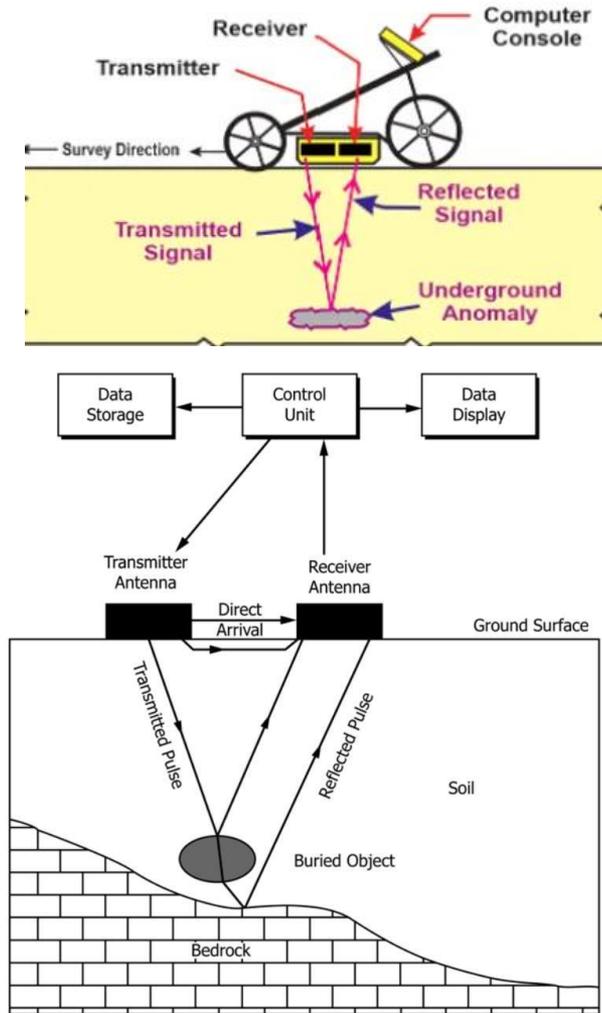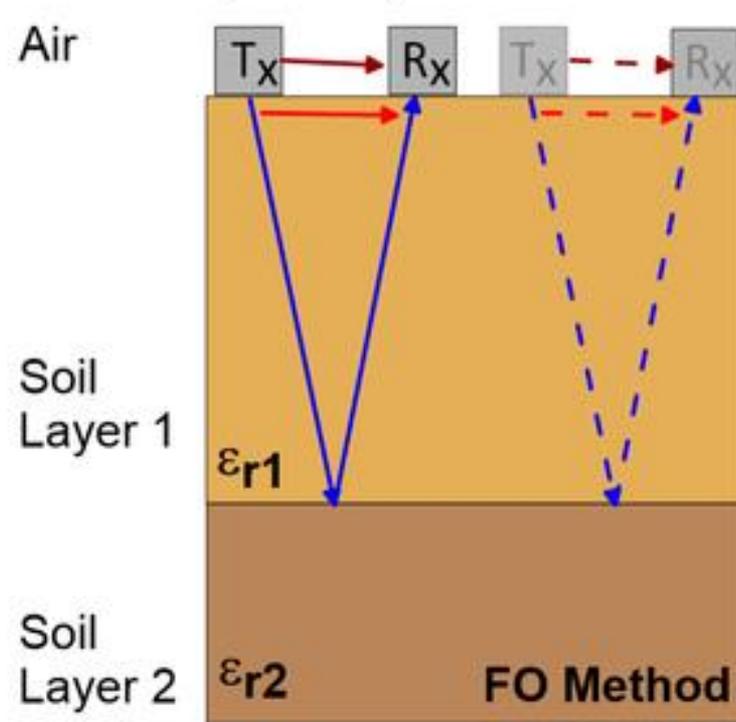
Field data collection: Data Survey Modes

- **Reflection profiling**
- **CMP**
- **WARR (Wide angle reflection and refraction)**
- **Transillumination**

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Field data collection: Data Survey Modes

Reflection Profiling (Common Offset Method or Fixed offset Method)

- **Geometry:** Transmitter (Tx) and Receiver (Rx) are maintained at a **fixed separation** and orientation.
- **Procedure:** Both antennas are moved simultaneously along a survey line at a constant station interval.
- **Objective:** To produce a **2D vertical cross-section** (radargram) of subsurface reflections and impedance boundaries.


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Field data collection: Data Survey Modes

Velocity-Sounding (CMP & WARR)
Objective: To determine the EM wave velocity of subsurface layers by measuring travel time vs. antenna offset.

- **Common Mid-Point (CMP):** Both antennas move apart symmetrically from a **fixed central point**. This minimizes the impact of dipping layers.
- **Wide-Angle Reflection and Refraction (WARR):** One antenna remains stationary while the other is moved away. Often used when space is limited for one side of the array.
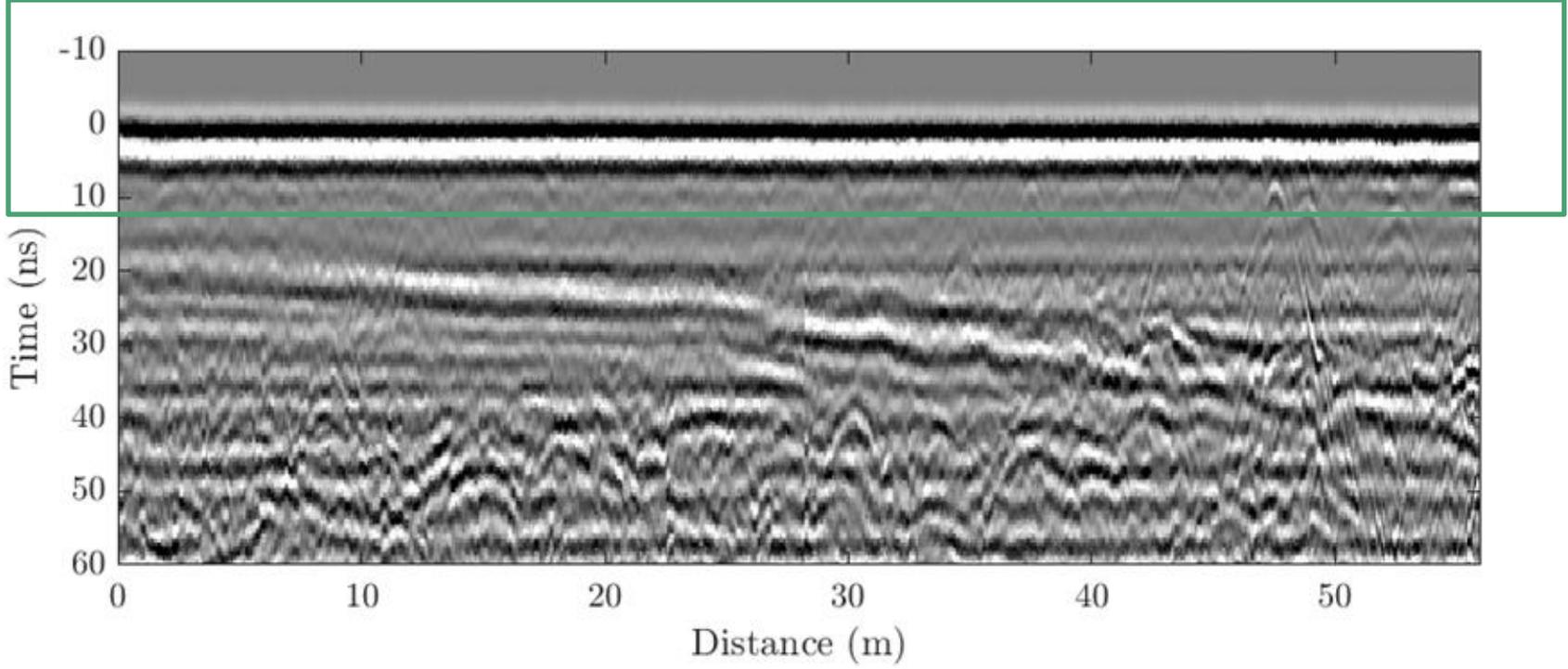

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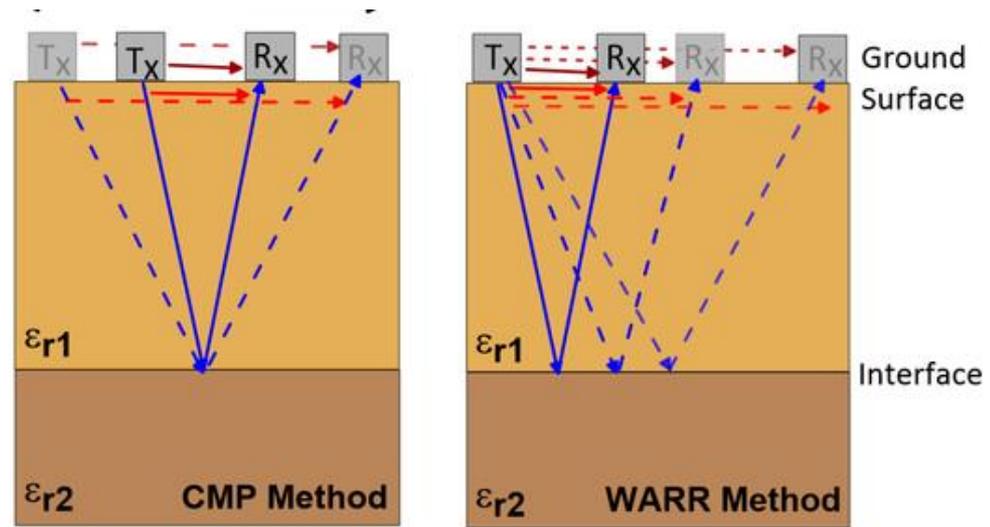
Field data collection: Data Survey modes

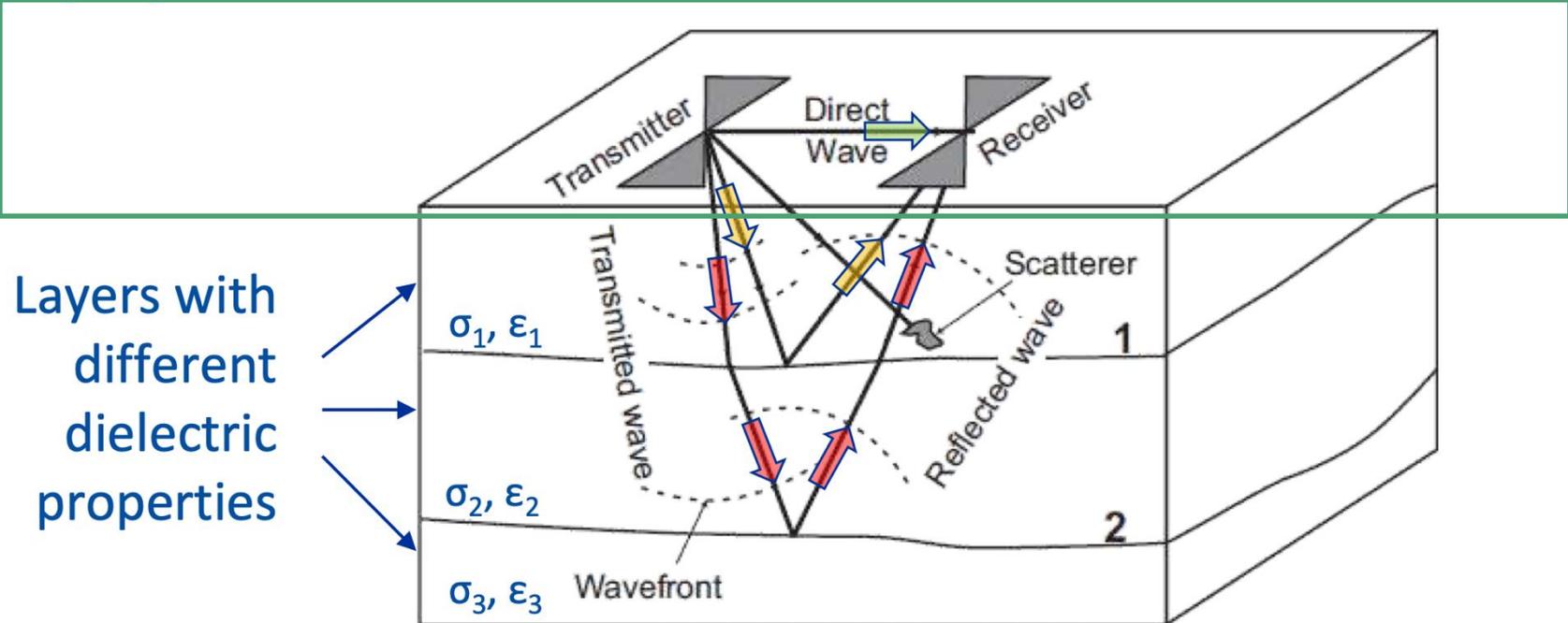**Transillumination (Tomographic Methods)**

- **Geometry:** Tx and Rx are placed on **opposite sides** of the medium (e.g., between two boreholes or opposite sides of a concrete pillar).
- **Zero-Offset Profiling (ZOP):** Tx and Rx move in tandem at the same depth/position to quickly map anomalous zones.
- **Multi-Offset Gathering (MOG):** One antenna is fixed while the other moves to multiple stations, providing the ray-path density required for **tomographic imaging**.
- **Vertical Reflection Profiling (VRP):** Tx is on the surface while Rx is in a borehole, providing high-resolution vertical velocity and reflection data.

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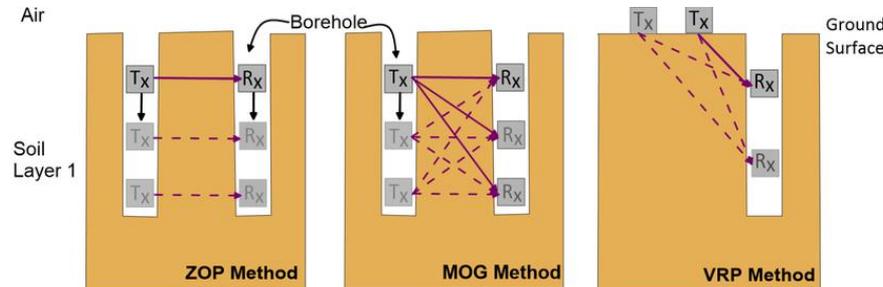
Do you see the horizontal band across the top of the profile?

It is the direct wave!

Layers with different dielectric properties

σ_1, ε_1

σ_2, ε_2

σ_3, ε_3
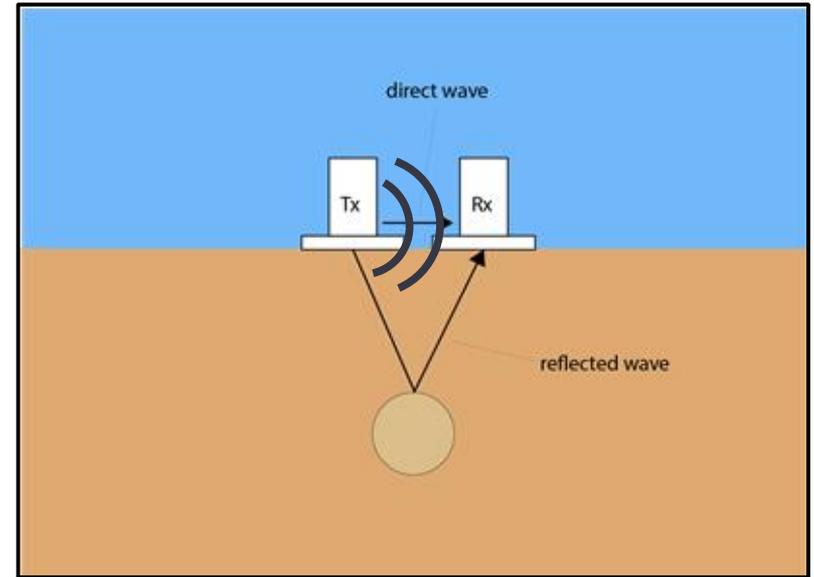
Issues with the Direct wave

- Transmitter emits energy in **all directions**, not just downward
- Some energy travels directly through the air from Tx to Rx, this is the **direct wave**
- Travels at the speed of light → always the **first arrival** in the record
- Tells us **nothing about the subsurface**
- Appears as a strong horizontal band at the **top of every radargram**
- Creates a **near-surface blind zone**, shallow features beneath it are masked

direct wave

Tx   Rx

reflected wave

Issues with the Direct wave
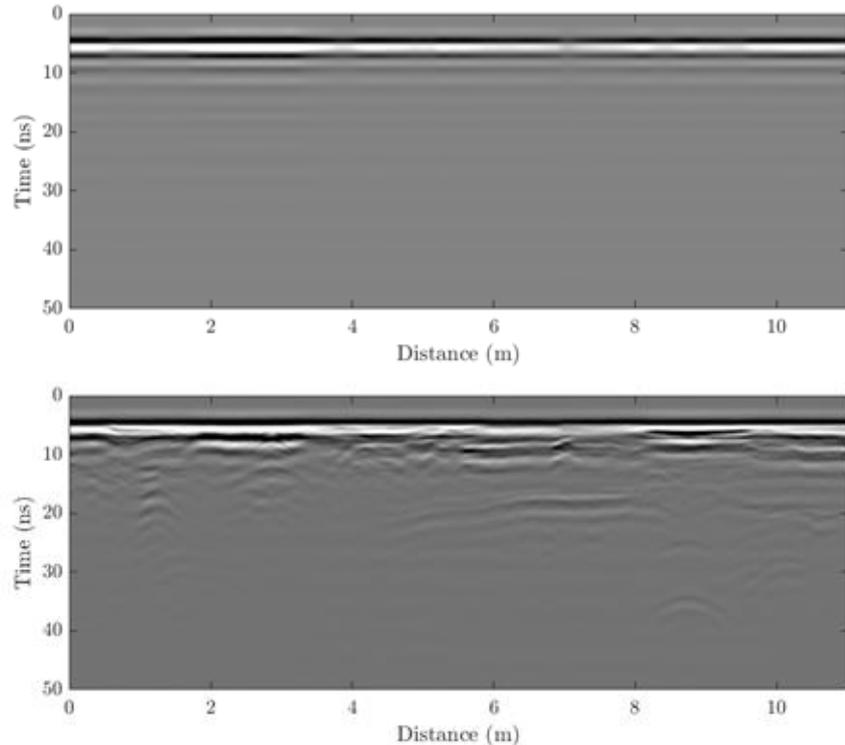
Direct waves can be nice and clean appearing as straight bands OR can be wavy due to interference with shallow objects
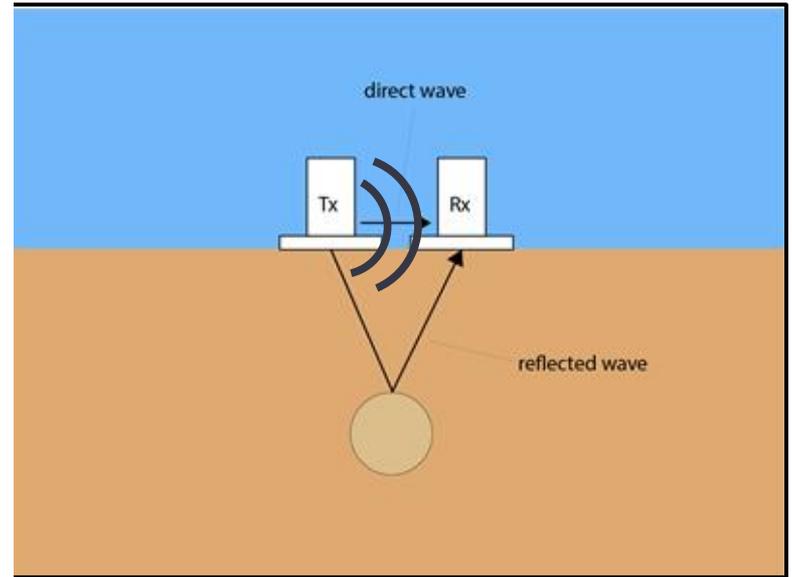
How does a buried pipe look like?

- GPR transmits and receives signal by gradually moving over a buried pipe.
- The receiver doesn't "know" where the object causing the return actually is -> As the antenna gets closer to the object, the reflected signal is received sooner.
- The resulting radargram looks like an upside-down "U". This is called a **diffraction pattern**, and follows the mathematical form of a hyperbola.