



Chap V: Electromagnetic methods used in Hydrogeology : Ground Penetrating Radar GPR

Electromagnetic methods [i.e., Ground Penetrating Radar (GPR), Borehole Radar (BHR), and Time-Domain Reflectometry (TDR)] are often used to explore the subsurface and differentiate between materials/formation **with different electric properties** (conductivity and resistivity). These methods **are distinguished** from **electrical/magnetic methods** by the fact that they typically **introduce combined electromagnetic waves** in the ground, rather than a current (DC or AC).

We will focus here on the GPR because of its wide use and due its cost effectiveness and relative easiest for deployment.

Ground penetrating radar (GPR): is a geophysical method for shallow investigations with high resolution using electromagnetic waves (EMW) propagation similar to those used in seismic method (reflection method); it sends **high frequency** EMW (10 MHz–10 GHz) and records reflections from dielectric contrasts **Daniels (2004)**. It measures the two-way travel time of electromagnetic pulses to detect changes in relative permittivity (ϵ_r), conductivity (σ), and magnetic permeability (μ) in the shallow subsurface (0–50 m) **Jol (2009)**. It is critical for vadose (unsaturated) zone characterization, water table detection, and contamination mapping **in unconsolidated sediments** (sand, gravel, alluvium).



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How it works?

GPR uses short pulses which are transmitted into the ground (Fig.15). A part of this energy is **reflected** or **scattered** at layer boundaries or buried objects. The direct and reflected amplitudes of the electric field strength E are recorded as a function of **travel time**.

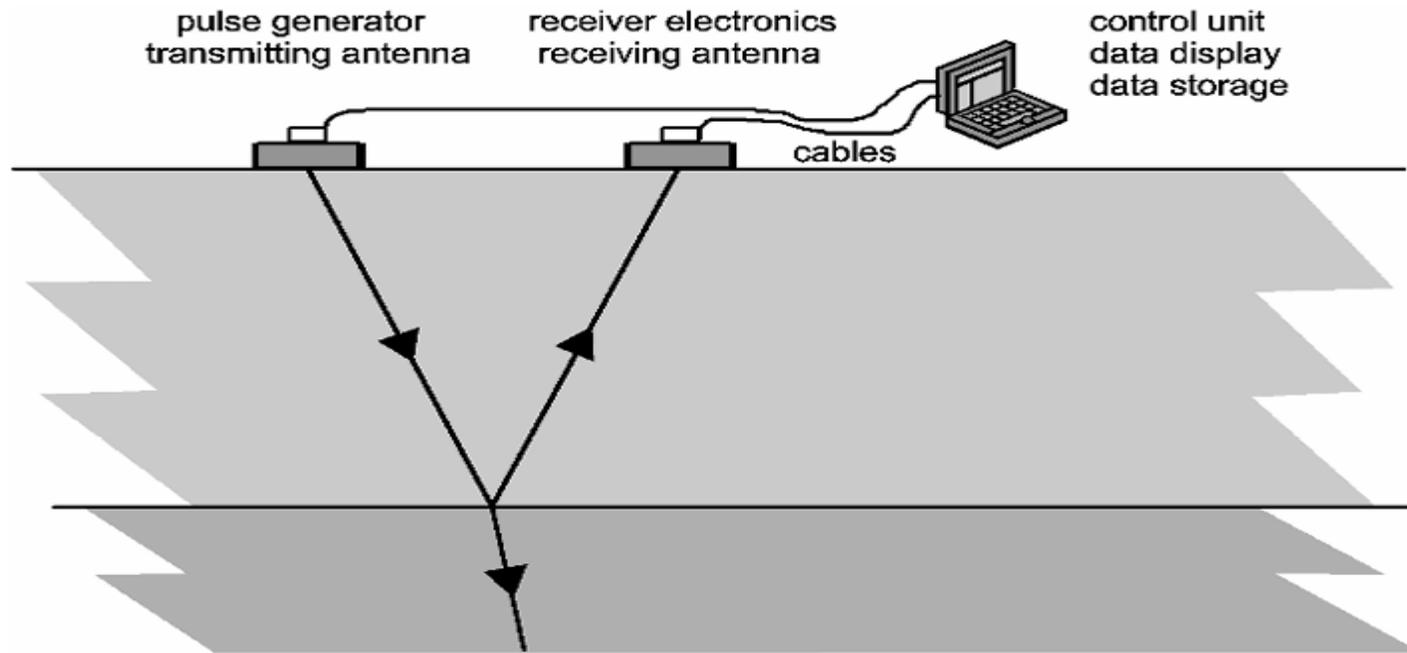


Figure 15: GPR Measurement Set up (Source: R Kirsch 2009)



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How it works?

In real life the propagation of electromagnetic waves can be described by a ray representation similar to seismic reflection. A simple horizontal two layer model with a reflector at depth h requires four wave paths and travel time curves as follow in below figure 16.

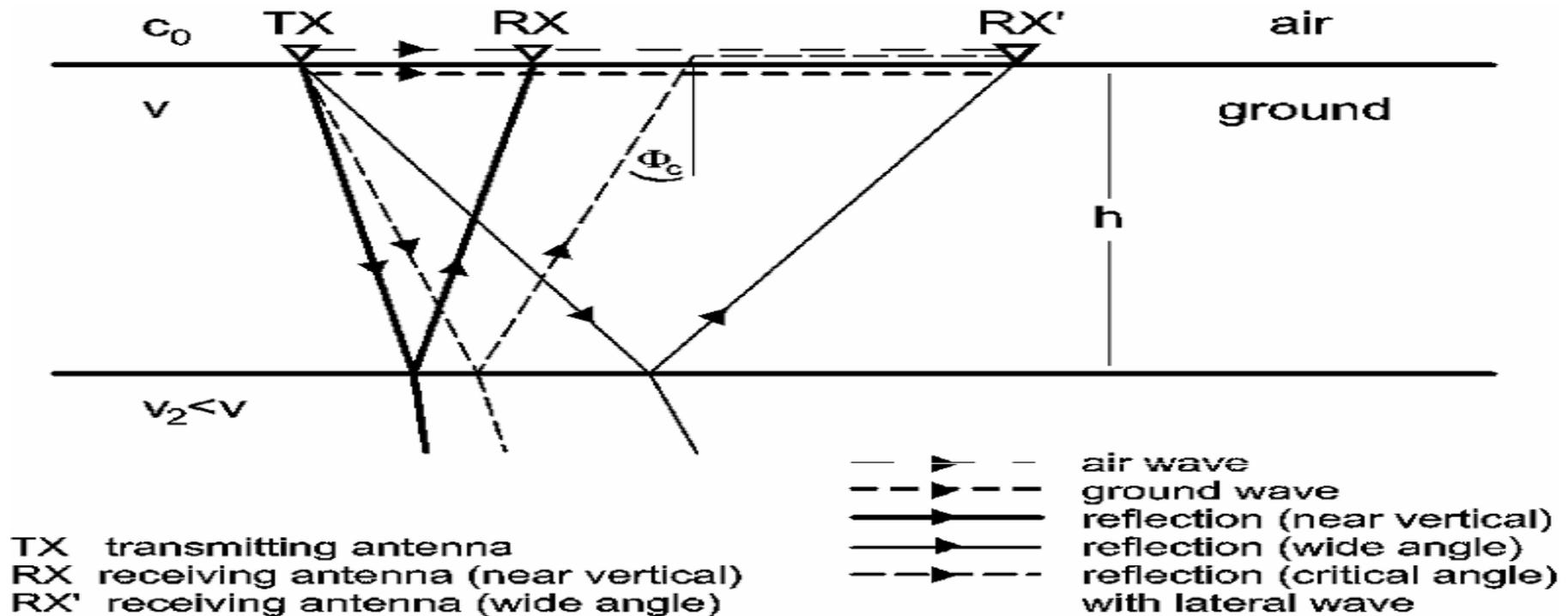


Figure 16: GPR ray paths for the horizontal two-layer case (Source: Reinhard Kirsch 2009)



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Electromagnetic wave propagation is governed by Maxwell's equations (which will not be discussed here). We will focus on important parameters that give information to hydrogeology.

Material properties relevant for electromagnetic wave propagation are the relative dielectric permittivity ϵ and the specific electric conductivity σ .

The propagation velocity v (phase velocity) of the radar waves is given by:

$$v \approx \frac{c_0}{\sqrt{\epsilon}}$$

Where C_0 is the speed of light in vacuum (or air) $C_0 = 2.998 \times 10^8$ m/s ≈ 300 m/ μ s.

The reflection coefficient is given by the below formula:

$$r = \frac{v_2 - v_1}{v_2 + v_1} = \frac{\sqrt{\epsilon_1} - \sqrt{\epsilon_2}}{\sqrt{\epsilon_1} + \sqrt{\epsilon_2}}$$

V_1 and V_2 velocities for different layers ; ϵ_1 and ϵ_2 are permittivity for the same previous layers.



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The attenuation coefficient (for frequencies that are low enough) can be estimated from the DC conductivity σ and the relative permittivity ϵ .

$$\alpha' = 1640 \frac{\sigma}{\sqrt{\epsilon}}$$

With α' the attenuation coefficient.

α' in dB/m and σ in S/m (Siemens/meter).

Attenuation can be calculated in function μ the magnetic permeability

α attenuation coefficient.

$$\alpha = \frac{1}{2} \sigma \sqrt{\frac{\mu}{\epsilon}}$$

α in dB/m, μ (magnetic permeability) in H/m (Henry/m)

For a successful application of GPR the two-way absorption along the ray path (from the transmitter down to the reflector and back to the receiver) should not exceed a maximum of 60 dB (Kirsch 2009).

With this condition $2 \cdot h_{\max} \cdot \alpha' < 60\text{dB}$ we will get:

$$h_{\max} \leq 0.018 \rho \sqrt{\epsilon}$$

with h_{\max} in m and ρ in Ωm . $\rho = \frac{1}{\sigma}$



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Table 5: Advantages and limitations of GPR use in hydrogeology

Advantages	Limitations
Highest resolution (cm-scale vertically)	Shallow depth (<50 m Operational depth)
Real-time imaging (field monitor)	High attenuation in clay/saline soils (common in DZ coastal areas)
Non-invasive (NDT) & portable	Requires flat terrain (dunes/wadis challenging)
Direct water table detection (dielectric contrast, sensitivity to water content)	The method is highly site specific ; users must be aware when selecting the method without detailed knowledge of a particular site. high electrical conductivity will limit signal penetration
Performs best in coarse-grained materials, such as sands and gravels	limited in finer-grained soils such as clays and silts, or in saline groundwater

GPR was used in a multi-method approach (combined with other methods) by Boucher, M. et al. (2022) used ground-penetrating radar (GPR) to monitor coastal aquifers in Algeria, specifically the Tipaza region, to understand seawater intrusion into groundwater. The study identified that overexploitation of the aquifer has negatively impacted groundwater quality and recommend a better groundwater management.



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Table 6: GPR reached depth Vs formation (Source Environmental Protection Agency EPA USA

Material/Formation	ϵ_r	v (m/ns)	Typical Depth Penetration
Dry sand	3–5	0.15–0.19	10–50 m
Wet sand	20–30	0.05–0.06	5–15 m
Clay (wet)	10–40	0.05–0.07	<5 m

Reamark: GPR has another application, it was used to detect water pipe leaks in Algiers by utilizing high frequency waves 1 Ghz (2023).