A.A. 2021-2022

Corso di Laurea Magistrale in GEOSCIENZE

Metodi Elettromagnetici in Geofisica (6 CFU)
- MEMAG -

UD-4a: Ground Penetrating Radar GPR - principles

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We already sow that...

$$\nabla \times \nabla \times \boldsymbol{E} + \mu\sigma \frac{\partial \boldsymbol{E}}{\partial t} + \mu\varepsilon \frac{\partial^2 \boldsymbol{E}}{\partial t^2} = 0$$

A **B** **C**

We already pointed out the physical meaning of different terms in the ABC equation (as well as of its corresponding one related to the magnetic field).
When the fields are sinusoidal in time, it reduces into:

$$\nabla \times \nabla \times \mathbf{E} \xcancel{- i\omega\mu\sigma\mathbf{E}} - \omega^2 \varepsilon\mu\mathbf{E} = 0$$

For HIGH FREQUENCY ($f>10^6$Hz) ➔ $\omega^2\varepsilon\mu >> \omega\mu\sigma$ so:

$$\nabla^2 \mathbf{E} \cong \mu\varepsilon \frac{\partial^2 \boldsymbol{E}}{\partial t^2}$$

Polarization currents dominate ➔ PROPAGATION REGIME

A **C**

Therefore, we exploit the possibility to PROPAGATE EM fields (waves) into the ground to IMAGE the sub-surface and possibly infer some EM properties.

High frequency EM methods: frequency range

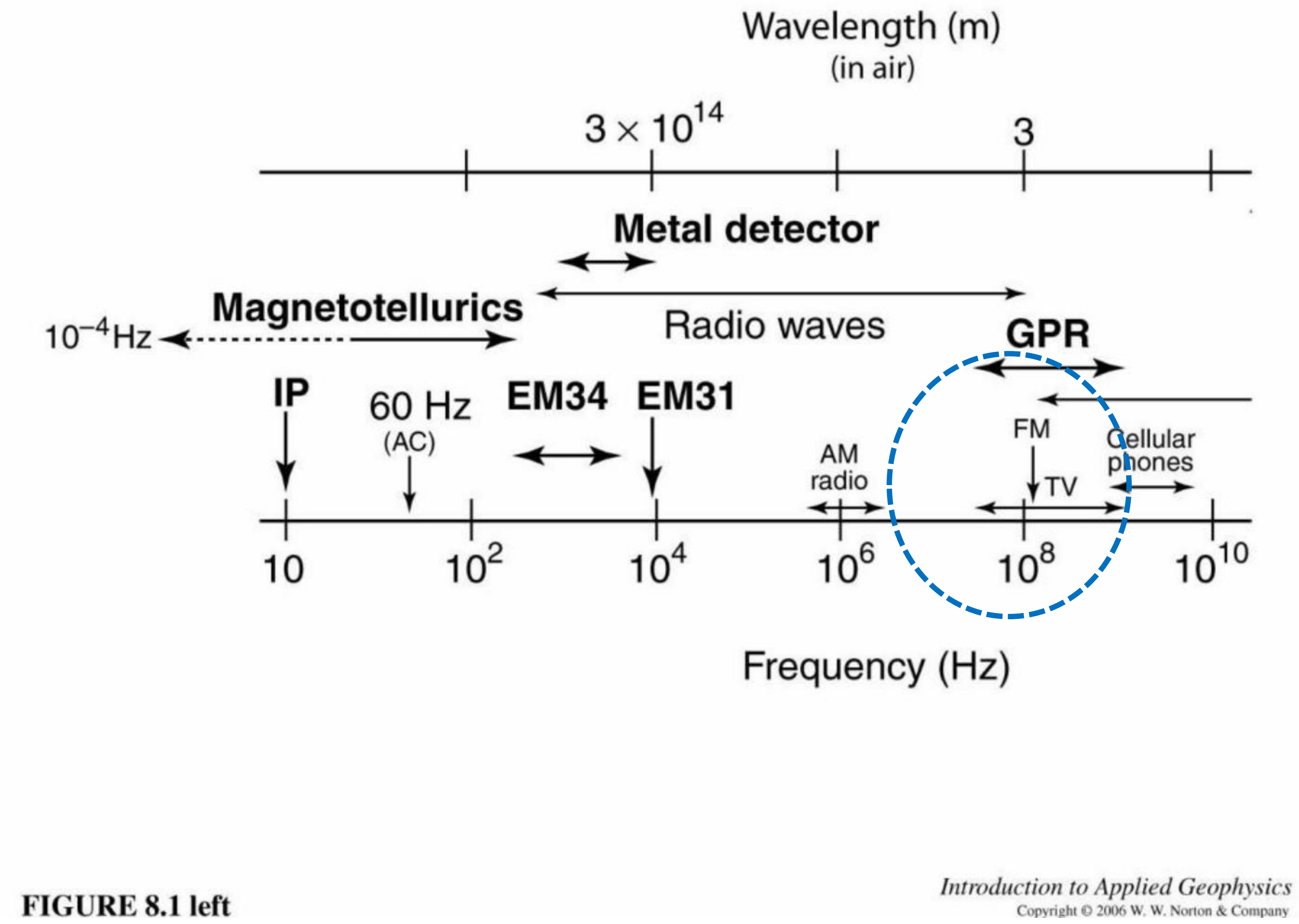


FIGURE 8.1 left

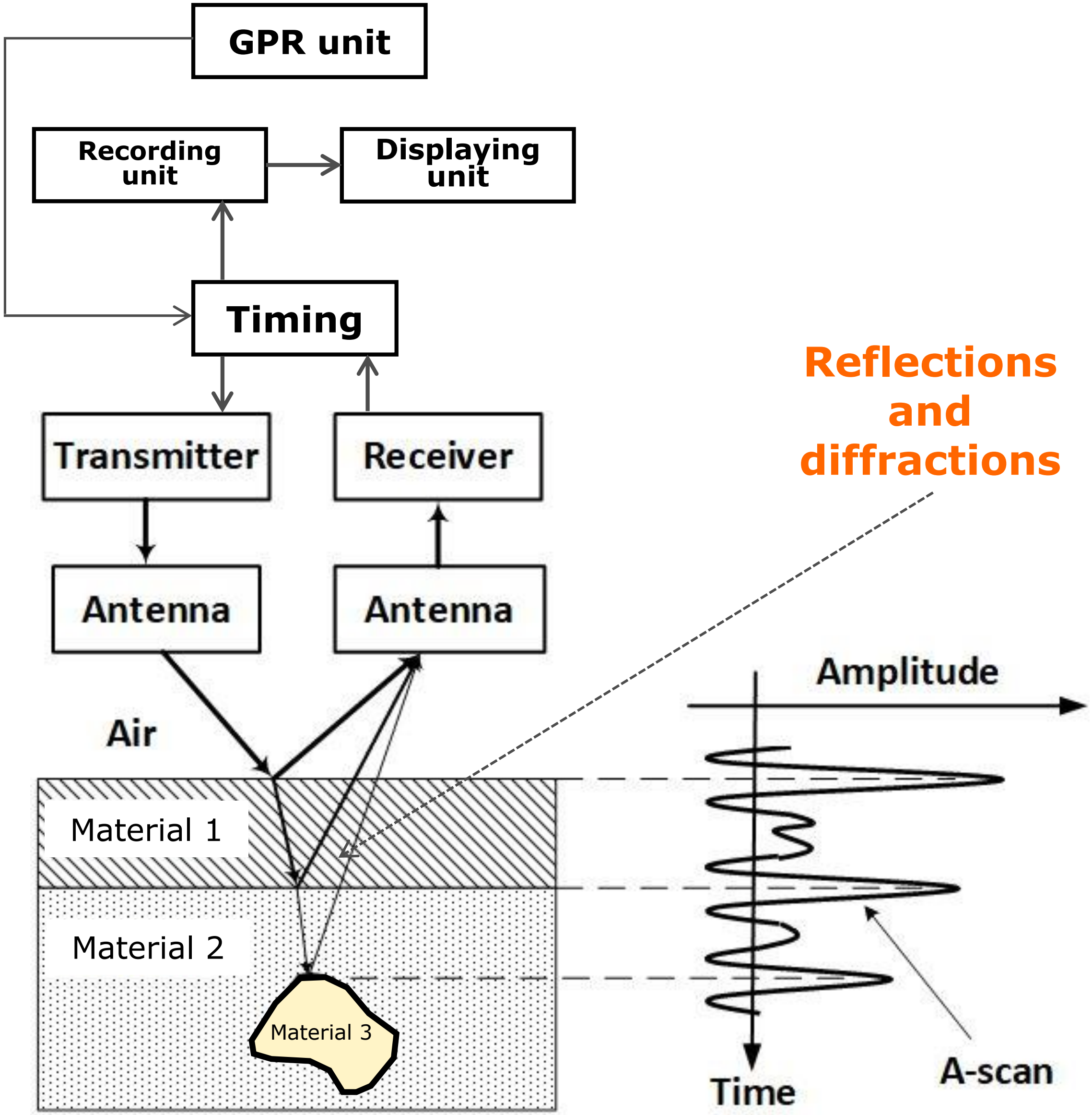
Introduction to Applied Geophysics

Ground Penetrating Radar: history

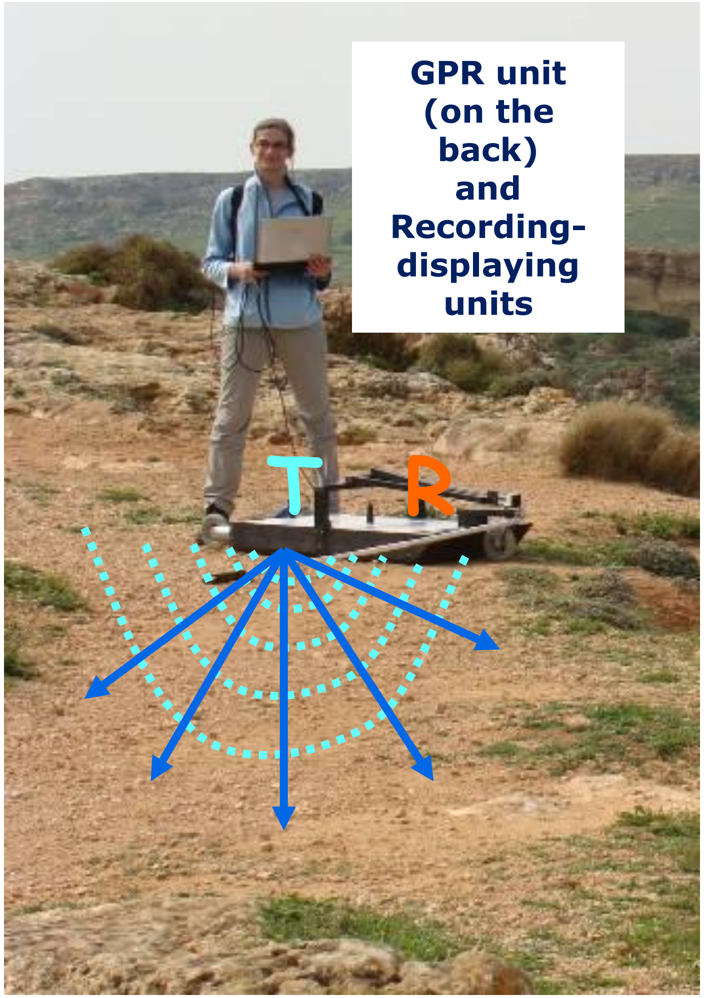
The foundation for **radar systems** in general was laid by Christian Hülsmeyer when he obtained the worldwide first patent in radar technology on April 30, 1904 (patent DE 165 546).
Six years later Gotthelf Leimbach and Heinrich Löwy applied for a patent to use **radar technology to locate buried objects** (patent DE 237 944). This prototipe used surface antennas together with a continuous-wave radar. **In 1926, a pulse radar system for subsurface applications** was introduced and filed for a patent (DE 489 434) by Hülsenbeck. Similar technologies are still widely used today.
One of the first worldwide "ground penetrating radar" survey was performed in Austria in 1929 by W. Stern when he measured the depth of a glacier. Thereafter GPR technology was not used anymore although some patents were filed in the field of "subsurface radar".

After the Second World War, different scientific teams began to work on radar systems for viewing into the ground, especially in the 1960's and 1970's. At the beginning, these radars were developed for military applications such as locating tunnels in the demilitarized zone between North and South Korea and in Vietnam as well as for the lunar exploratory missions.
It is very interesting that radio frequency sounding of geological materials came about when the USAF reported altimeter errors when attempting to land aircrafts on the Greenland ice sheet (Waite and Schmidt, 1961), thus deducing some penetration of EM pulse into the ice.
Soon thereafter public utility and construction companies were interested in such radars as a practical tool to map pipes and utility lines. Other investigations were started to use ground penetrating radar technology to explore, among others, water tables and salt deposits.
Geophysical Survey Systems Inc (GSSI), still on the market, has been manufacturing and selling ground penetrating radars since the 1970's (Morey, 1974).

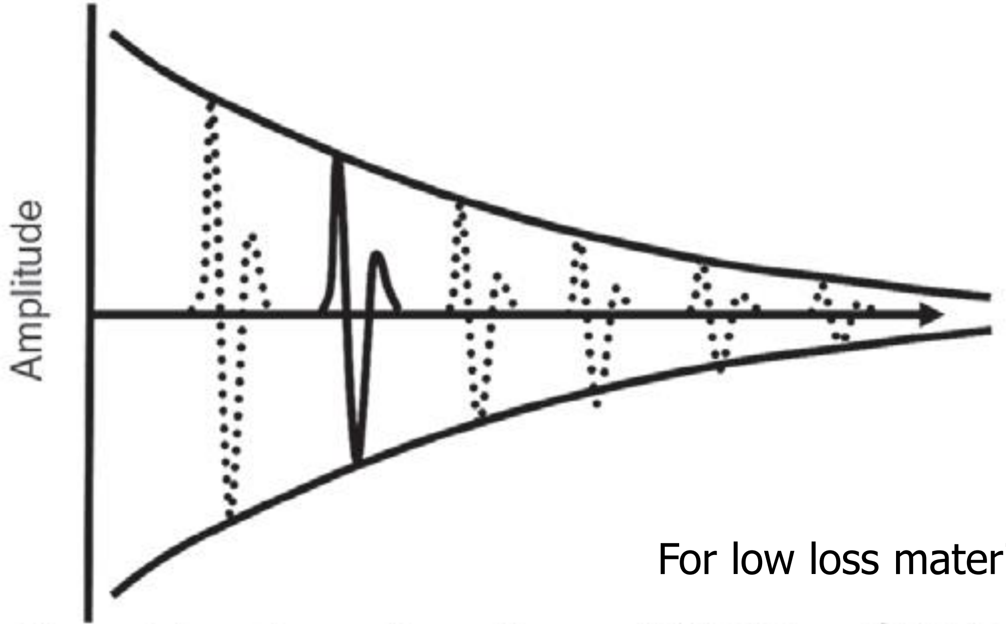
Ground Penetrating Radar: scheme of the system



Modified from Ukaegbu et al., 2019



Ground Penetrating Radar: basis



Field translates at speed v and decays exponentially

$$f(\beta,t)=f(\beta\pm vt)$$

For low loss materials

Velocity

$$v=\frac{1}{\sqrt{\varepsilon\mu}}$$

Attenuation

$$\alpha \cong \frac{\mu\sigma f}{2}$$

EM fields propagate as spatially damped waves when electrical losses are small. The signal amplitude decays exponentially in the direction of field translation while the field shape remains invariant.

Ground Penetrating Radar: EM impedance

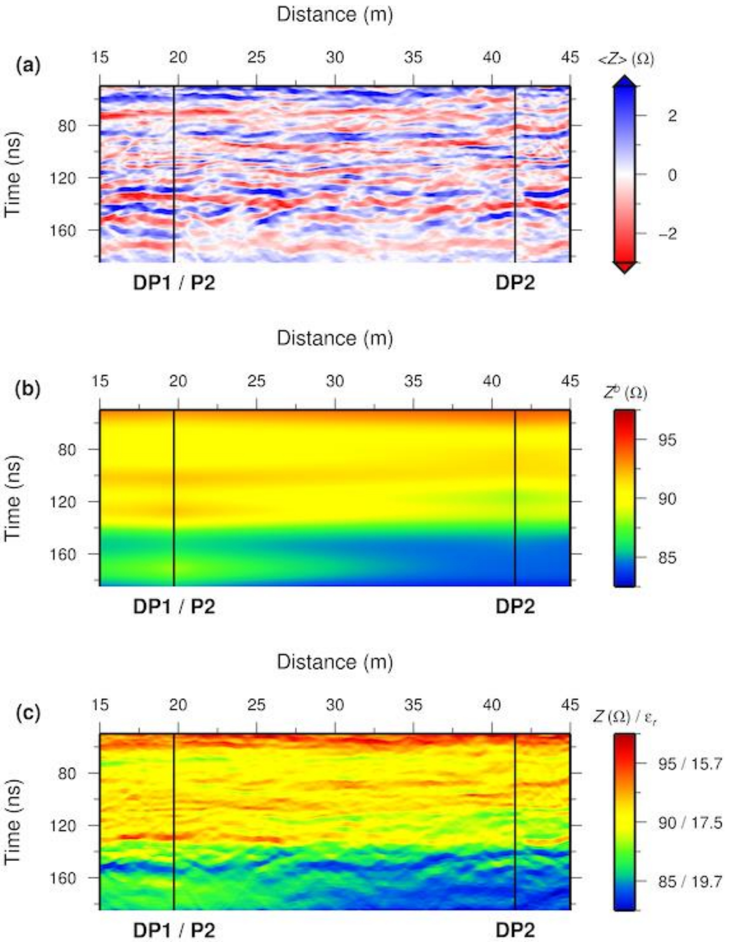
For EM waves, the magnetic field intensity is analogous to the electric current or material displacement while the electric field is equivalent to the driving voltage or the mechanical stress applied. The Electromagnetic impedance Z for the plane-wave fields is defined as the scalar ratio of the field amplitudes:

For non conductive materials

$$Z = \frac{|\boldsymbol{E}|}{|\boldsymbol{H}|} = \mu v = \sqrt{\frac{\mu}{\varepsilon}}$$

When the conductivity is not negligible:

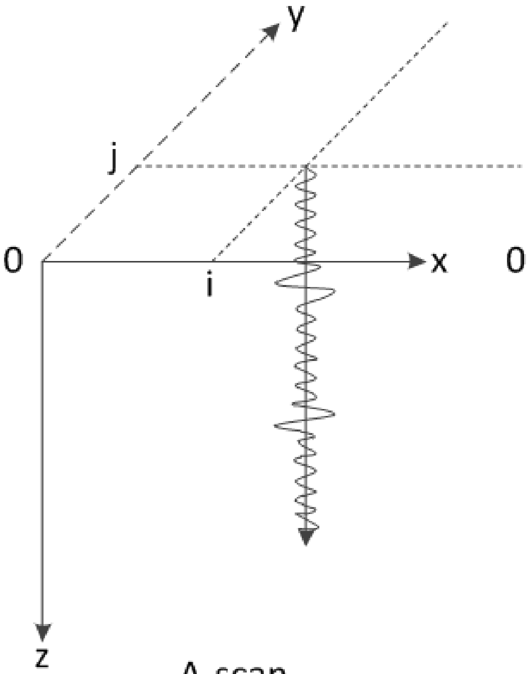
$$Z \approx \sqrt{\frac{\mu}{\varepsilon}}\left(1 - i\,\frac{\sigma}{2\omega\varepsilon}\right)$$



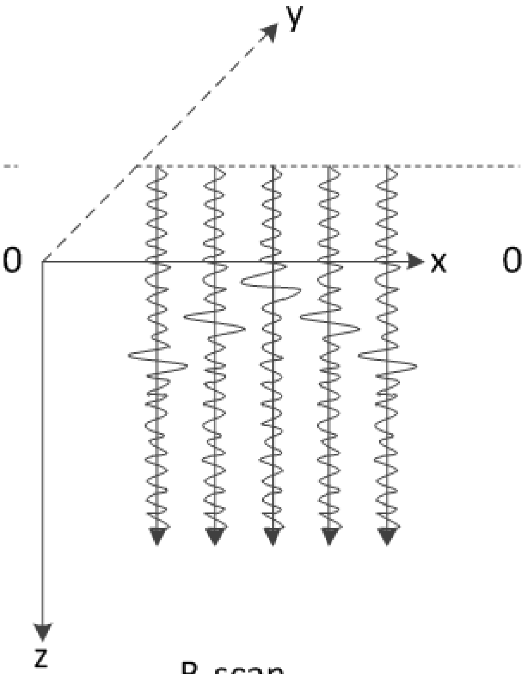
Schmelzbach et al., 2012

Ground Penetrating Radar: type of measurement

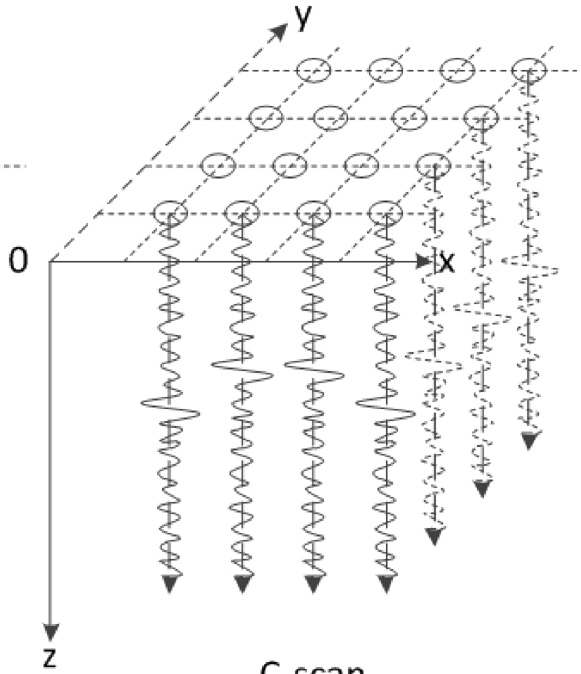
A-SCAN, B-SCAN, C-SCAN



A-scan



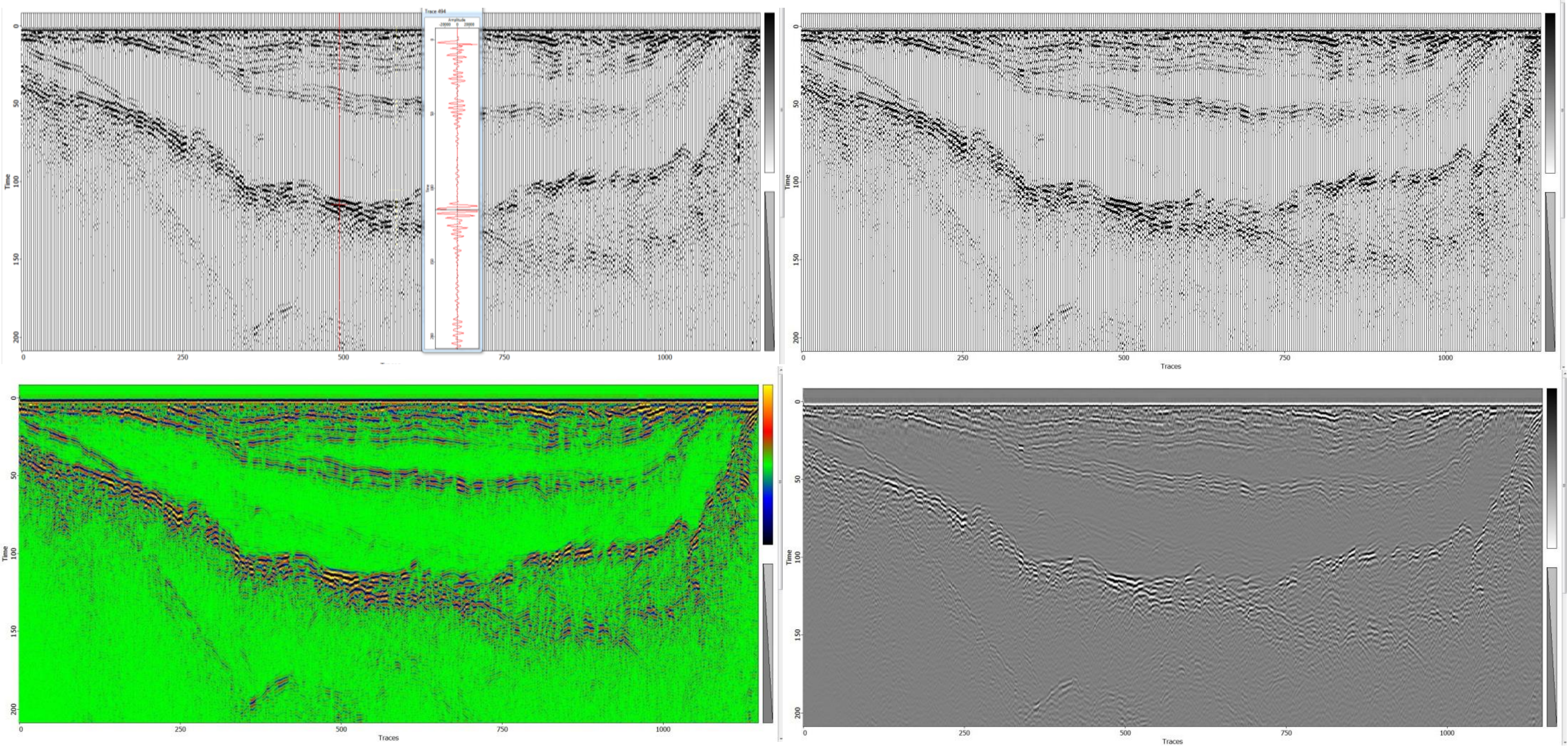
B-scan



C-scan

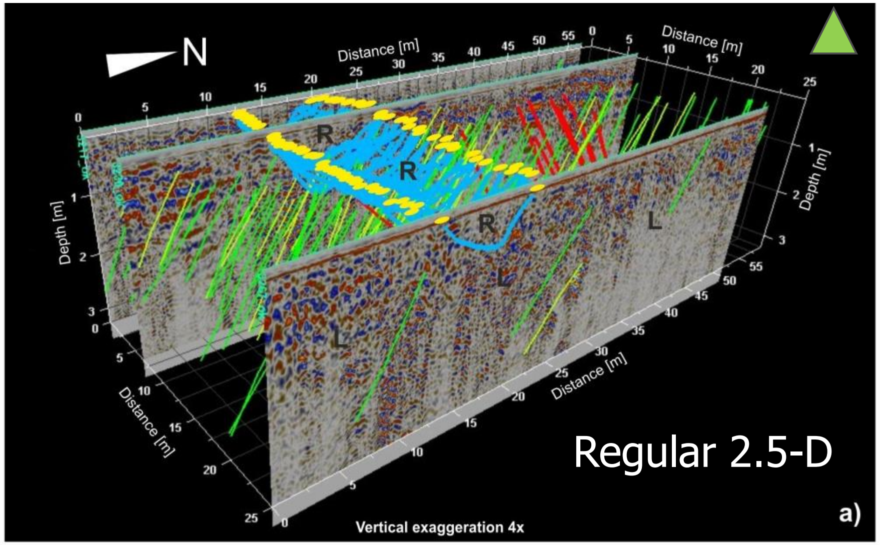
Ground Penetrating Radar: type of measurement

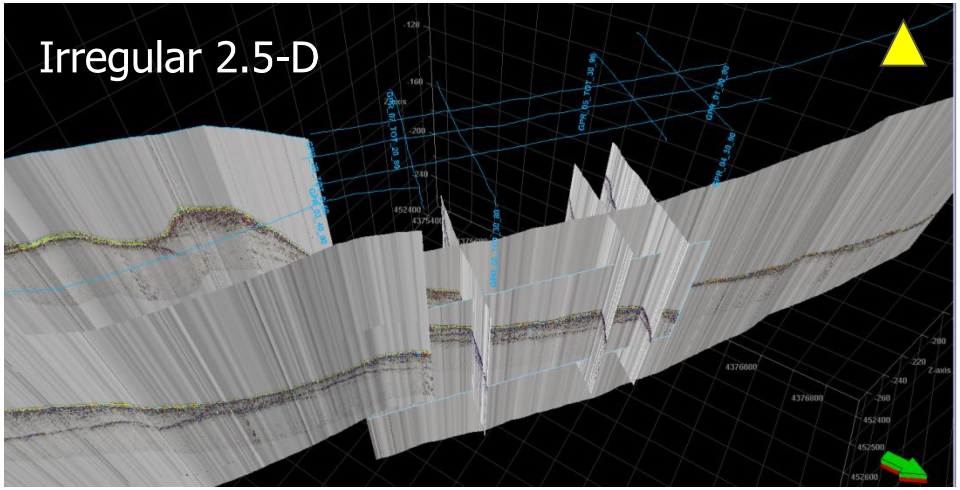
A-SCAN, B-SCAN, C-SCAN

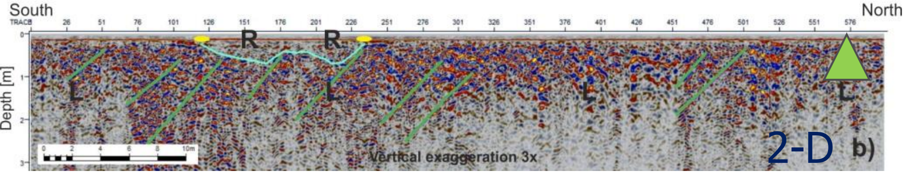


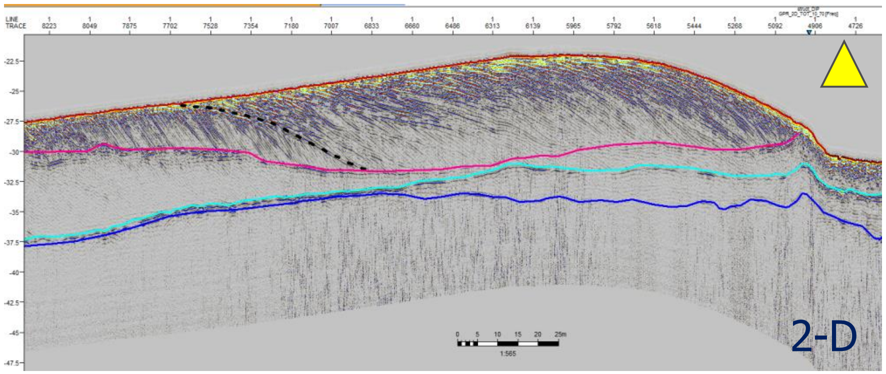
Ground Penetrating Radar: type of measurement

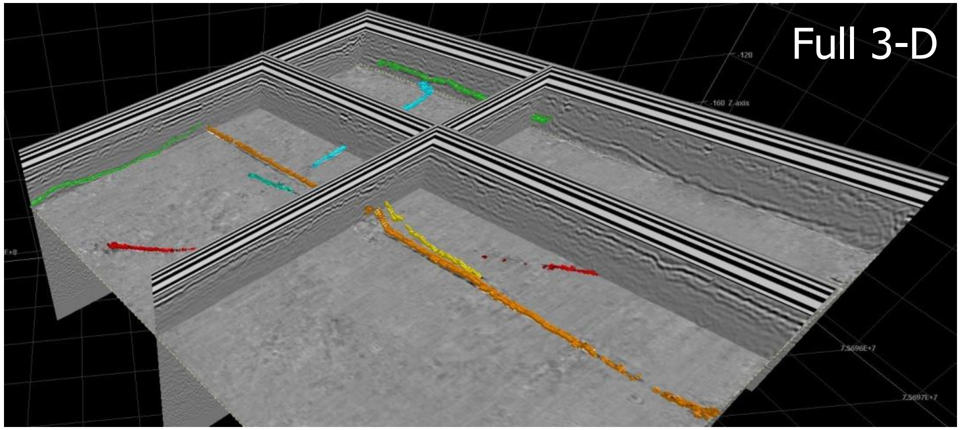
2-D, 2.5-D, 3-D











Ground Penetrating Radar: EM properties

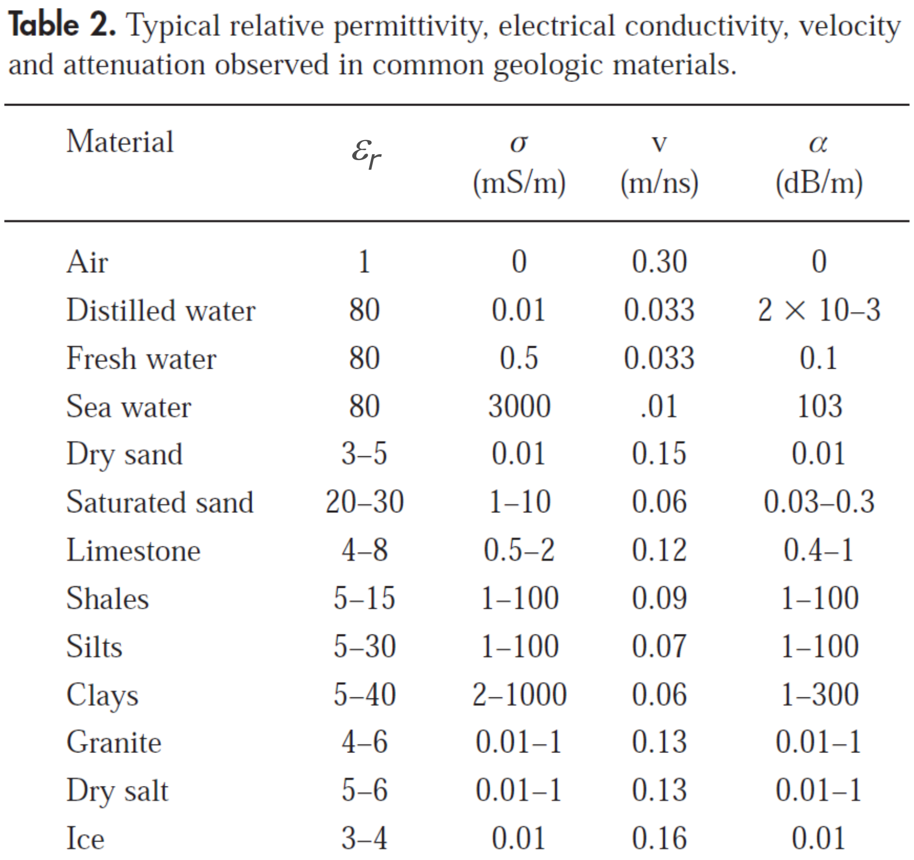


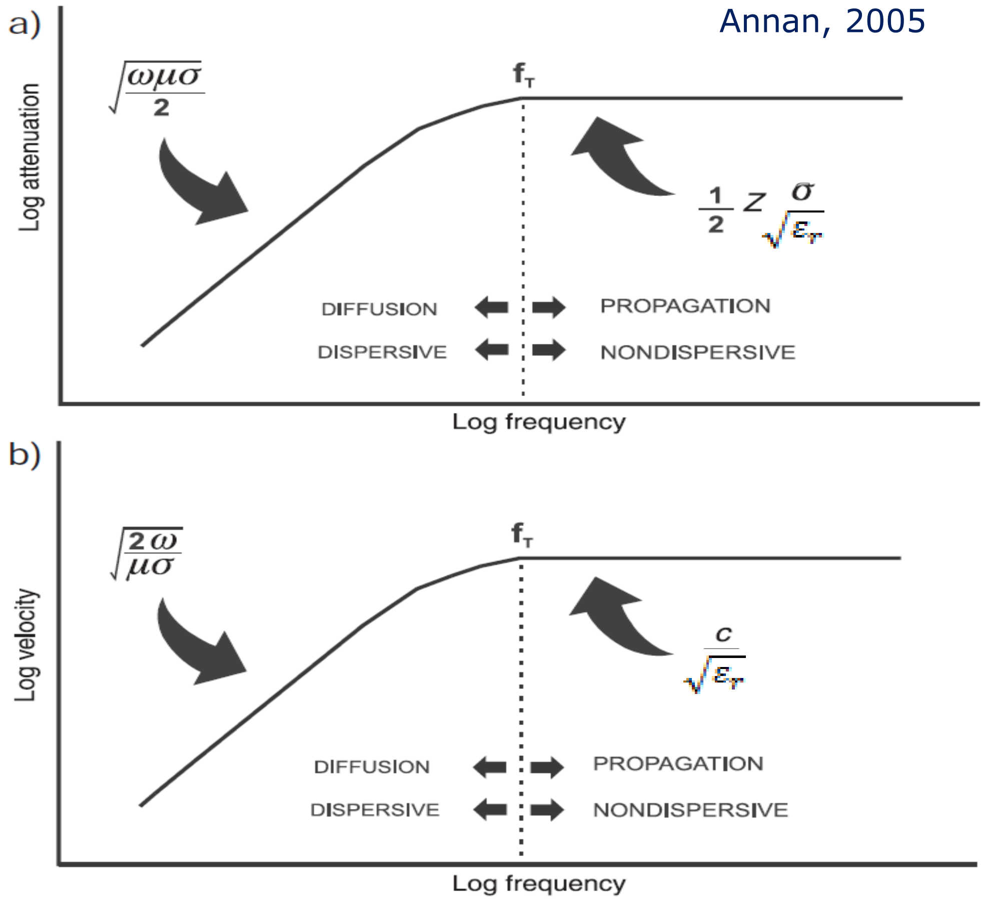
Table 2. Typical relative permittivity, electrical conductivity, velocity and attenuation observed in common geologic materials.

Material	ε_r	σ (mS/m)	v (m/ns)	α (dB/m)
Air	1	0	0.30	0
Distilled water	80	0.01	0.033	2 × 10–3
Fresh water	80	0.5	0.033	0.1
Sea water	80	3000	.01	103
Dry sand	3–5	0.01	0.15	0.01
Saturated sand	20–30	1–10	0.06	0.03–0.3
Limestone	4–8	0.5–2	0.12	0.4–1
Shales	5–15	1–100	0.09	1–100
Silts	5–30	1–100	0.07	1–100
Clays	5–40	2–1000	0.06	1–300
Granite	4–6	0.01–1	0.13	0.01–1
Dry salt	5–6	0.01–1	0.13	0.01–1
Ice	3–4	0.01	0.16	0.01

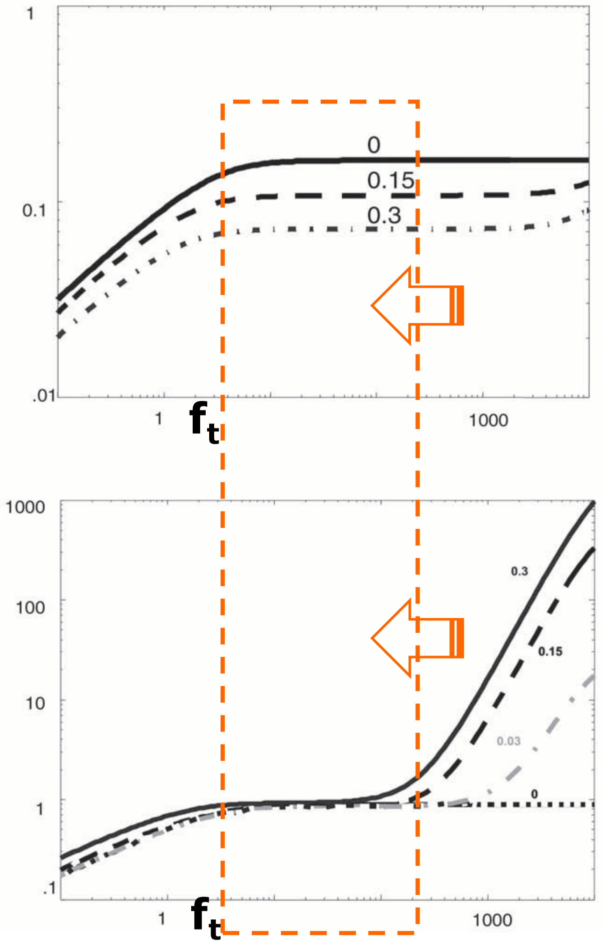
Annan, 2005

- Bulk minerals and aggregates in mixtures generally are good dielectric insulators. They typically have a relative permittivity in the range of 3 to 8 and are usually insulating with a close to zero conductivity.
- Soils, rocks, and construction materials such as concrete, asphalt, etc., have empty space between the grains (pore space) available to be filled with air, water, or other material.
- Water is by far the most polarizable, naturally occurring material (in other words it has a high permittivity with $\varepsilon_r = 80$).
- Water in the pore space normally contains ions and the water conductivity associated with ion mobility is the dominant factor in determining bulk material conductivity.
- Since water is invariably present in the pore space of natural (geologic) materials, except in such unique situations where vacuum drying or some other mechanism assures the total absence of water, it has a dominant effect on electrical properties.

Ground Penetrating Radar: EM properties



Annan, 2005



Within the **GPR plateau**, i.e. **between about 10 MHz to a few GHz**, the electromagnetic field propagates as **waves** through the medium. All frequency components travel at the same velocity and suffer the same attenuation ➔ i.e. **no DISPERSION** occurs. An impulsive signal will travel with its shape intact with time (except for amplitude decreasing due to attenuation).

For a simple material (i.e. no mixed, no heterogeneous, isotropic) the **transition frequency f_t** can be estimated as:

$$f_t = \frac{\sigma}{2\pi\varepsilon}$$

For real material containing varying water contents some dispersion can occur even within the **GPR plateaux**.

Ground Penetrating Radar: velocity

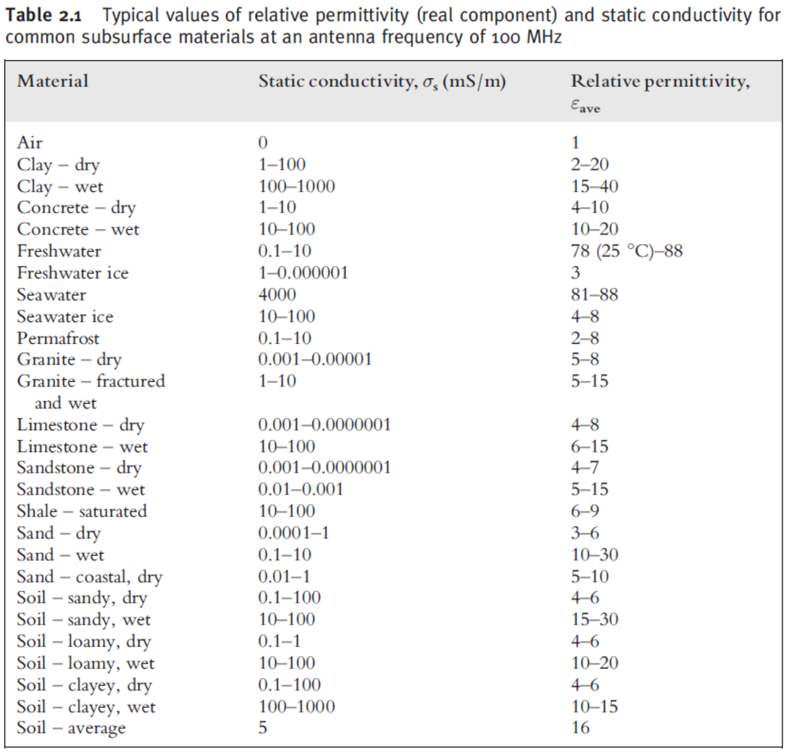


Table 2.1 Typical values of relative permittivity (real component) and static conductivity for common subsurface materials at an antenna frequency of 100 MHz

Material	Static conductivity, σ_s (mS/m)	Relative permittivity, ε_{ave}
Air	0	1
Clay – dry	1–100	2–20
Clay – wet	100–1000	15–40
Concrete – dry	1–10	4–10
Concrete – wet	10–100	10–20
Freshwater	0.1–10	78 (25 °C)–88
Freshwater ice	1–0.000001	3
Seawater	4000	81–88
Seawater ice	10–100	4–8
Permafrost	0.1–10	2–8
Granite – dry	0.001–0.00001	5–8
Granite – fractured and wet	1–10	5–15
Limestone – dry	0.001–0.0000001	4–8
Limestone – wet	10–100	6–15
Sandstone – dry	0.001–0.0000001	4–7
Sandstone – wet	0.01–0.001	5–15
Shale – saturated	10–100	6–9
Sand – dry	0.0001–1	3–6
Sand – wet	0.1–10	10–30
Sand – coastal, dry	0.01–1	5–10
Soil – sandy, dry	0.1–100	4–6
Soil – sandy, wet	10–100	15–30
Soil – loamy, dry	0.1–1	4–6
Soil – loamy, wet	10–100	10–20
Soil – clayey, dry	0.1–100	4–6
Soil – clayey, wet	100–1000	10–15
Soil – average	5	16

Jol, 2009

The EM velocity within geological media has a range between about **0.03 and 0.3 m/ns.**

In a conductive medium (possibly due to both conduction and polarization):

$$v_m = \frac{c}{\sqrt{\frac{\varepsilon_r \mu_r}{2}\left[\sqrt{1+p^2}+1\right]}}$$

Where, as already shown

$$p = \tan\delta = \frac{\sigma' + \omega\varepsilon''}{\omega\varepsilon' - \sigma''} \cong \underbrace{\frac{\varepsilon''}{\varepsilon'}}_{\text{Polarizazion losses}} + \underbrace{\frac{\sigma_{DC}}{\omega\varepsilon'}}_{\text{Conduction losses}}$$

In a dielectric medium (with only possible polarization effects):

$$v_m = \frac{1}{\sqrt{\varepsilon_m \mu_m}} = \frac{1}{\sqrt{\varepsilon_0 \varepsilon_r \mu_0 \mu_r}} = \frac{c}{\sqrt{\varepsilon_r \mu_r}} \cong \frac{c}{\sqrt{\varepsilon_r}}$$

being c equals to v_{EM} in the void (i.e. v_0)

$$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} = \frac{1}{\sqrt{8.85x10^{-12} \cdot 4\pi x10^{-7}}} \cong 3x10^8 m/s$$

Ground Penetrating Radar : velocity

v_{EM} [cm/ns] in some low loss (σ<0.1S/m) geologic materials

Medium	ε_r	v_{EM} [cm/ns]
Air	1	30
Fresh water	80	3.3
Dry sand	4-8	12-15
Saturated sand	30	5.5
Permafrost	5	13
Ice	3	17
granite	5	13
Carbonatic rocks	7-9	10-11

Therefore, mainly depending by the polarization effects, the velocity of the EM waves is decreased by a factor which is maximum when water is present in liquid state, while ice is a quite good dielectric with only moderate polarization effects.

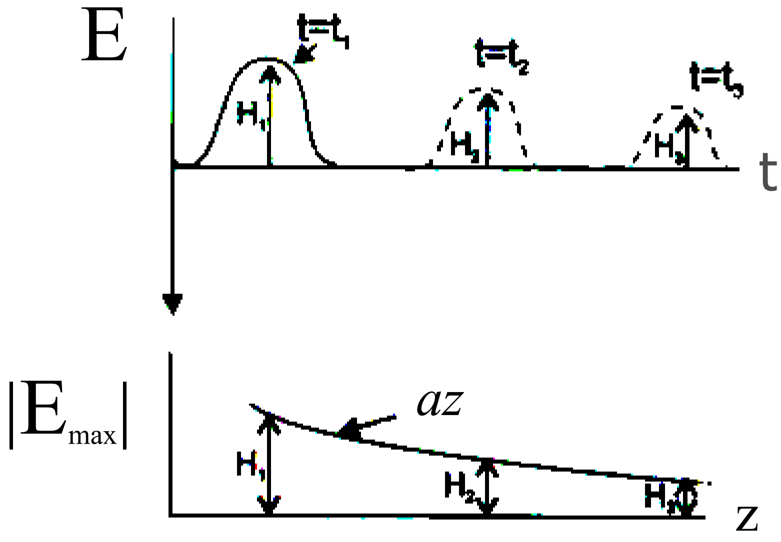
The main physical parameter defining the EM velocity is ε.

Ground Penetrating Radar: attenuation

In the general case:

$$\alpha = \omega\sqrt{\left[\frac{\mu\varepsilon'}{2}\sqrt{1+(tan\delta)^2}-1\right]}$$

$$\tan\delta = \frac{\sigma' + \omega\varepsilon''}{\omega\varepsilon' - \sigma''}$$



For low loss materials:

$$\tan\delta \cong \frac{\sigma_{DC}}{\omega\varepsilon} \qquad \alpha \cong \frac{\mu\sigma f}{2}$$

α is often referred as **INTRINSIC ATTENUATION** since it depends by EM medium parameters. The main physical parameter controlling the attenuation is the electrical conductivity σ, which varies by several order of magnitude. A minor effect is related to the dielectrical conductivity (polarization) ➔ ε varies by just two order of magnitude.

Within the GPR plateaux the dispersion effects for both σ and ε can be disregarded.

The main physical parameter determining the EM intrinsic attenuation is σ.
This in turn is related to the maximum penetration depth.

Questions?