Ground Penetrating Radar

GPR, RADAR (Radio detection and Ranging)

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Introduction

- GPR is a geophysical measurement technique which can be applied to explore near-surface underground structures.

- The measurement principle is based on the transmittance (transmitting antenna) of high-frequency (50MHz – 2.5 GHz) electromagnetic pulses into the ground. Reflection or Refraction at inhomogeneities are received (receiving antenna).

- Travel time and amplitude give information about the structure and depth of the inhomogeneities.

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Applications

- **Geological**
  - Detection of cavities and fissures
  - Mapping of superficial deposits, subsidence, soil stratigraphy, fractures, etc.
  - Mineral exploration and resource evaluation
  - (Paleo-) Lake and riverbed mapping
- **Environmental**
  - Contaminant plume mapping
  - Location of gas leaks
  - Groundwater-level
  - Mapping of pollutants within groundwater
- **Glaciological**
  - Ice thickness and snow stratigraphy

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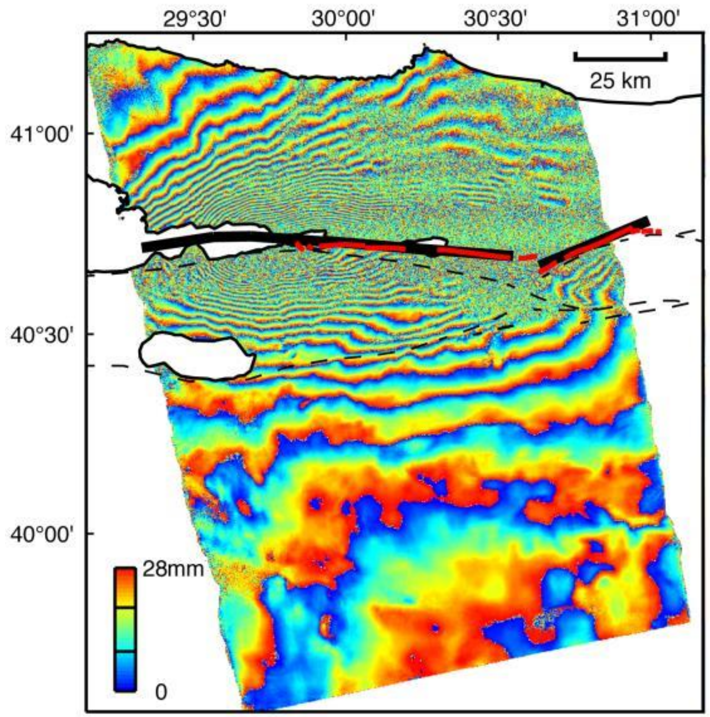
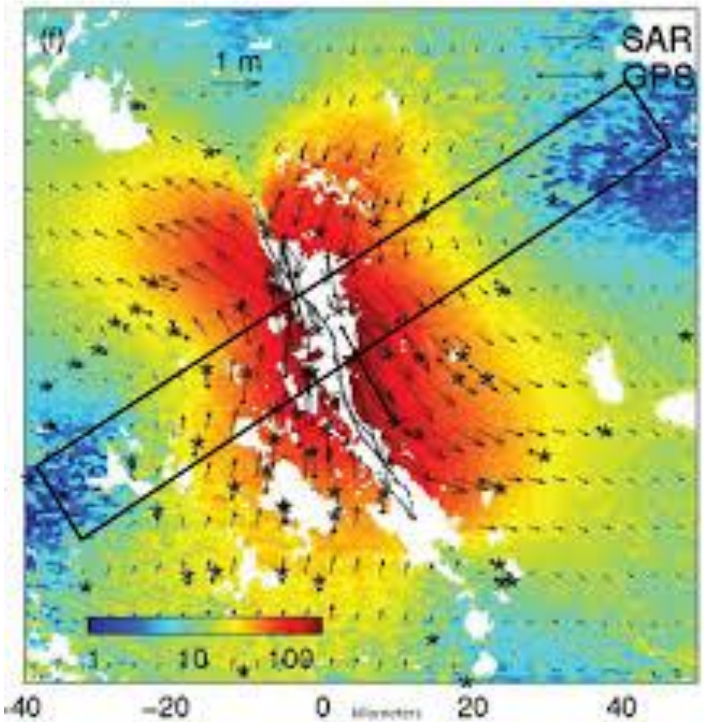
Applications

- **Engineering and construction**
  - Void detectiaon
  - Road pavement
  - Concrete testing
  - Location of public utilities
- **Archaeology**
  - Location of buried structures
  - Pre-excavation mapping
  - Location of graves, crypts, etc.
- **Forensic science**
  - Location of buried corpses

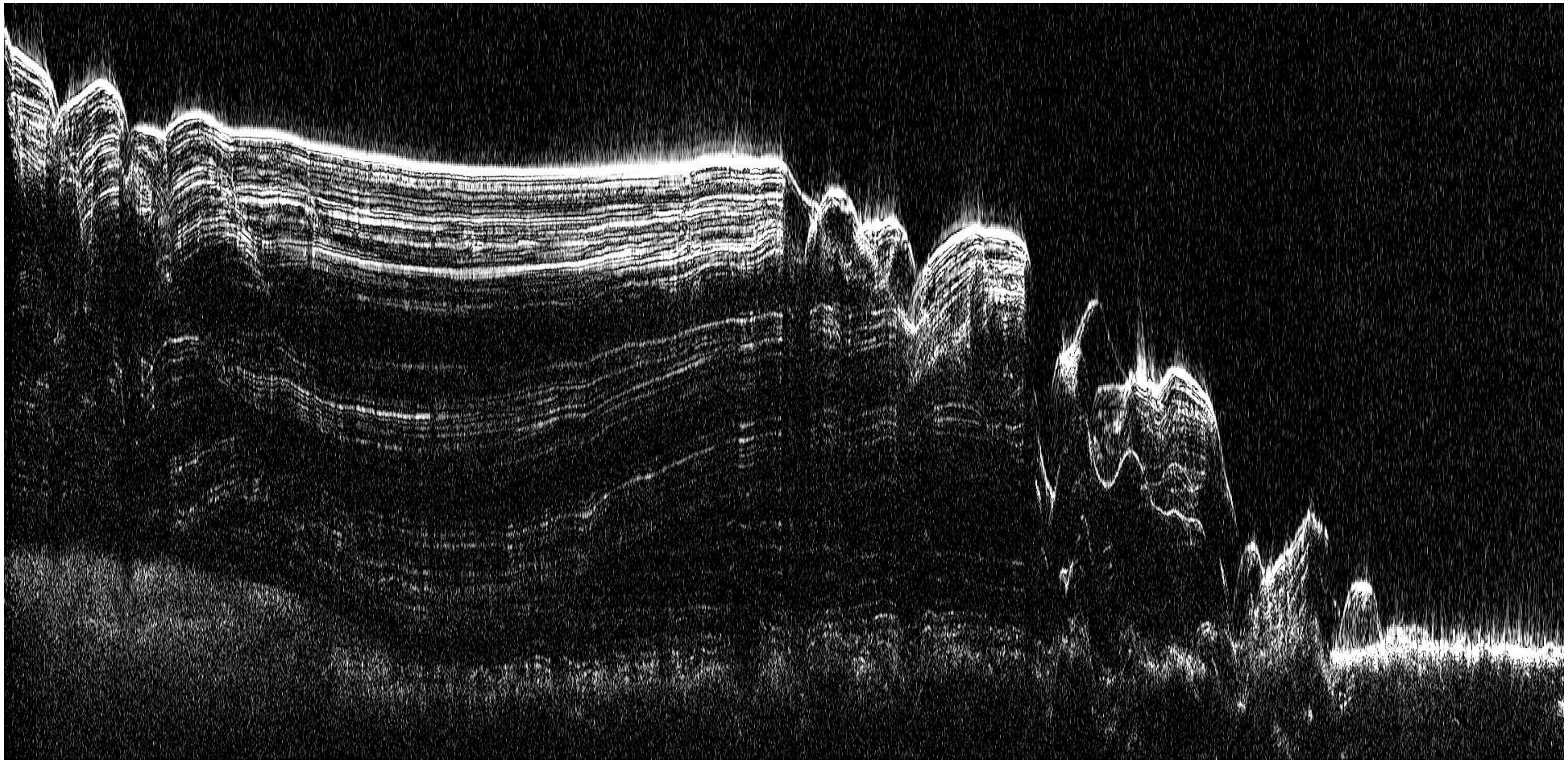
Interferometric synthetic aperture radar - InSAR



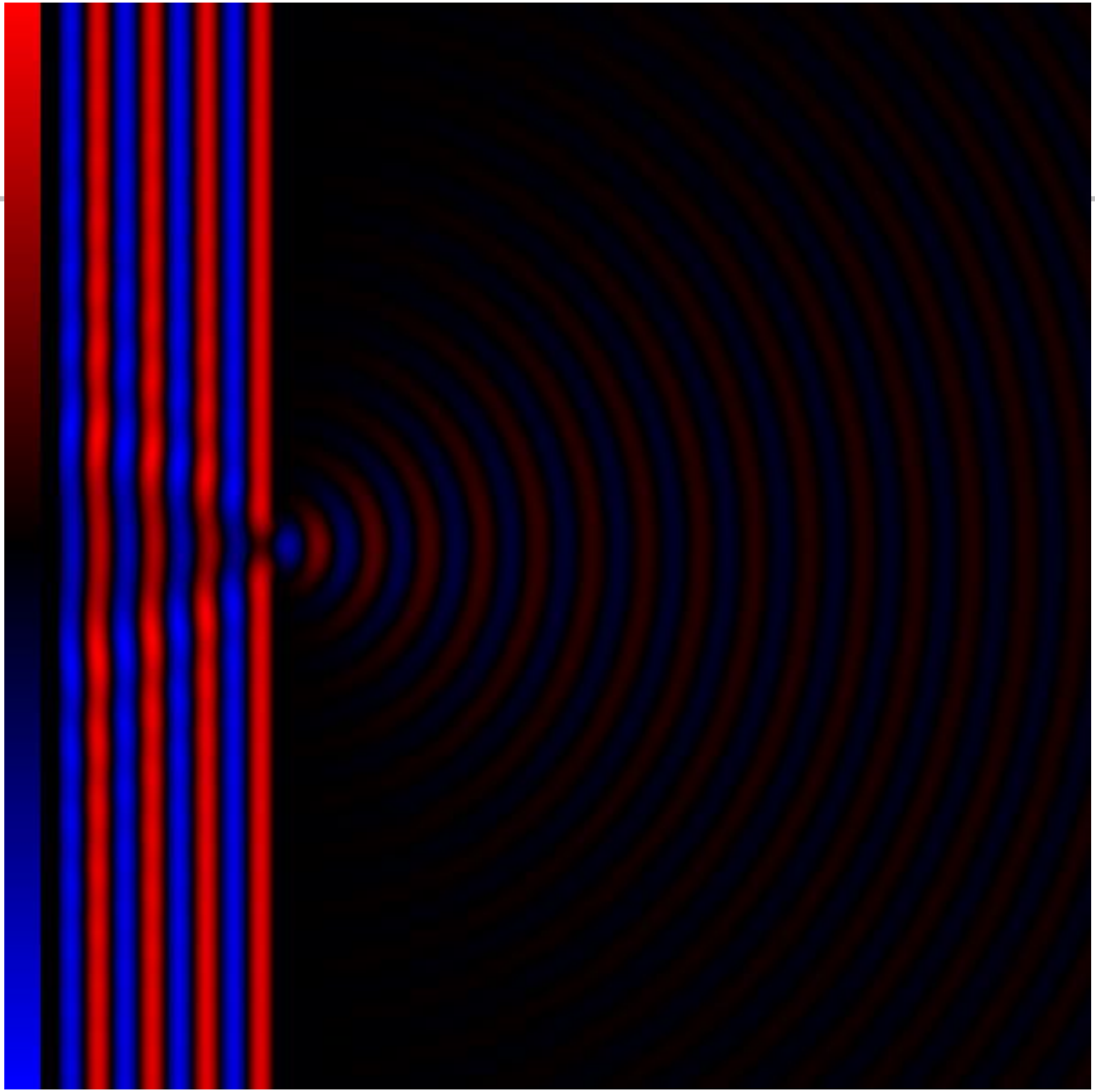


Interferogram produced using ERS-2 data from 13 August and 17 September 1999, spanning the 17 August Izmit (Turkey) earthquake. (NASA/JPL-Caltech)

Shallow radar sounder - SHARAD



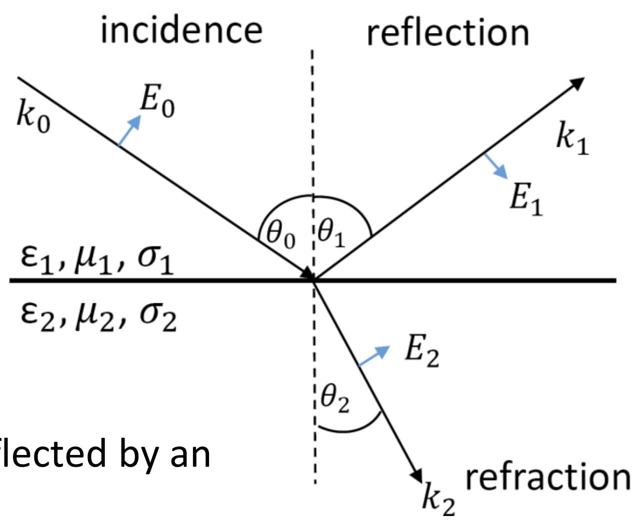
Radargram of north pole layered deposits (ASI, Mars Reconnaissance Orbiter)



Diffraction of a scalar wave passing through a 1-wavelength-wide slit (Wikipedia)

Propagation of electromagnetic waves

- **The emitted electromagnetic waves are affected by**
  - Dielectric properties ε_r
  - Magnetic susceptibility μ_r
  - Electrical conductivity σ_e

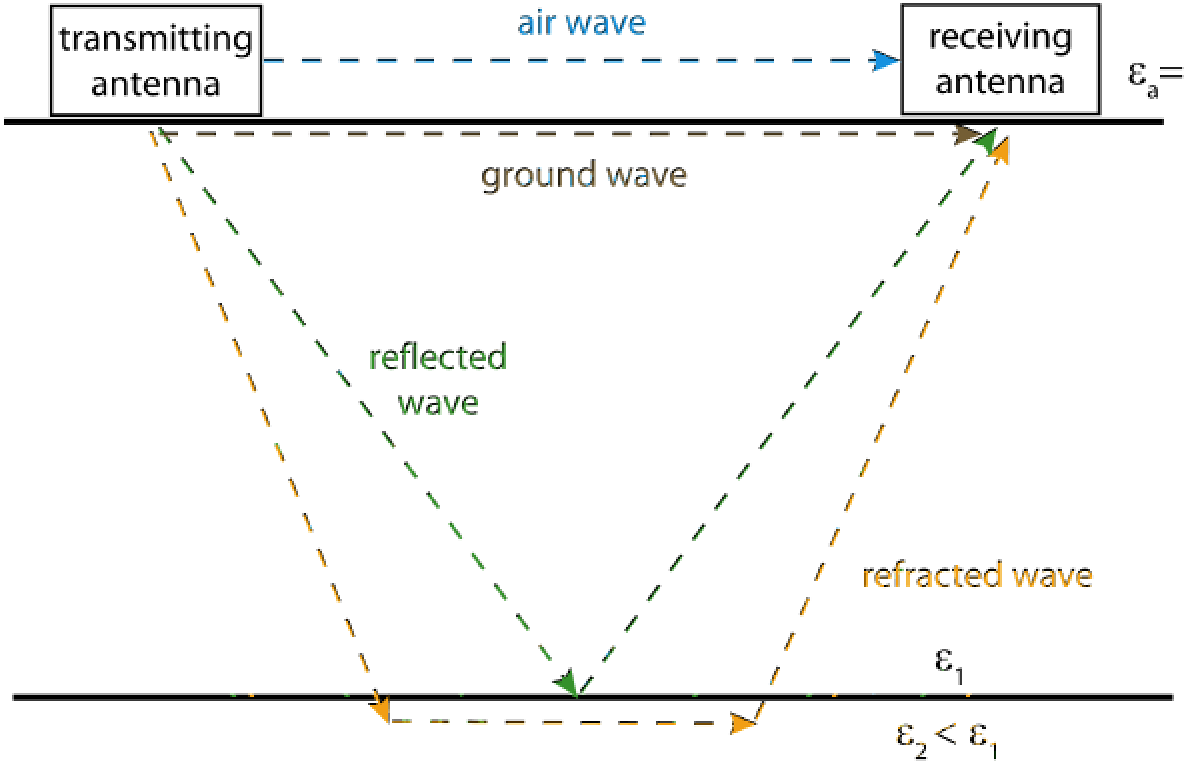


- **Reflection coefficient**
  - Describes how much of an electromagnetic wave is reflected by an impedance discontinuity in the transmission medium.
  - Of a plane (fraction of the reflected energy at the plane for normal inclination is:

$$R = \frac{v_1 - v_2}{v_1 + v_2} = \frac{\mathrm{sqrt}(\varepsilon_2) - sqrt(\varepsilon_1)}{sqrt(\varepsilon_2) + sqrt(\varepsilon_1)}$$

Measurement principle

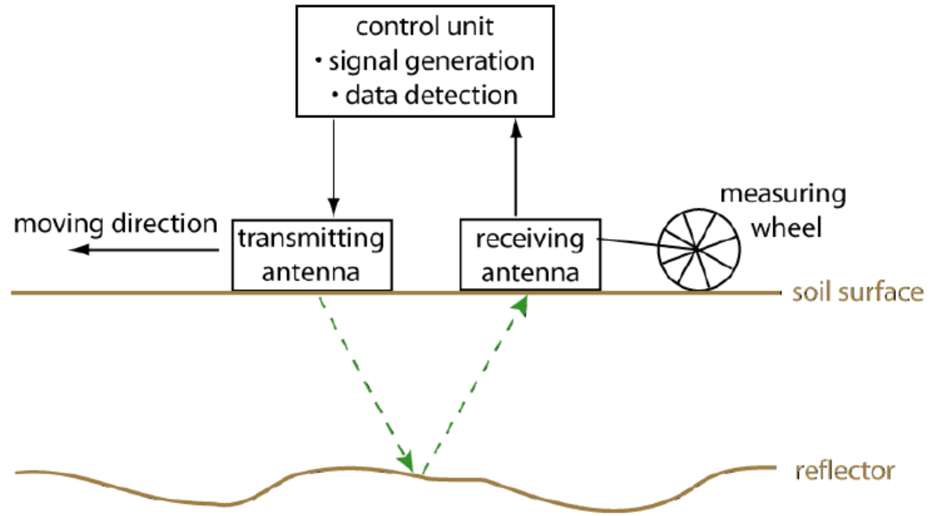
- The standard system consist of a transmitting and receiving antenna. The radar wave propagates through the soil while the velocity of the wave depends on the dielectric properties of the ground. At interfaces, where the dielectric properties of the different media change, the electromagnetic wave is partially reflected. The travel time and amplitude of the wave is recorded by the receiving antenna.



Ludwig et al. (2011)

Measurement principle

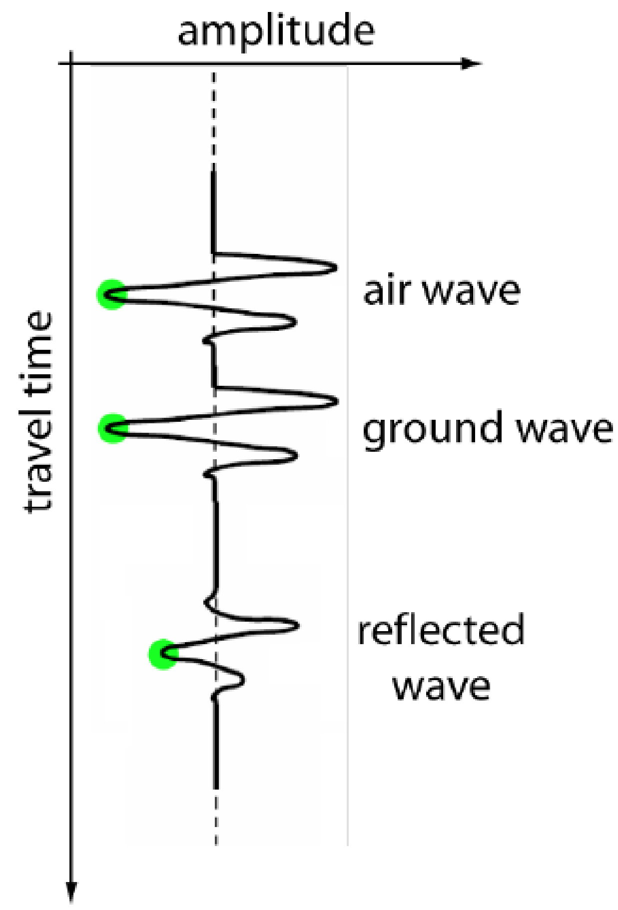
- In a standard GPR measurement, the antennas are pulled along the survey track while traces are triggered at a fixed interval by a measurement wheel which is connected to the back of the antenna. This results in a series of traces which are finally displayed by the measurement software as a function of position and time in a so-called radargram.
- The sampling interval and the antenna frequency has to follow the Nyquist-Shannon sampling theorem:
- $f_{Nyq} = \frac{1}{2\Delta t} > fma_x \ (f_{max} \ is \sim antenna \ frequency + 50\%)$



Ludwig et al. (2011)

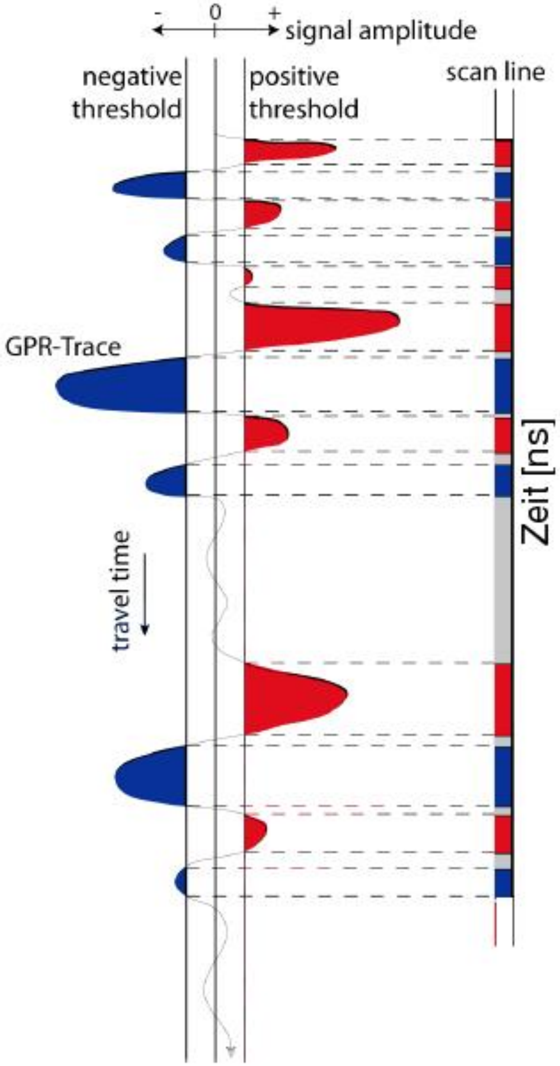
Measurement principle

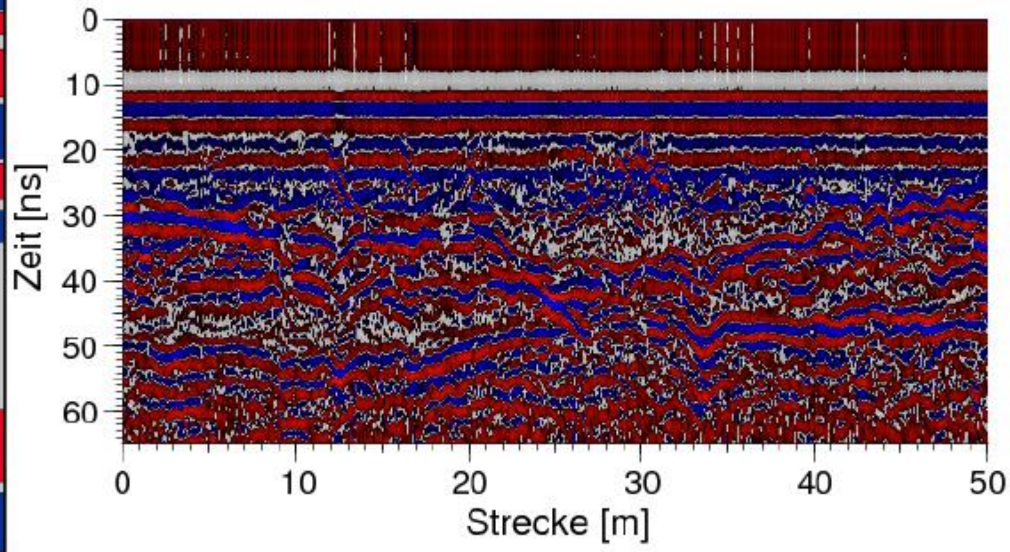
- The signals of the emitted waves reach the receiving antenna at different times. Plotting the recorded amplitudes as a function of time results in a so-called “trace”.



Ludwig et al. (2011)

Measurement principle





Origin of a radargram. Amplitudes which excess a pre-defined positive or negative threshold are displayed in color. Negative amplitudes are shown in blue while positive amplitudes are displayed in red (Ludwig et al., 2011 after Reynolds, 2011).

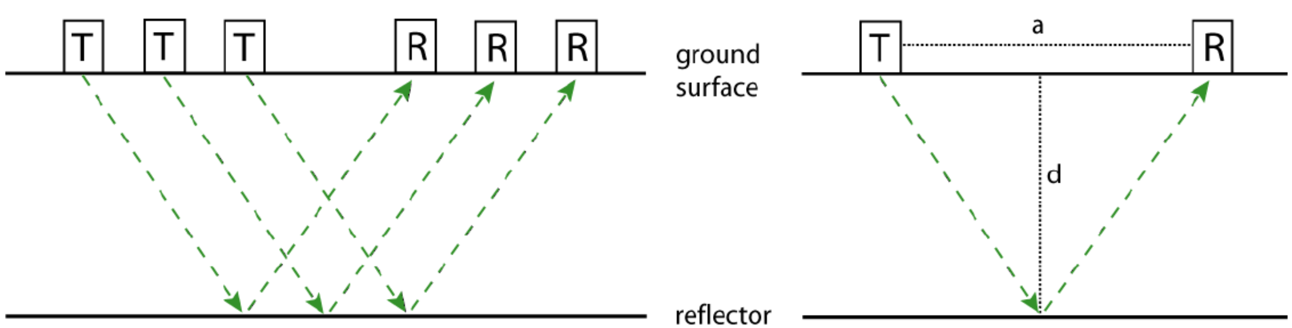
Measurement principle

- **Common offset (CO):**
  - Is the simplest and most widespread GPR measurement technique. Transmitter and receiver antenna are moved along the survey track while the distance between both antenna is kept constant. Electromagnetic pulses are emitted at equidistant intervals which are controlled by the survey wheel.
  - From the measured travel time *t* of the reflected signal the depth *d* of a horizontal reflector can be determined by:

$$s = 2 \cdot \sqrt{d^2 + \left(\frac{a}{2}\right)^2} = \sqrt{4d^2 + a^2}$$, with a as distance between antennas.

  - Assuming a homogeneous medium the travel time is determined by:

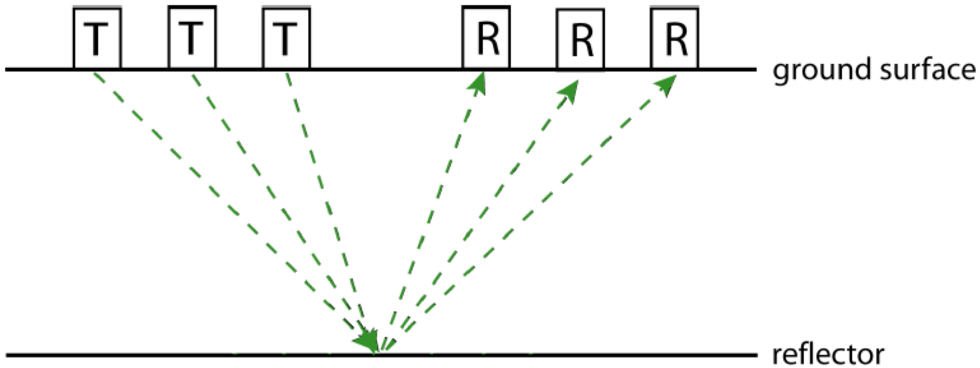
$$t = \frac{s}{v} = \frac{\sqrt{4d^2 + a^2}}{\frac{c}{\sqrt{\varepsilon'}}}.$$

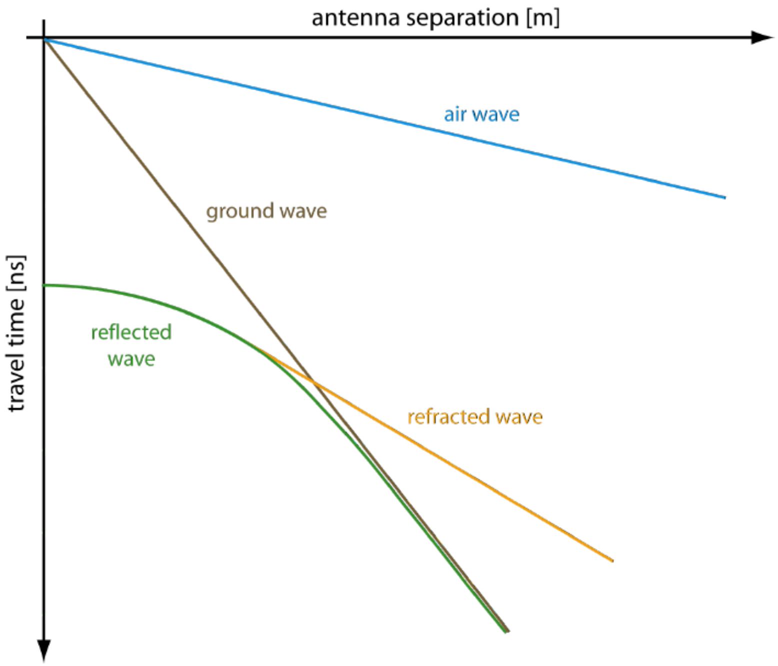


Ludwig et al. (2011)

Measurement principle

- **Multi offset: Common midpoint**
  - In a common-midpoint measurement (CMP) transmitter and receiver are moved away from each other in equidistant steps. The resulting radargram displays the travel time as a function of the antenna separation.





Ludwig et al. (2011)

Measurement principle

- **Multi offset: Common midpoint**
  - Air and ground wave travel directly between the antenna.
  - Linear relationship between the travel time t and the antenna separation a with the constant of proportionality $\frac{1}{v}$:

$$t = \frac{a}{v}, \text{with } v = c \text{ (airwave) and } v = \frac{c}{\sqrt{\varepsilon}} \text{ (groundwave)}$$

  - Reflector depth below the midpoint between the transmitting and the receiving antenna: the relation between travel time t reflector depth is given by:

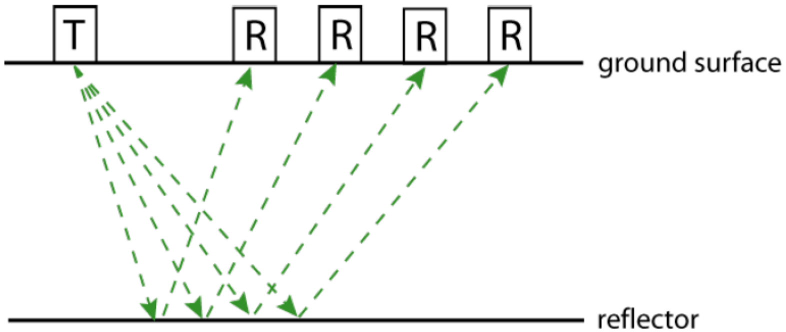
$$s = 2 \cdot \sqrt{d^2 + \left(\frac{a}{2}\right)^2} = \sqrt{4d^2 + a^2}$$

  - Plotting the measured data in a t^2-a^2-diagram, leads to a linear relationship between t and a:

$$t^2 = \frac{1}{v^2}a^2 + \frac{4h^2}{v^2}$$

Measurement principle

- **Multi offset: Wide Angle Reflection and Refraction (WARR)**
  - Only the transmitting or receiving antenna is moved along the measurement line while the other antenna stays stationary.
  - In principle, a WARR measurement follows the same relationships concerning travel time as a CMP measurement. The difference is that the reflection point moves along the reflector. This is why a WARR measurement strictly is only applicable in the presence of horizontal or slightly sloping reflectors and material properties are homogeneous.



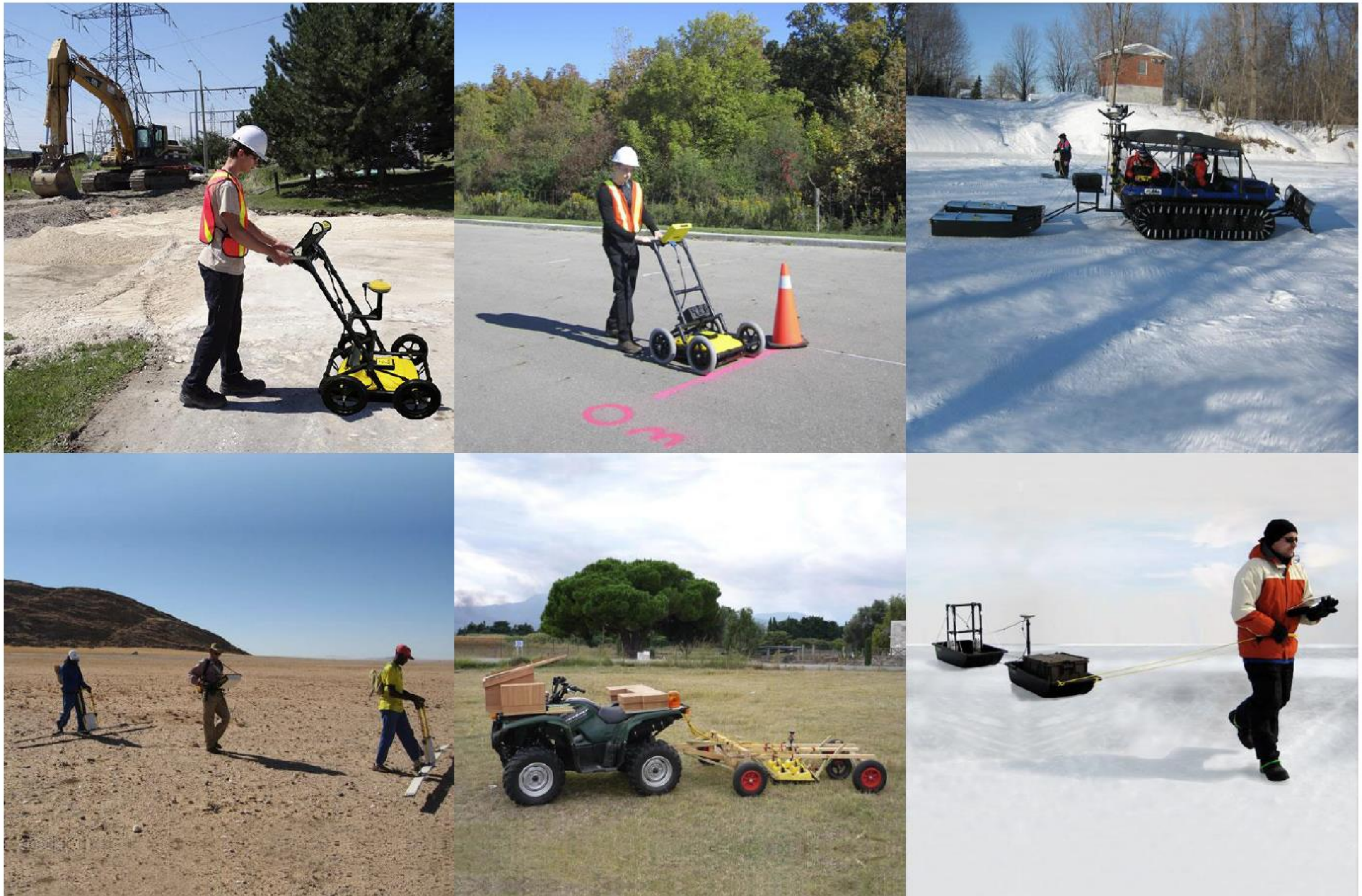
Ludwig et al. (2011)

  - CMP and WARR measurements provide more information than a CO measurement. The drawback of these techniques is the high measurement effort since both procedures only provide point information for a specific location. Both method are hardly applicable along long measurement lines

Measurement Systems

Fieldwork with ZOND 100 and 300 MHz antennas

Measurement Systems



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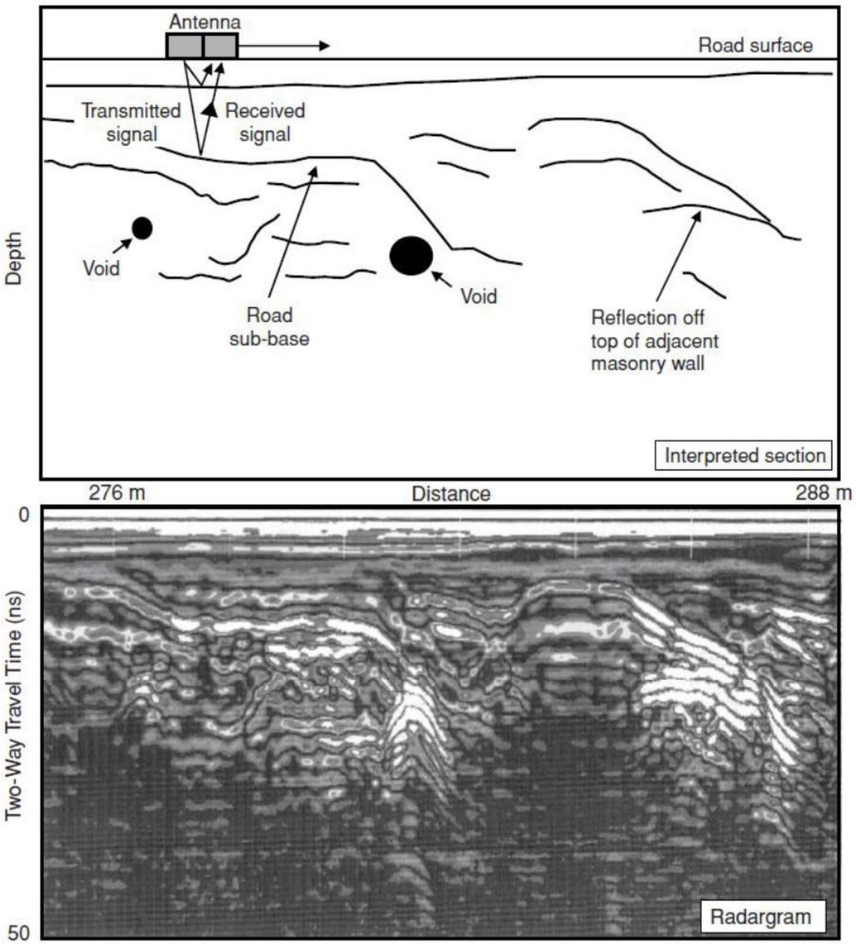
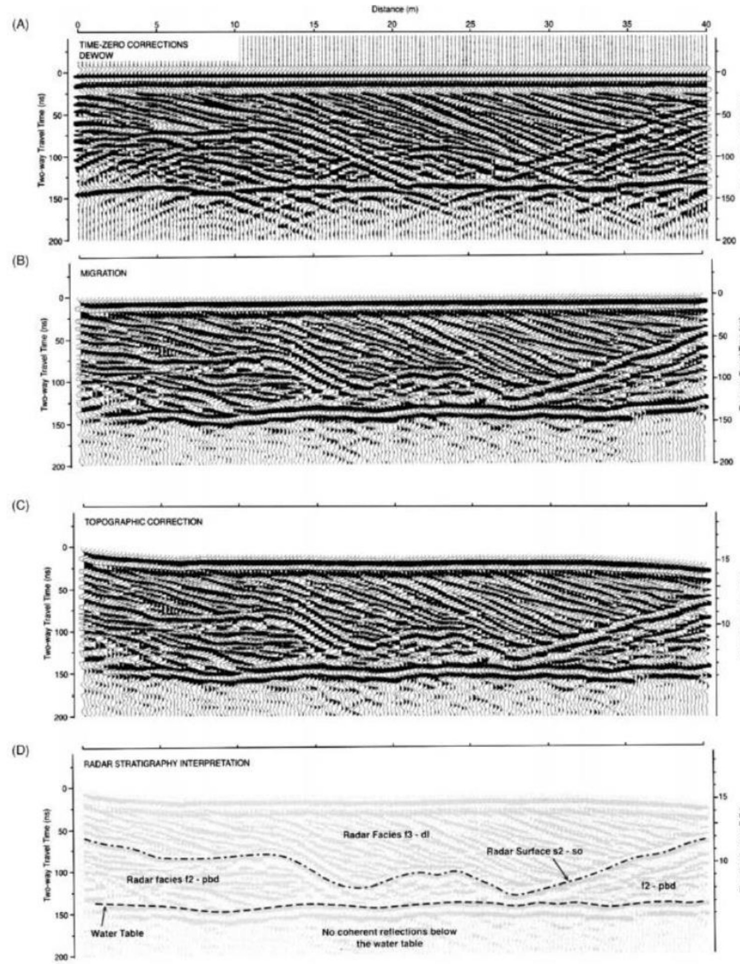
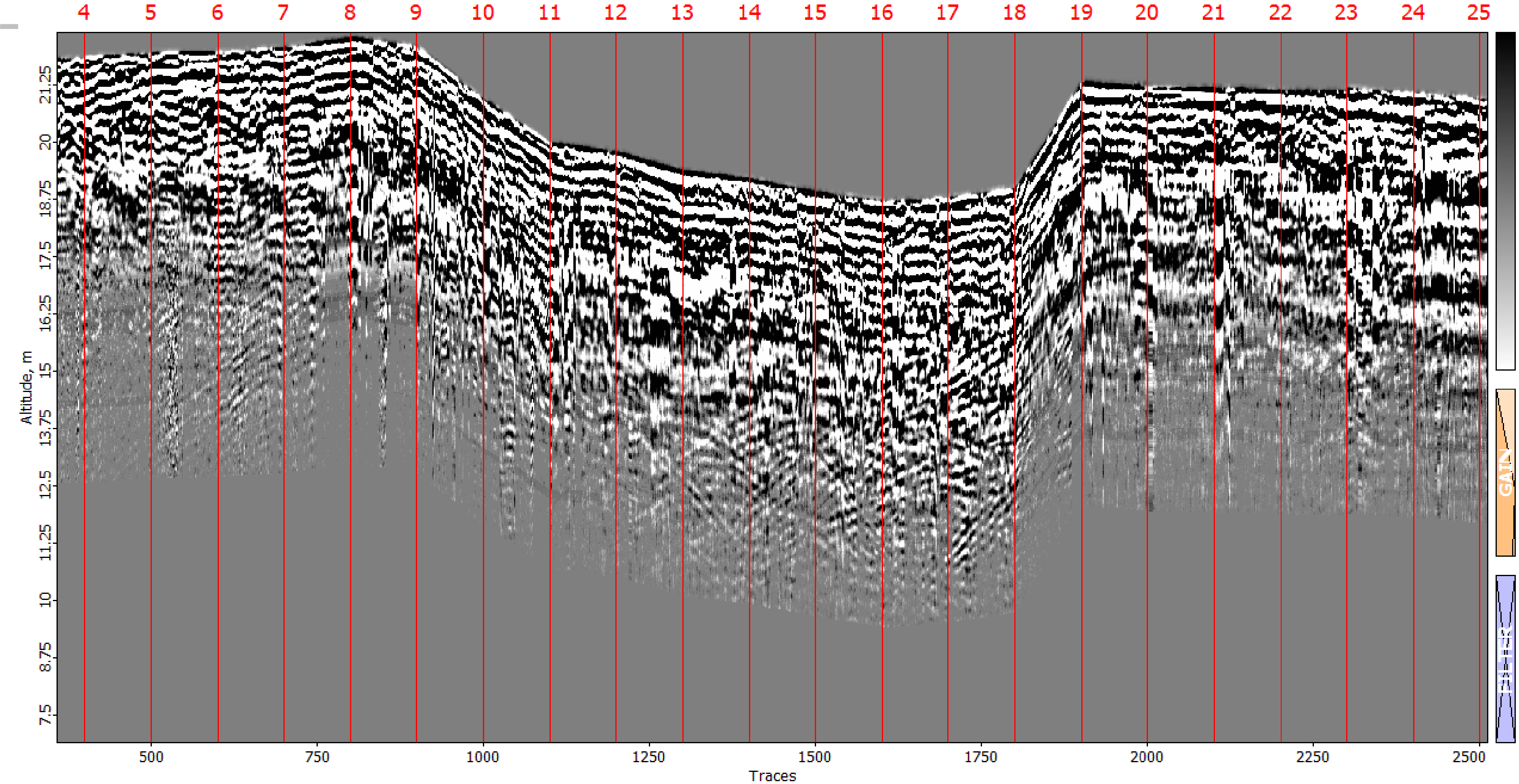
Measurement Systems





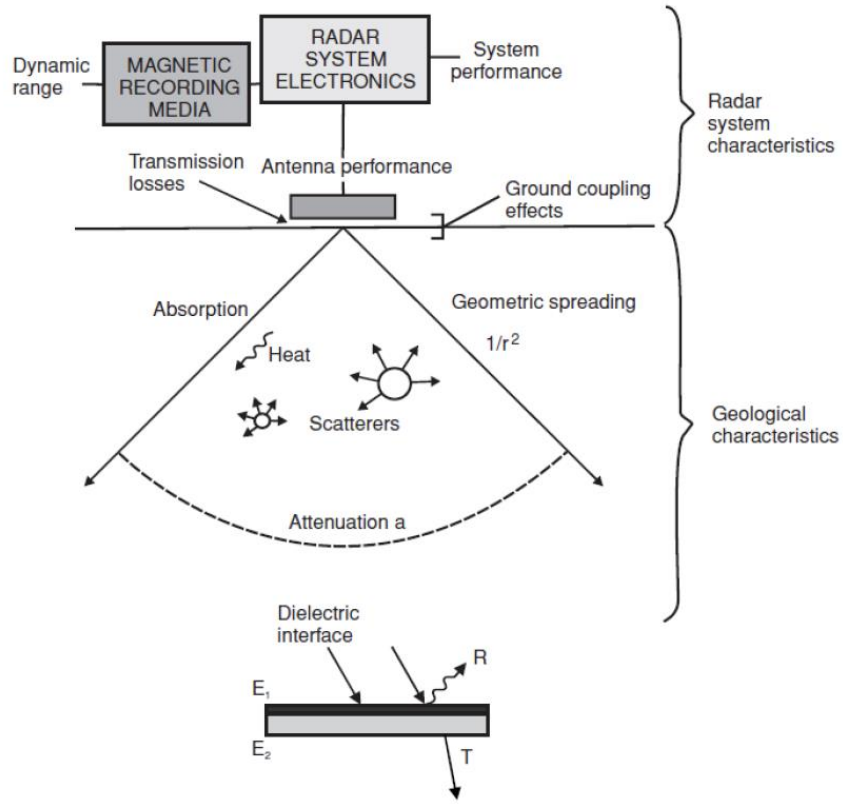
Reynolds, (2011)



Radargram Kaali Crater, Estonia

Energy loss and Penetration

- The electromagnetic signal is attenuated by different processes on its way through the soil.



Reynolds, (2011)

Energy loss and Penetration

- The largest amount of energy loss results from damping of free charge carrier movement. The material dependent attenuation is induced by the direct current electric conductivity σ_{dc} of the investigated medium. Depending on the traveled distance x the amplitude *E* of the electromagnetic wave decreases exponential with respect to its starting value E_0:

$$E(x) = E_0 e^{-\beta x}, \text{ with } \beta = \frac{\sigma_{dc}}{2 c_0 \varepsilon_0 \sqrt{\varepsilon}}.$$

- The higher σ_{dc} of the medium, the higher is the attenuation of the electromagnetic wave. In soils, electrical conductivity for example increases due to an increasing in soil moisture content, clay content or amount of dissolved solutes in the solution.

- The penetration depth of the electromagnetic waves reduces with increasing electrical conductivity of the medium. For salt water the penetration depth is only 1cm:

$$\delta = \frac{1}{\beta}$$

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