COST Action TU1208

Civil Engineering Applications of Ground Penetrating Radar

This lecture is part of the
TU1208 Education Pack

Environmental applications of GPR

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Lecture Layout

Part 1 – GPR inspection of trees

- Importance of health inspection of trees (trunks and roots).
- Use of GPR for the inspection of trees (main difficulties, assessment of trunks, assessment of roots).
- Case-studies: Tree trunk monitoring.

Part 2 – GPR inspection of agricultural fields

- Importance of agricultural field monitoring (soil moisture evaluation, soil erosion pipes detection, …).
- Use of GPR for precision agriculture.
- Case-studies: Soil moisture mapping.

References and **Author biographies**

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Part 1
GPR inspection of trees

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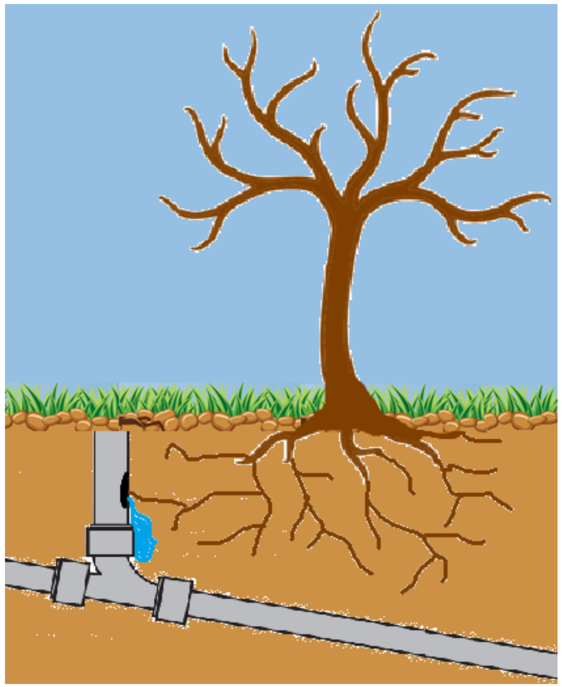
Importance of reliable monitoring of tree roots

- Importance of tree root investigation
  - Tree roots are the main organs influencing the health and stability of a tree
  - They absorb water and mineral nutrients
  - They anchor the tree into the ground and support it
  - They work as a nutrients storage
  - They are competing with other plants and obstacles

- Possible damages caused by tree roots
  - Construction damages
  - Utility damages
  - Stability problems



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Importance of reliable monitoring of tree trunks

- Importance of tree trunk investigation
  - The trunk is the body of a tree and supports its whole mass.
  - Voids and diseases can be hidden inside a trunk.
  - Voids and rotten wood can seriously harm the supporting function of a tree.
  - The collapse of a tree can injure people or destroy urban infrastructure.
  - Up-to-date information about the tree disease can help to stop infecting other trees.
  - Wood is an important building material -> it is very useful to detect voids, cracks, knots, …

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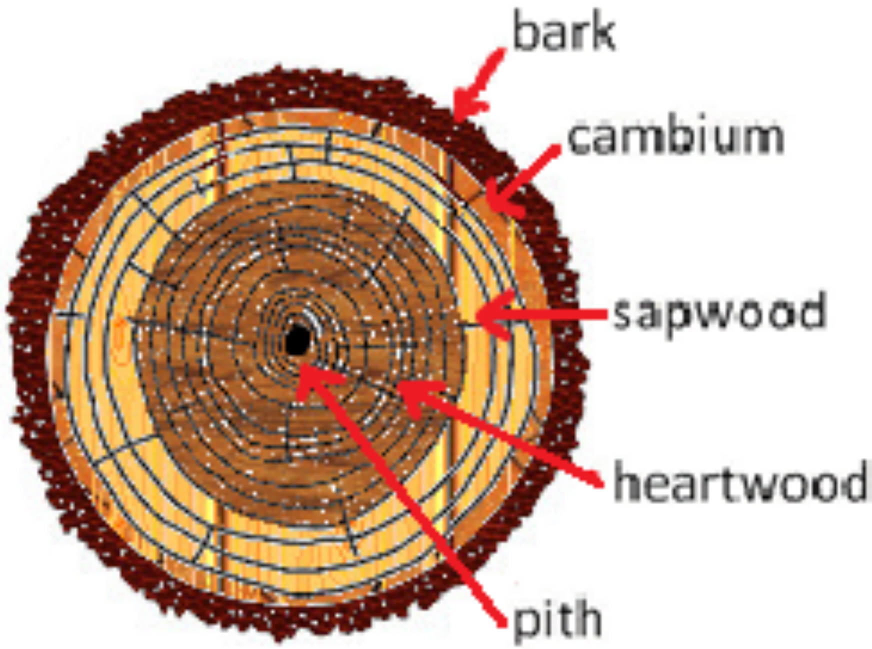
Importance of reliable monitoring of tree trunks

- Tree-trunk structure
  - A tree trunk is a complex medium, composed by bark, vascular cambium, xylem (heartwood and sapwood) and pith.
  - All parts have different electromagnetic and physical properties.



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Use of GPR for the inspection of trees

- Main obstacles for GPR testing
  - Bark (smooth vs rough), shape (circular vs irregular)

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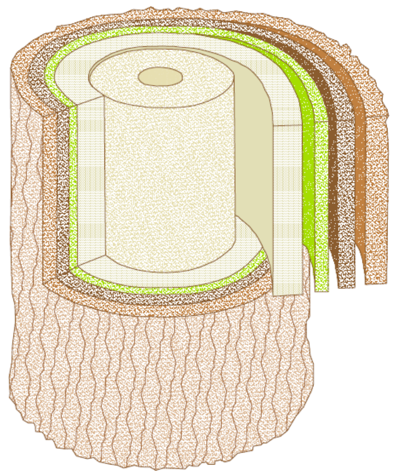
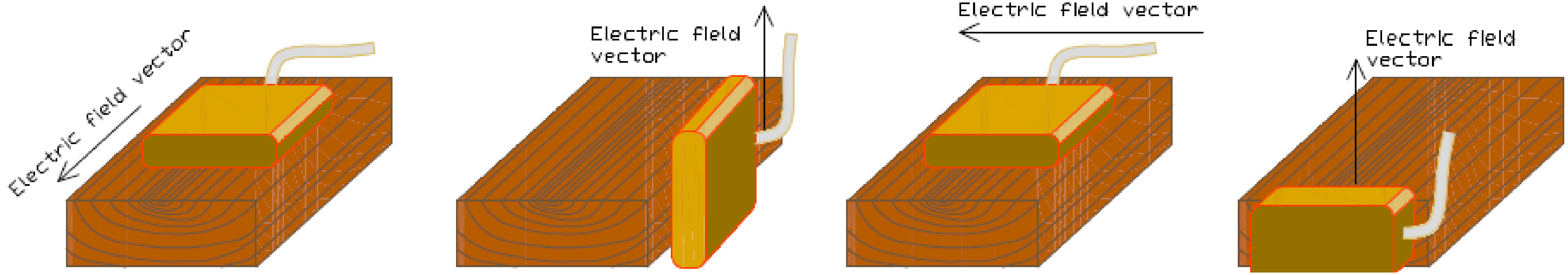
Use of GPR for the inspection of trees

- Main obstacles for GPR testing
  - ➢ High moisture of living wood leads to:
  - High permittivity -> strong surface reflection
  - High conductivity -> attenuation
  - Heterogeneity of the trunk -> complex reflections

  - ➢ Anisotropy of wood -> grain orientation dependent





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GPR assessment of tree roots

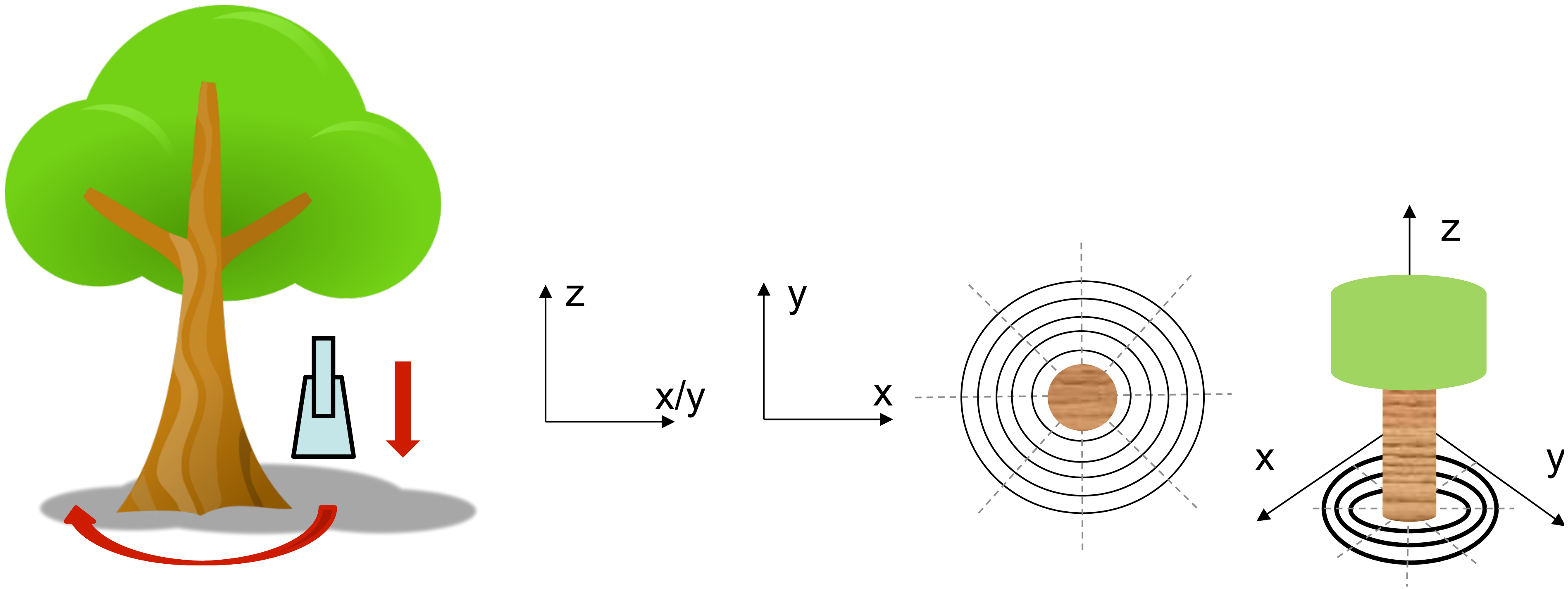
- GPR investigation of tree roots is carried out to detect their position and prevent harming of infrastructures and utilities. It is also important to protect the roots against damaging.

- GPR can help to map the tree roots and evaluate their condition.

- The investigation is carried out as a conventional soil or road investigation, by using ground-coupled antennas. In particular, data acquisition over the roots is very similar to data acquisition in utility mapping works.

GPR assessment of tree roots

- It is advised to acquire data on a high-resolution grid, all around the tree.



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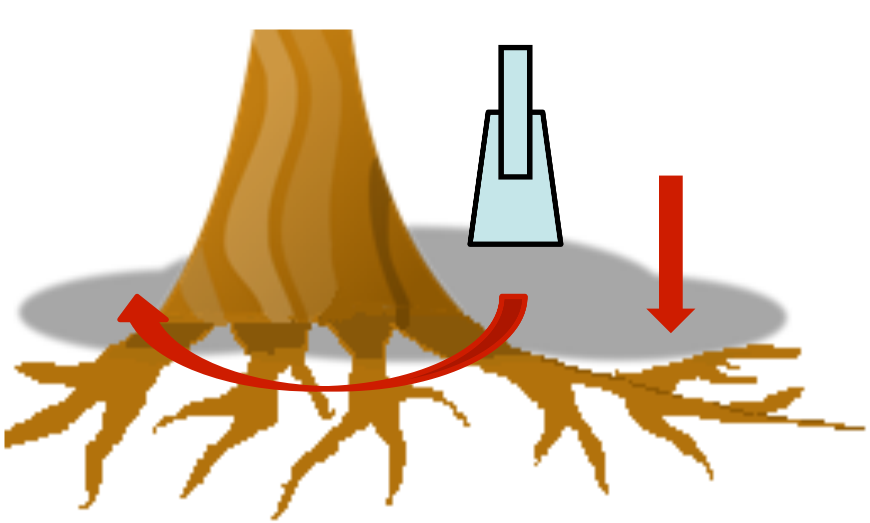
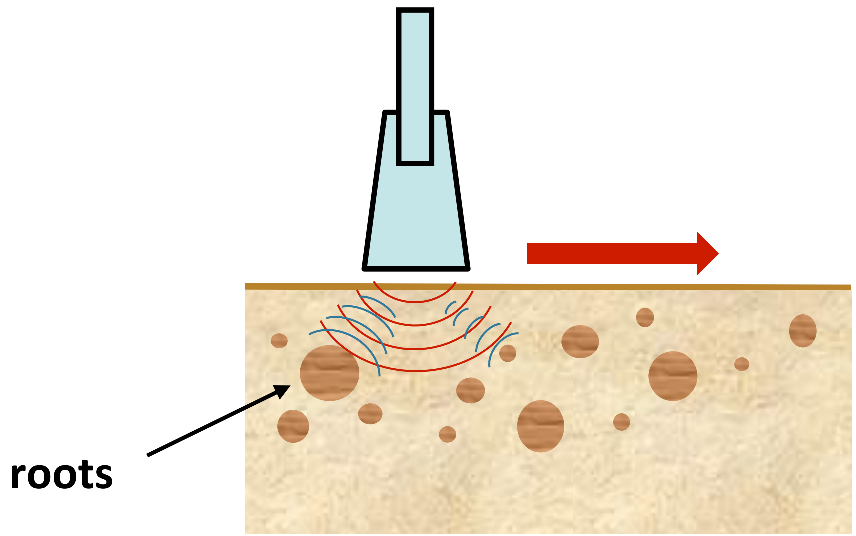
GPR assessment of tree roots

- The GPR transmits electromagnetic waves into the soil and they are reflected back by the roots -> The main problems are:

  1. The limited differences between the electromagnetic properties of soil and roots, which also depend strongly on the soil moisture.

  2. The irregular shape of the roots.





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GPR assessment of tree roots

- Equipment and method
  - ➢ A time- or frequency-domain GPR can be used. It is suggested to fix the ground-coupled antenna to a cart, to take the measurements easily. The antenna should be in a good contact with the soil.
  - ➢ The operating center frequency should be between 400 MHz and 900 MHz.

- Data presentation
  - ➢ GPR data collected over roots can be presented as B-Scans and C-Scan slices (horizontal sections corresponding to different depths).

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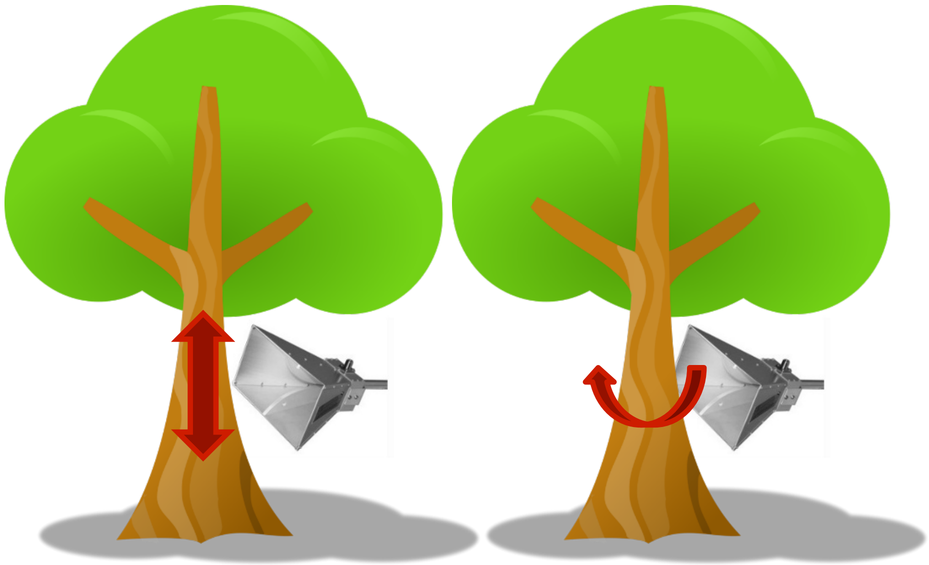
GPR assessment of tree trunks

- GPR investigation of tree trunks is carried out to detect voids and prevent a possible collapse.

- Data acquisition can be done:
  - In longitudinal direction (to find voids and measure their elevation)
  - In circumferential direction (to observe voids in details)



Each longitudinal or circumferential profile can be acquired by a continuous movement (then, a positioning system is needed), or progressively with small steps (i.e., as a series of static measurements).

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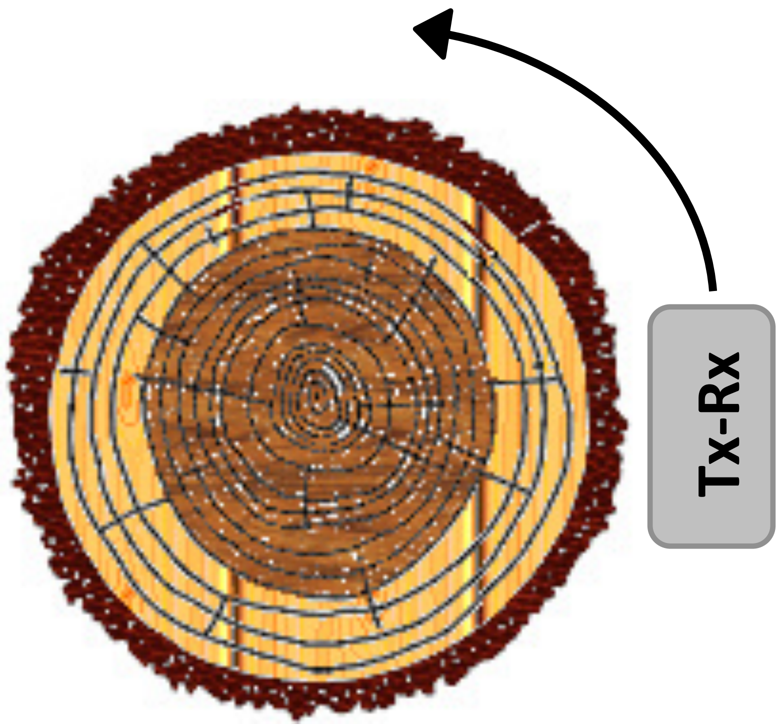
GPR assessment of tree trunks

- Tree trunks can be investigated with the use of:
  - **A monostatic radar system, or a bistatic system with Tx and Rx antennas enclosed in the same module**
    - Antenna(s) moved around the trunk
    - Use of a perfect electrical conductor on the other side of the tree is suggested, to help the detection of the opposite side of the tree



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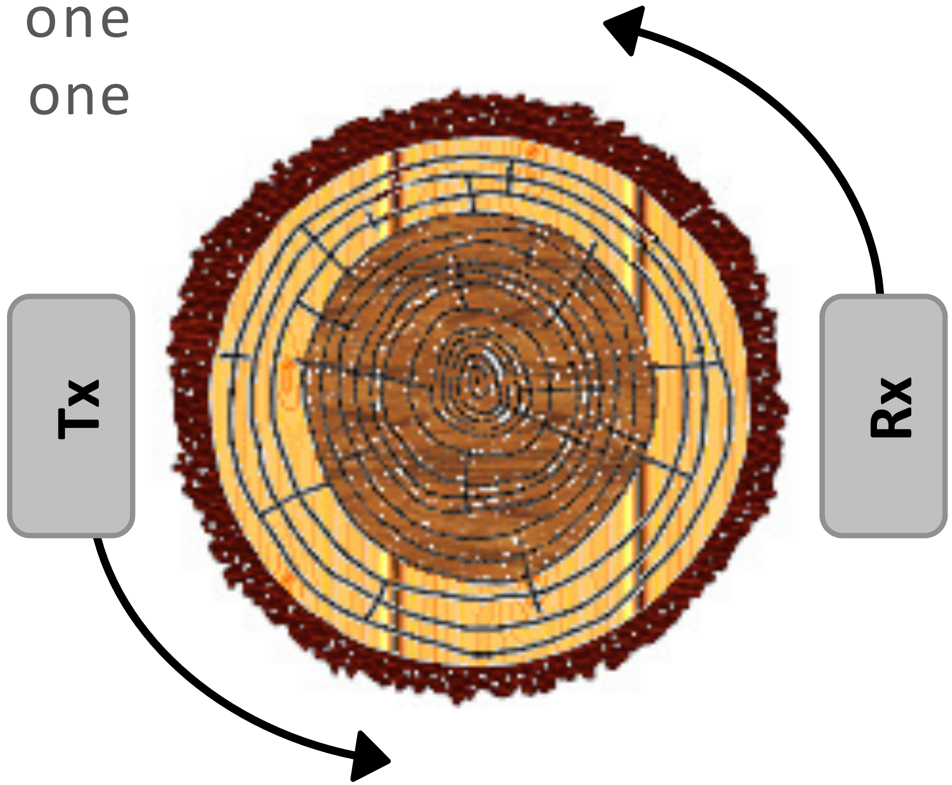
GPR assessment of tree trunks

- Tree trunks can be investigated with the use of:
  - **A bistatic radar system with Tx and Rx antennas in separate modules**
    - Antennas moved around simultaneously, or one static antenna and one moving antenna



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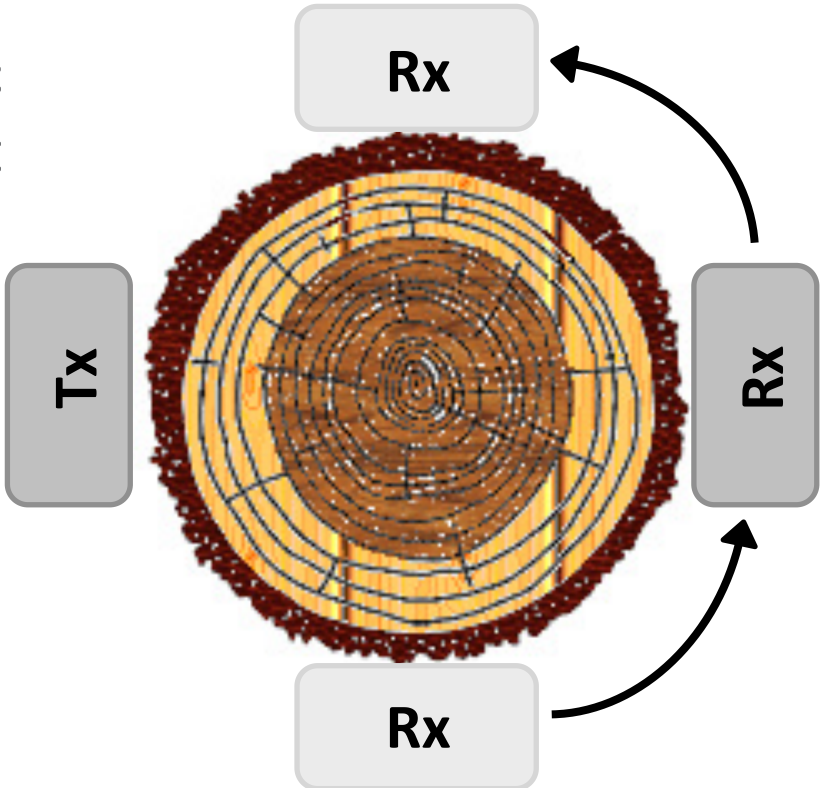
GPR assessment of tree trunks

- Tree trunks can be investigated with the use of:
  - **A multistatic radar system**
    - Array of antennas placed around the tree trunk
    - Similar to ultrasonic tomography, not yet common with GPR



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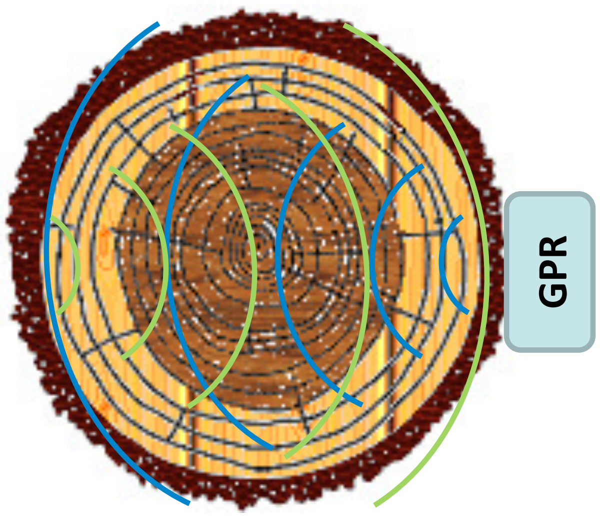
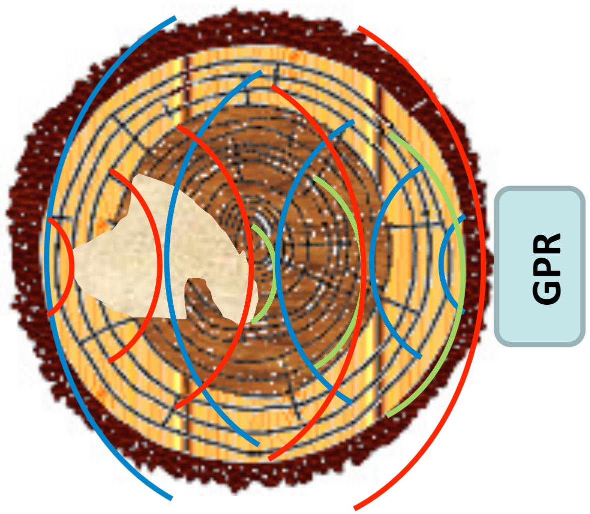
GPR assessment of tree trunks

- Propagation of electromagnetic waves through a tree trunk
  - The simplest model assumes the trunk as homogeneous, with a void (if present). In such model, reflections occur from the opposite side of the trunk and from the void.
  - In a real scenario, reflections are much more complicated (reflections from heartwood, layers, etc.).



Absence of a void: Reflection from the opposite side.



Presence of a void: Reflections from the void and from the opposite side

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GPR assessment of tree trunks

- Equipment and method
  - As already mentioned, a perfect electrical conductor at the opposite side of the trunk can be used.
  - A conventional time- or frequency-domain radar system can be used. The antenna should be in a good contact with the bark, to minimize surface reflections. The antenna should be as small and light as possible, because it has to be ergonomic.
  - The operating frequency of the antenna should be 0.5-1.8 GHz.

- Data presentation
  - Presentation of GPR data is usually carried out in the form of B-Scans and C-Scan slices (horizontal sections corresponding to different heights). Polar or real shape representation is suggested.

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Case studies (tree trunks)

- Longitudinal measurement
- B-scan around a tree trunk (European beech)
- Different GPR radar systems were tested
- Always good contact with the bark!
- Positioning system for continuous measurement was used

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Case studies (tree trunks)

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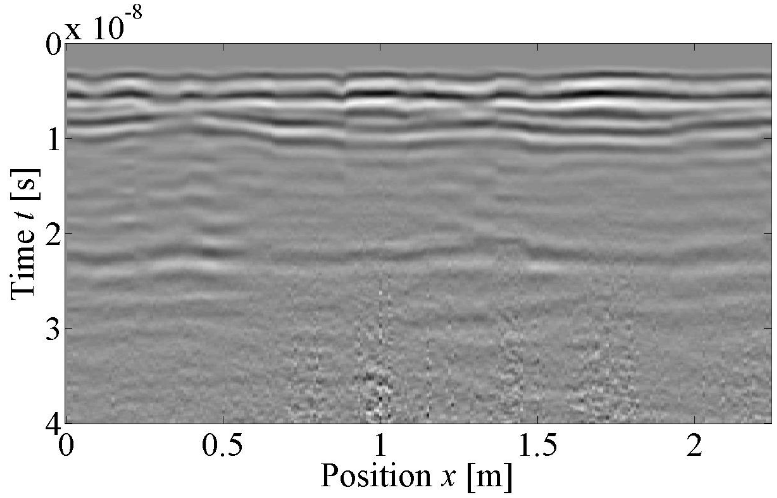
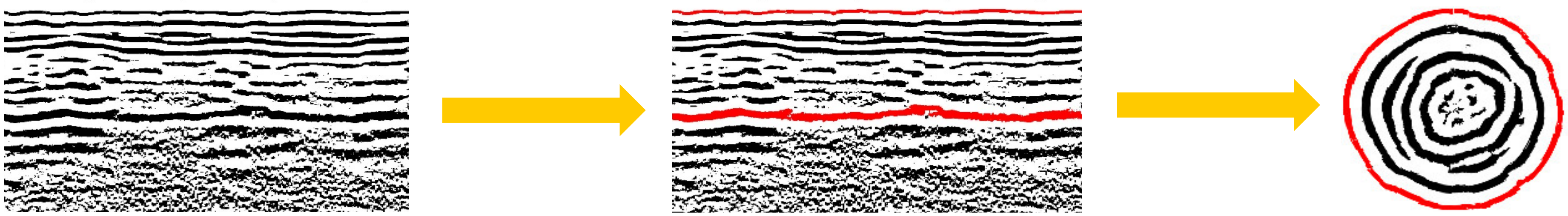
Case studies (tree trunks)

B-scan around the tree trunk:

- First, it was necessary to detect reflections on the surface and on the opposite side of the tree. Then, internal reflections were studied.
- Polar representation of the GPR image can be done.





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Part 2
GPR inspection of agricultural fields

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Importance of reliable investigation of agricultural fields

- GPR inspection of soils is carried out in order to improve agricultural management (e.g., irrigation)

- There are several aspects influencing the quality of soils for agricultural usage, such as:

  - Soil moisture -> growth of plants, decay of roots, …
  - Stones presence -> tillage management
  - Soil erosion piping -> ground stability, hydrological changes, …
  - Soil roughness -> evaporation, runoff, …

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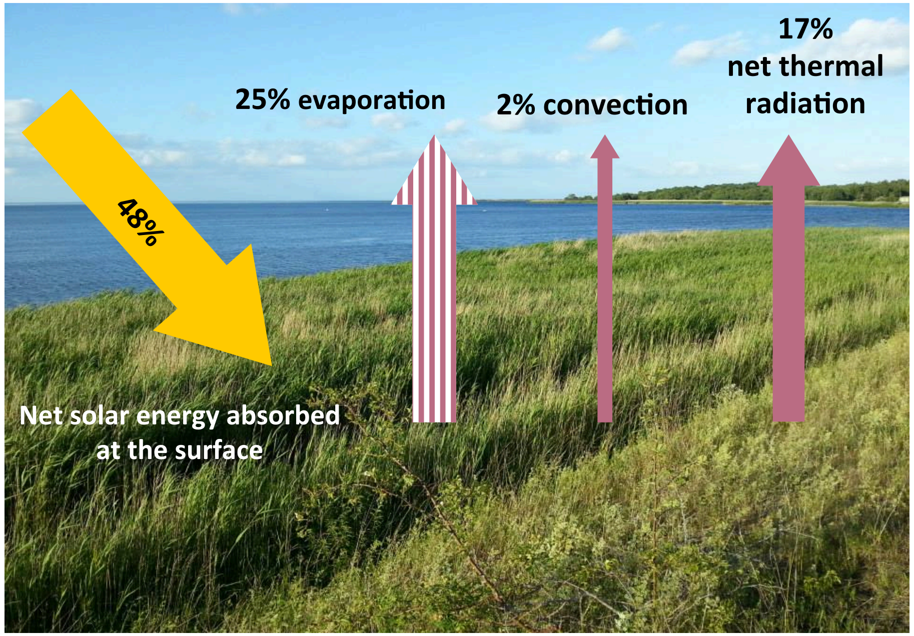
Importance of soil moisture assessment

- Soil moisture is a key variable of the water cycle (it influences the partitioning of the rainfall into runoff and infiltration).
- Soil moisture is also a key variable of the climate system (it influences the exchange of water and energy between the land surface and the atmosphere).
- Having reliable and distributed information about soil moisture is of great importance in hydrology and climate studies, due to its high spatial and temporal variability.
- Soil moisture determines the availability of water for the plants.

Importance of soil moisture assessment

- Soil moisture
  - A key variable of the water cycle
  - Plant growth and germination control
  - Partitioning of rainfall into runoff and infiltration control
  - Land water and energy budgets control



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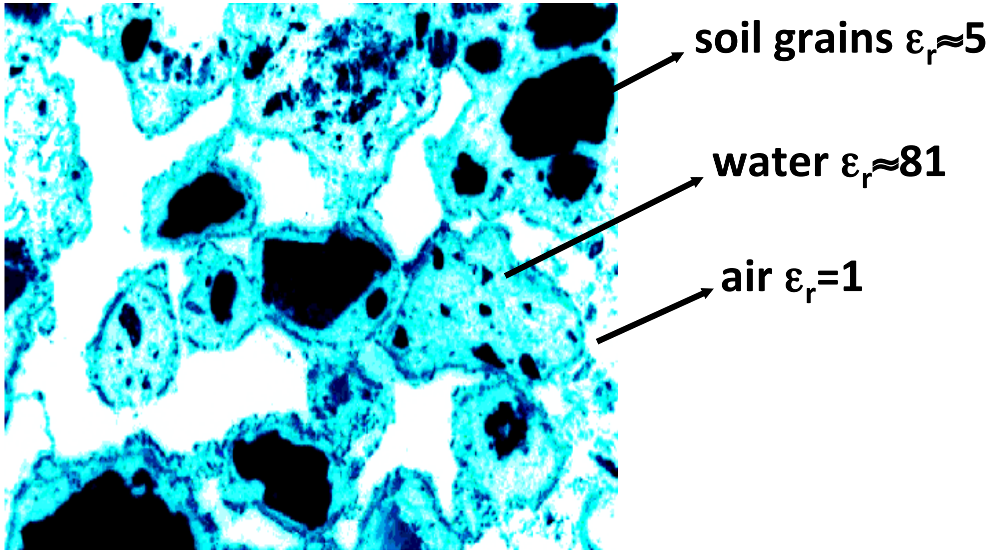
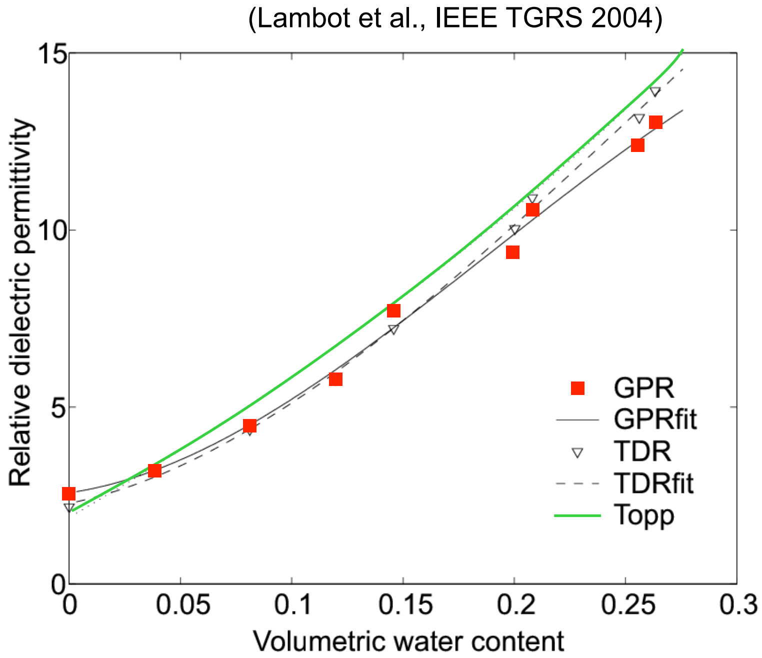
Soil moisture

- Relationship between soil water content and dielectric permittivity





Empirical Topp's equation

$$\theta = -5.3\times10^{-2} + 2.92\times10^{-2}\varepsilon_r - 5.5\times10^{-4}\varepsilon_r^2 + 4.3\times10^{-6}\varepsilon_r^3$$

Dielectric mixing models (e.g., Complex Refractive Mixing Model CRIM):

$$\theta = \frac{\varepsilon_b^\alpha - (1-n)\varepsilon_s^\alpha - n\varepsilon_a^\alpha}{\varepsilon_w^\alpha - \varepsilon_a^\alpha}$$

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Soil moisture: presence of clay in soil

- Relationship between soil clay content and electrical conductivity
  - ➢ Higher clay content => higher electrical conductivity σ

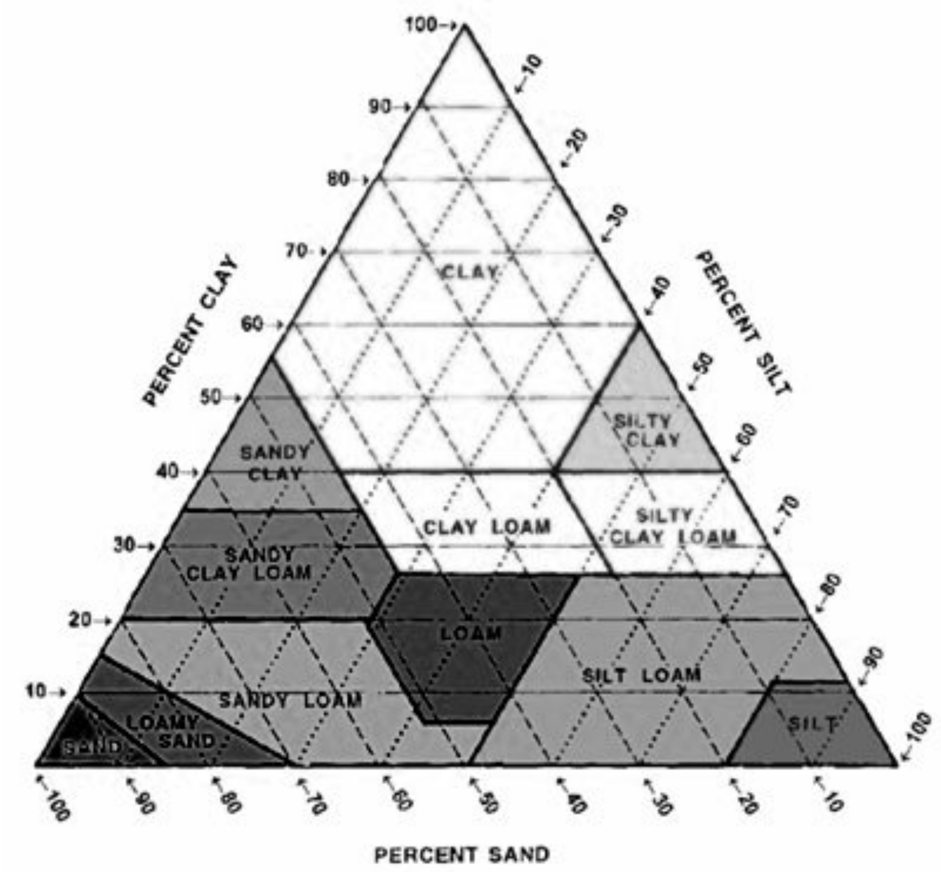
Model of Rhoades (1976)

Water electrical conductivity (salinity)

$$\sigma(\theta) = (a\theta^2 + b\theta)\sigma_w + \sigma_r$$

Water content

f (clay content)



Soil textural triangle

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Importance of soil roughness assessment

- The soil roughness:
  - Represents a major difficulty in the development of soil sensors (e.g., satellites).
  - Is a major source of clutter in various subsurface sensing applications.
  - Causes distortion of electromagnetic signals -> it is important to take roughness into account in signal processing.
  - Rough surfaces cause diffuse scattering.

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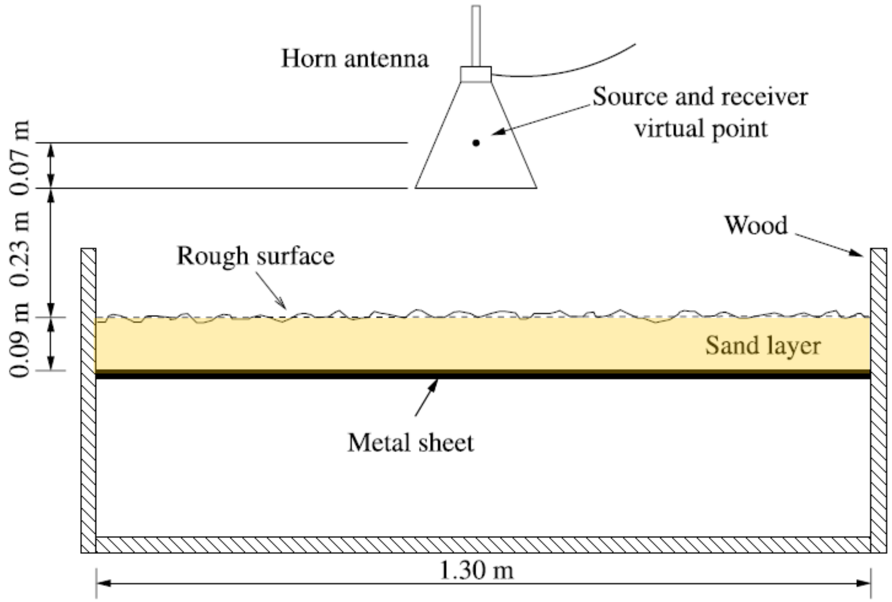
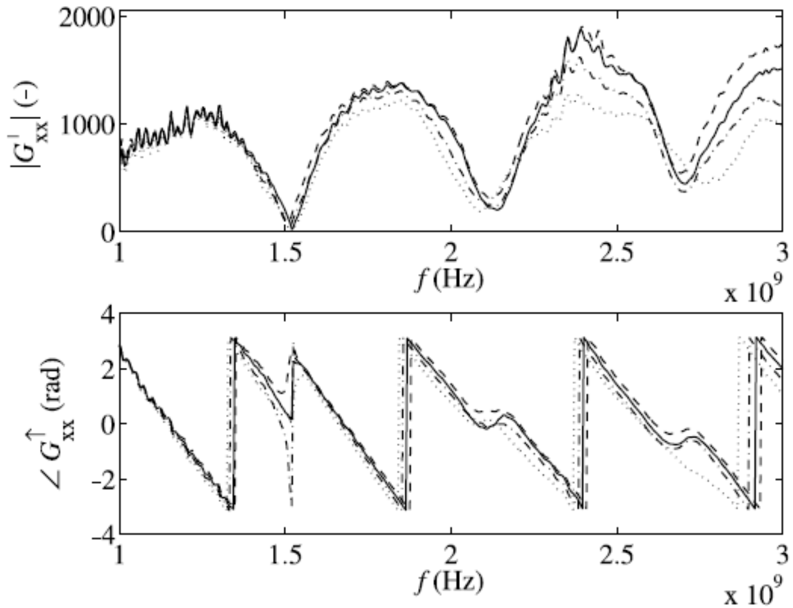
Importance of soil roughness assessment





(Lambot et al., WRR, 2006)

Importance of soil pipe detection

- Soil pipes:
  - Natural underground erosion pipes are made by water
  - They create drainage subsurface networks with flowing water
  - They can be problematic for the ground stability -> tunnel erosion
  - In extreme cases, sinkholes can appear
  - They have a significant influence on hydrological processes

- GPR can detect:
  - Position of the pipes and networks
  - Size of the pipe, to some extent
  - Depth of the pipe
  - Presence of water in the pipe

(Courtesy of Jean-Baptiste Got)

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Use of GPR for precision agriculture

- GPR inspection of soils is carried out in order to improve agricultural management.

- Different antennas for evaluating tillage quality or hydrological status can be used, such as:
  - Ground-coupled antennas for soil moisture, soil piping and void detection
  - Air-coupled antennas for soil moisture and roughness evaluation

- Very similar data acquisition to the utility mapping and road inspection.

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Use of GPR for precision agriculture

- A plane wave approximation can be adopted and the basic surface reflection coefficient method can be used.
- The soil is commonly assumed to be a homogeneous halfspace.
- The electric conductivity is assumed to be negligible.
- The soil magnetic permeability is assumed to be μ_0 (free space).

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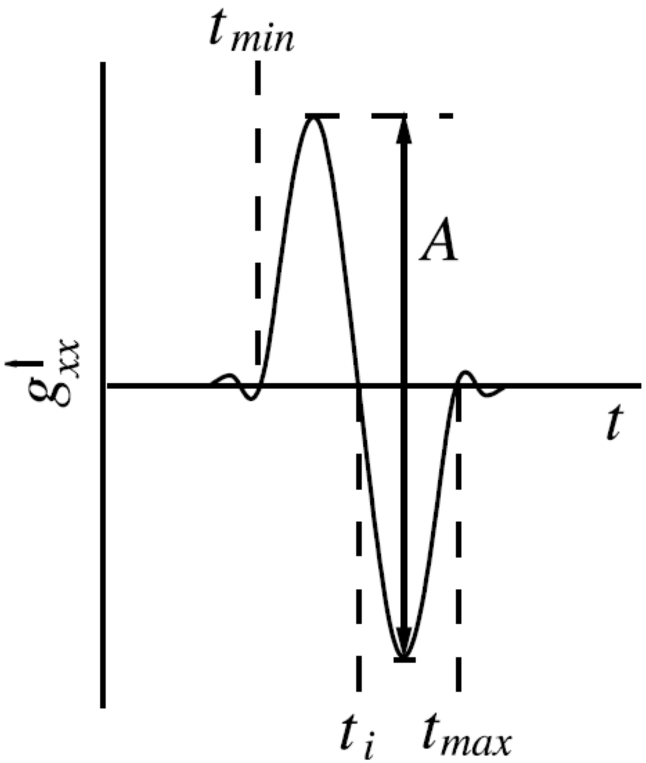
Use of GPR for precision agriculture

$$R = \frac{1-\sqrt{\varepsilon_r}}{1+\sqrt{\varepsilon_r}}$$



$$\varepsilon_r = \left(\frac{1-R}{1+R}\right)^2$$

$$\frac{R}{R_{PEC}} = \frac{\frac{E_s}{E_i}}{\frac{E_{s,PEC}}{E_i}}$$

with $R_{PEC} = -1$

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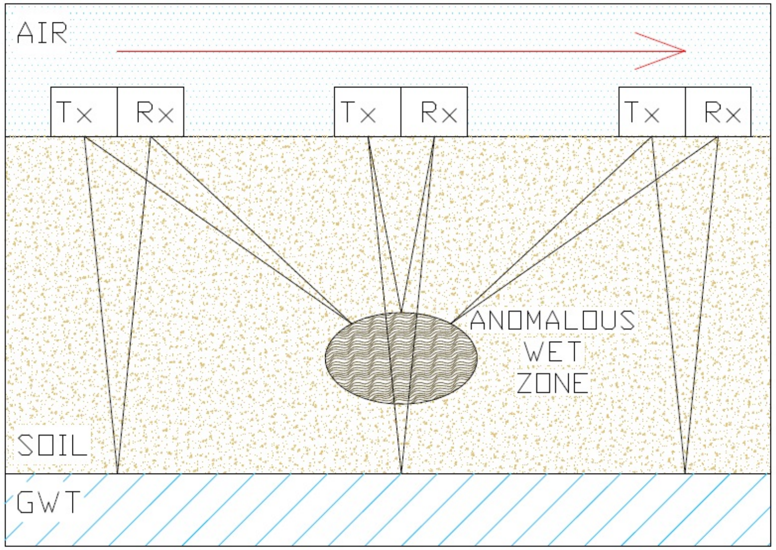
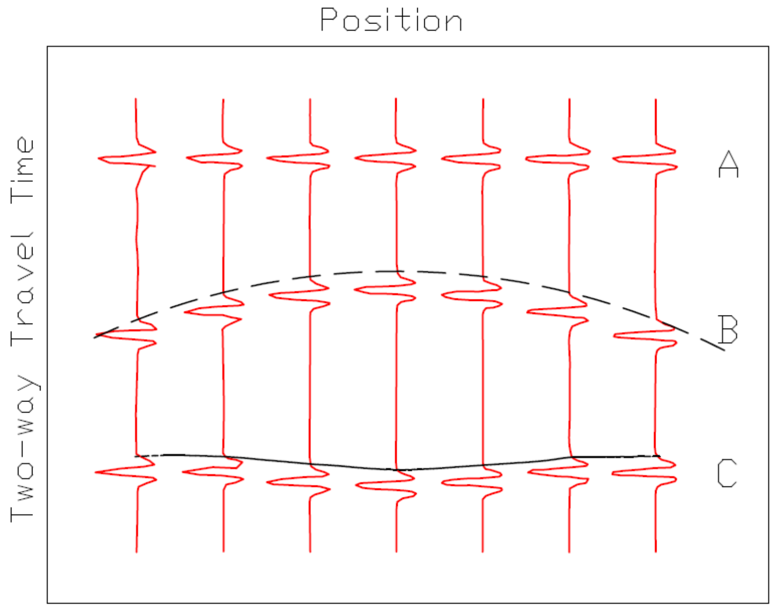
Use of GPR for precision agriculture

- Reflection hyperbola





➢ Velocity is determined from the convexity of the reflection hyperbola. The presence of a scattering object is required.

$$v_{soil} = \frac{\sqrt{(x - 0.5a)^2 + d^2} + \sqrt{(x + 0.5a)^2 + d^2}}{t_{rw,x}}$$

a: being the distance between the two antennas

d: being the depth of the object

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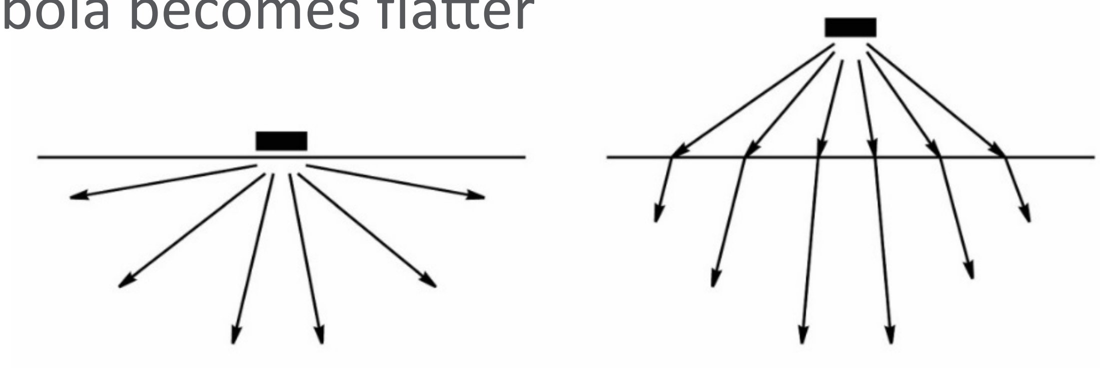
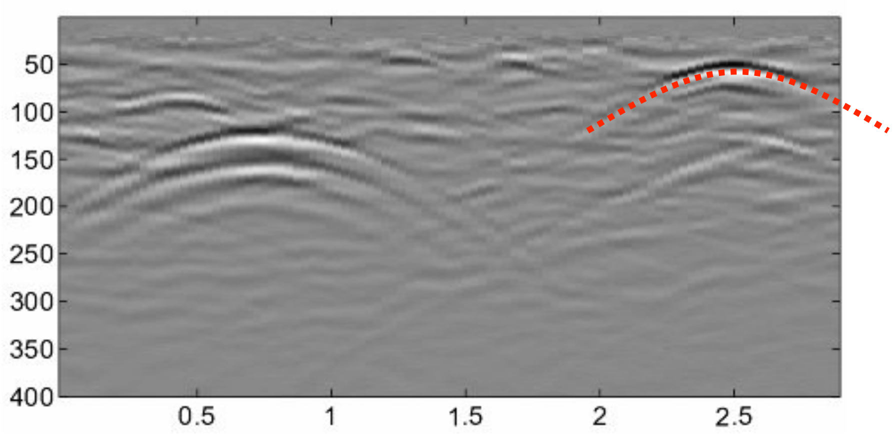
Use of GPR for precision agriculture: soil piping detection

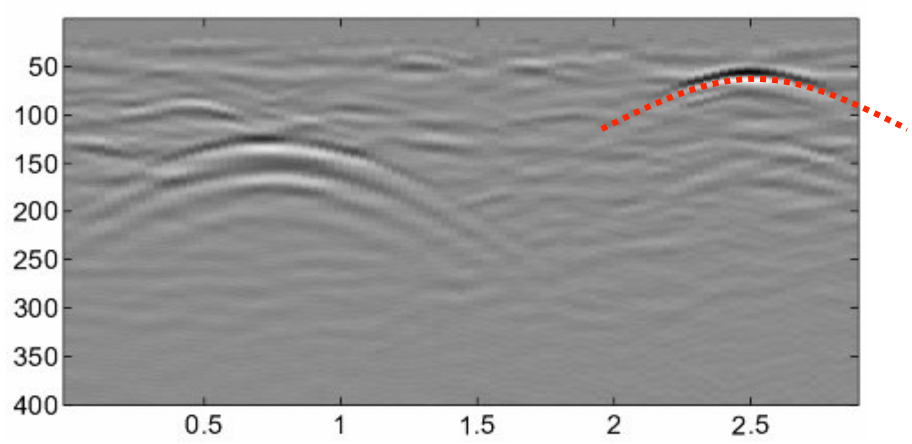
- Effect of antenna height: focusing
- Hyperbola becomes flatter



Elevation 0 cm



Elevation 2 cm



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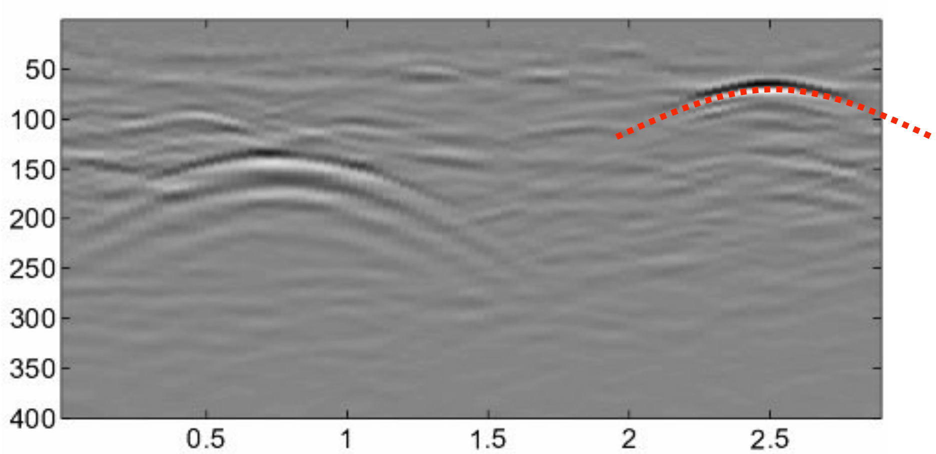
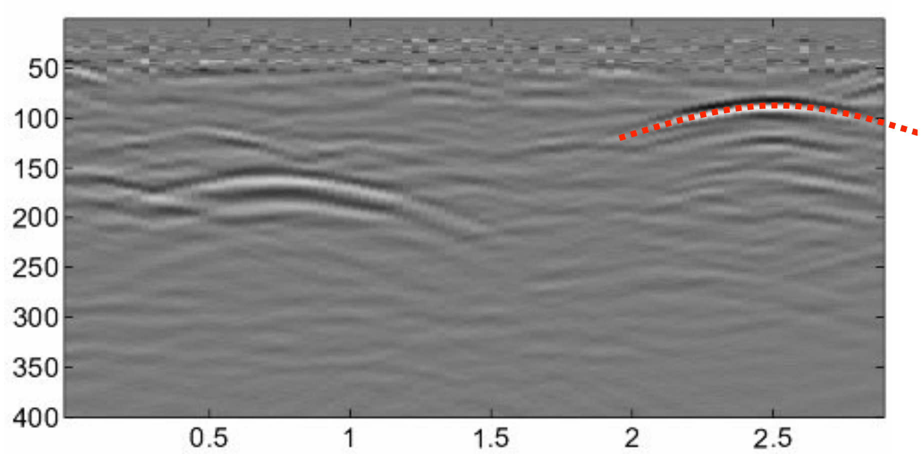
Use of GPR for precision agriculture: soil piping detection

Elevation 5 cm



Elevation 20 cm



(Courtesy of Evert Slob, NL)

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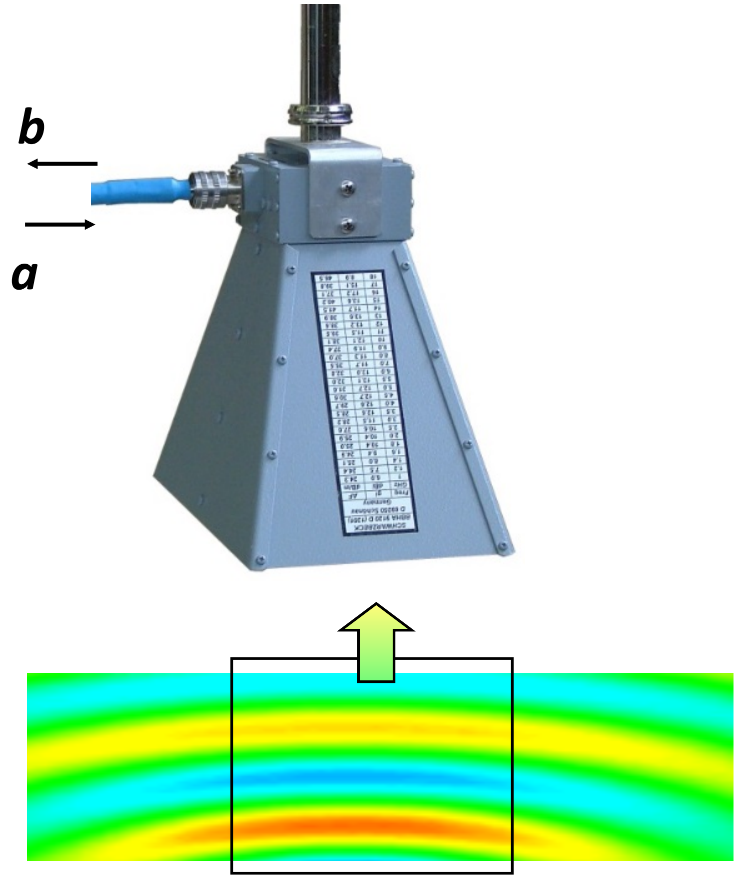
Use of GPR for precision agriculture: soil piping detection

Full-wave radar modelling

Radar equation in the frequency domain

$$S_{11}(\omega) = \frac{b(\omega)}{a(\omega)} = R_i(\omega) + \frac{T_i(\omega) G_{xx}^{\uparrow}(\omega) T_s(\omega)}{1 - G_{xx}^{\uparrow}(\omega) R_s(\omega)}$$

Backscattered field distribution assumed to be homogeneous over the antenna aperture



(Lambot *et al.*, IEEE TGRS, 2004)

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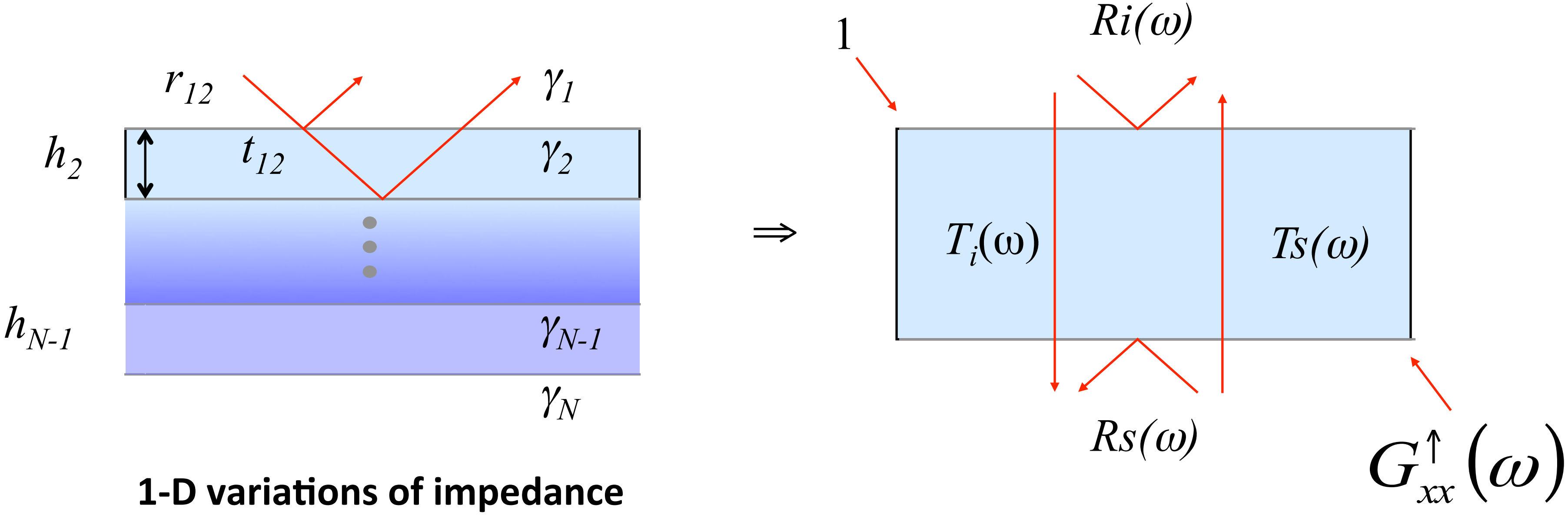
Use of GPR for precision agriculture: soil piping detection

Full-wave radar modelling



1-D variations of impedance

Only amplitudes and phases change from the antenna aperture to the radar reference plane

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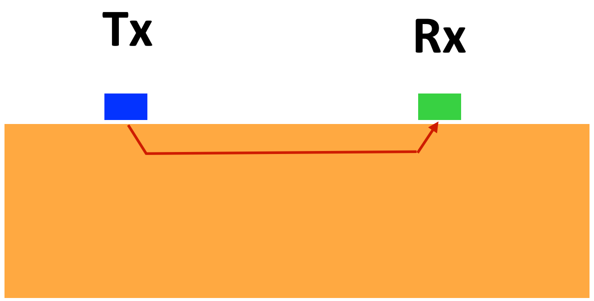
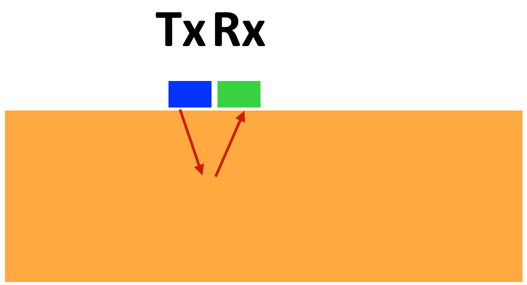
Use of GPR for precision agriculture: soil roughness mapping

- The use of GPR for the estimation of surface properties are always carried out with higher frequency antennas (> 1 GHz)



Ground-wave propagation time between antennas



1D surface reflection coefficient

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Use of GPR for precision agriculture: soil roughness effects

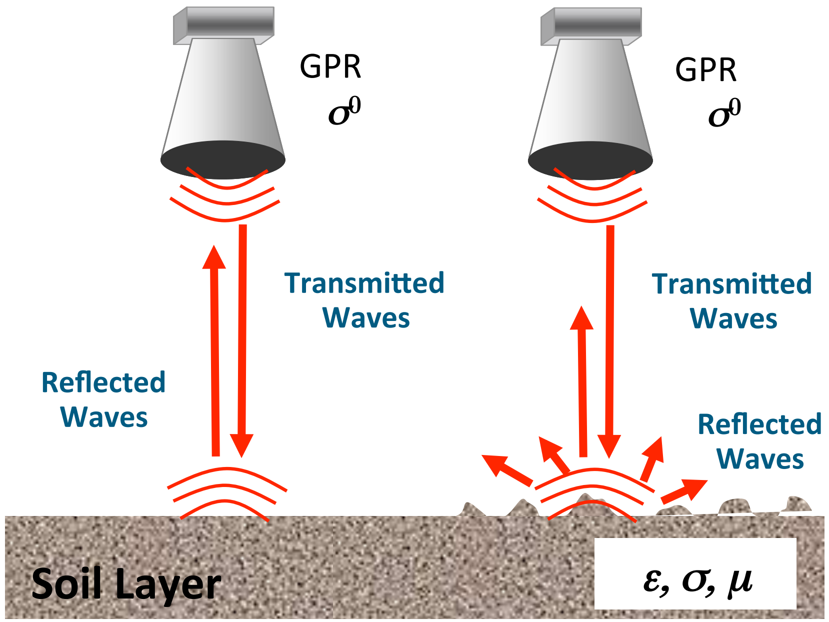
- Roughness effects on GPR data can be avoided by using low frequency signals (200–800 MHz), according to the Rayleigh criterion
- Surface roughness and soil permittivity cannot be easily retrieved simultaneously (positive correlation between parameters)
- Better estimation of the permittivity/ water content can be achieved with the use of a roughness model

Distinction between smooth and rough surfaces

Rayleigh criterion

$$h_c = \lambda/8$$

(Courtesy of François Jonard, FR)



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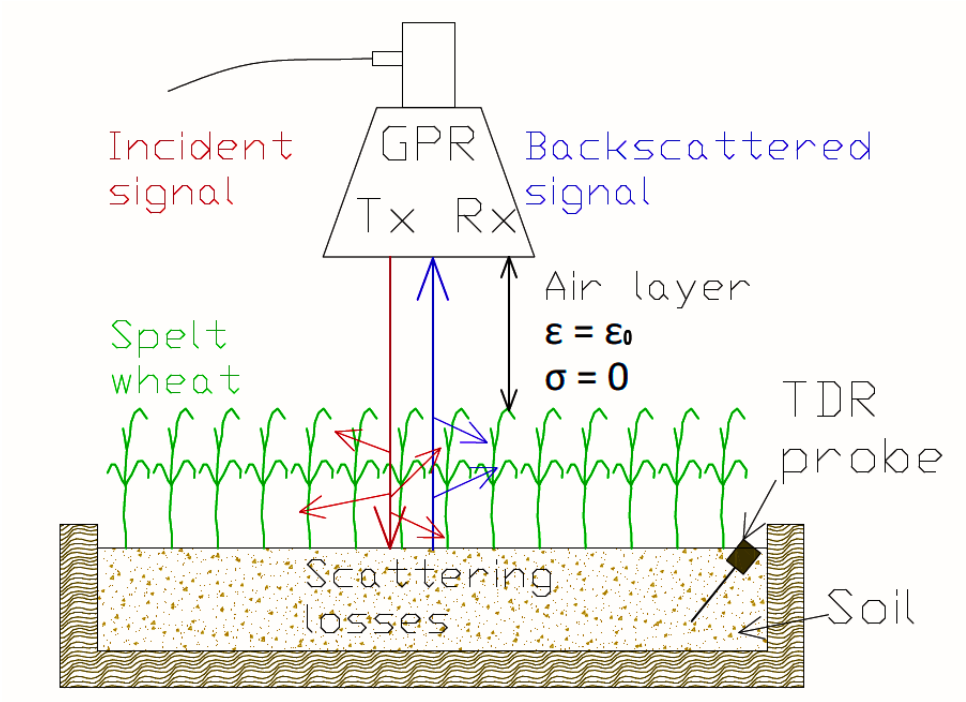
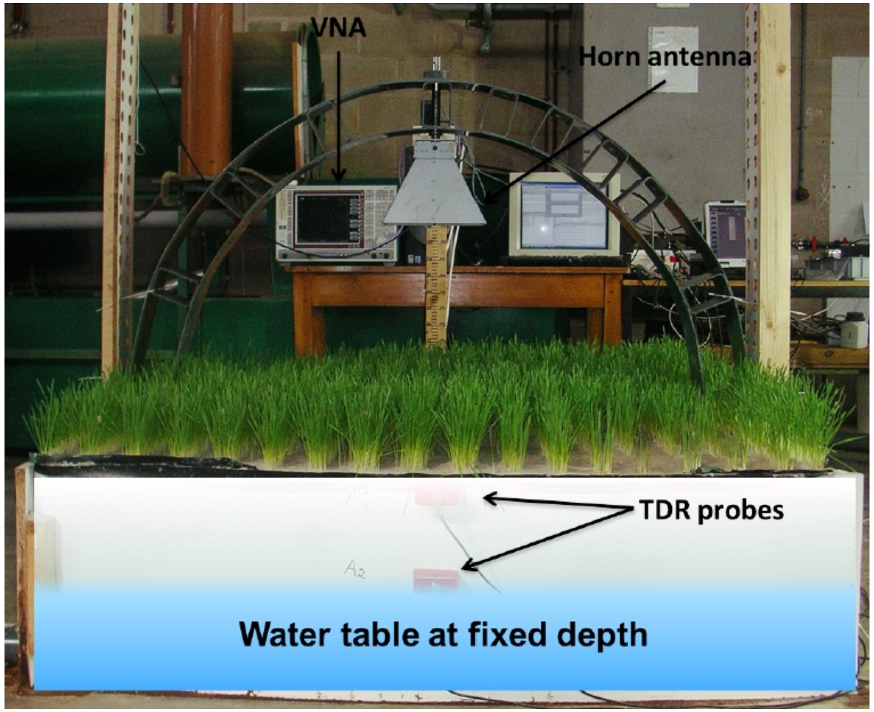
Use of GPR for precision agriculture: soil roughness effects

- The technique has also been successfully used to derive vegetation properties





(Ardekani *et al.*, IEEE, 2015)

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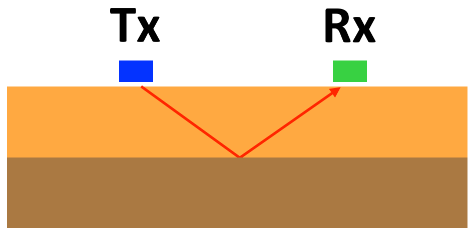
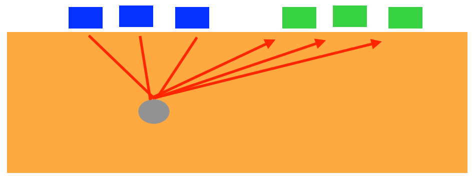
Use of GPR for precision agriculture: soil moisture mapping

- Different radar configurations are possible

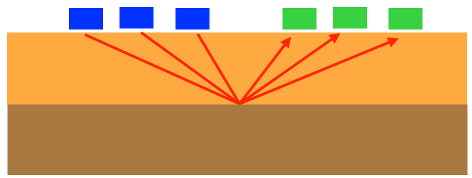
Propagation time to a known interface



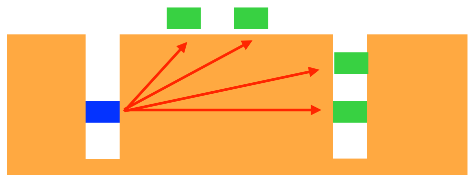
Reflecting hyperbola of an inhomogeneity



Common midpoint (CMP) or WARR



Propagation time between boreholes (tomography)



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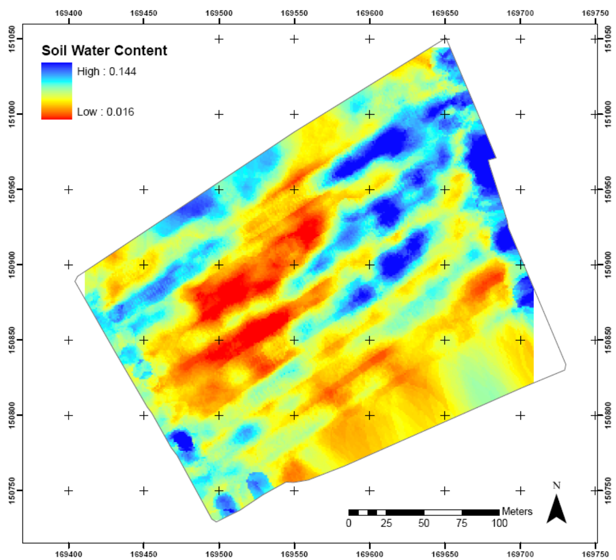
Use of GPR for precision agriculture: soil moisture mapping

- High-resolution soil moisture maps can be obtained at the field scale using full-wave inversion
  - Shallow characterization for improving remote sensing
  - Root-zone characterization for precision agriculture
- Low frequency antennas (0,3-0,8 MHz), both air-coupled and ground coupled, can be used for data acquisition



(Minet *et al.*, HESS, 2011)

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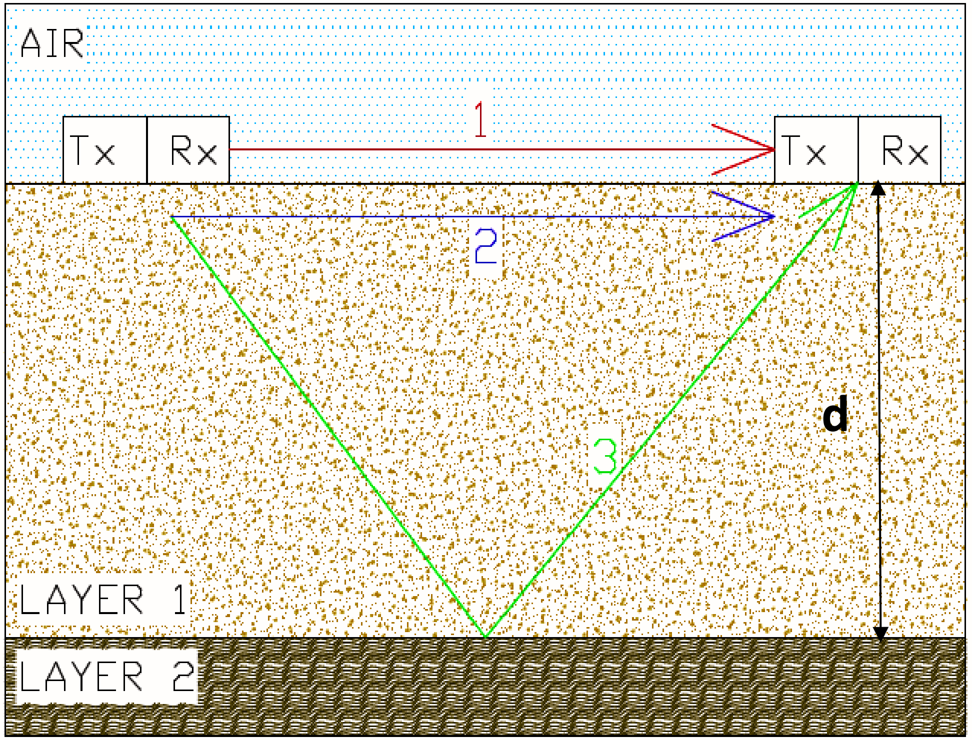
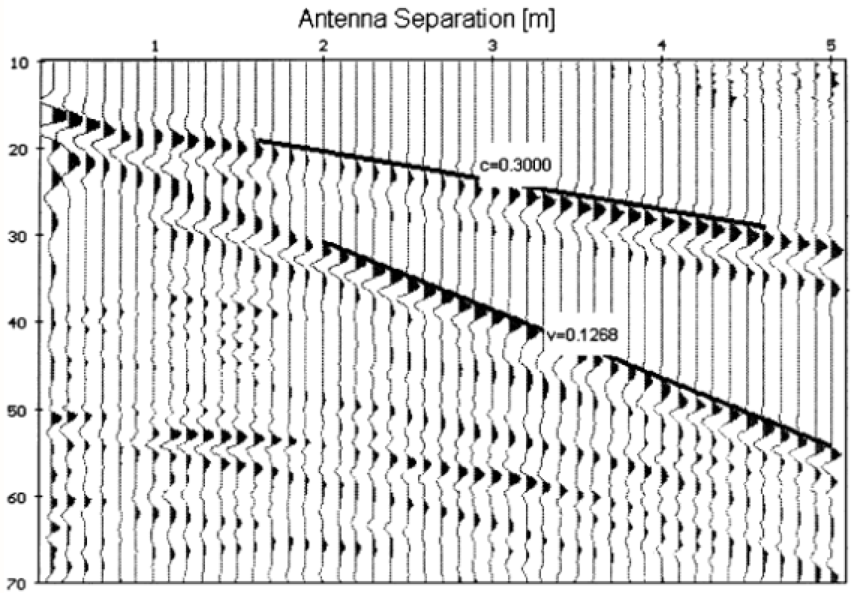
Use of GPR for precision agriculture: soil moisture mapping

- Surface ground wave method





(Huisman et al., VZJ, 2003)

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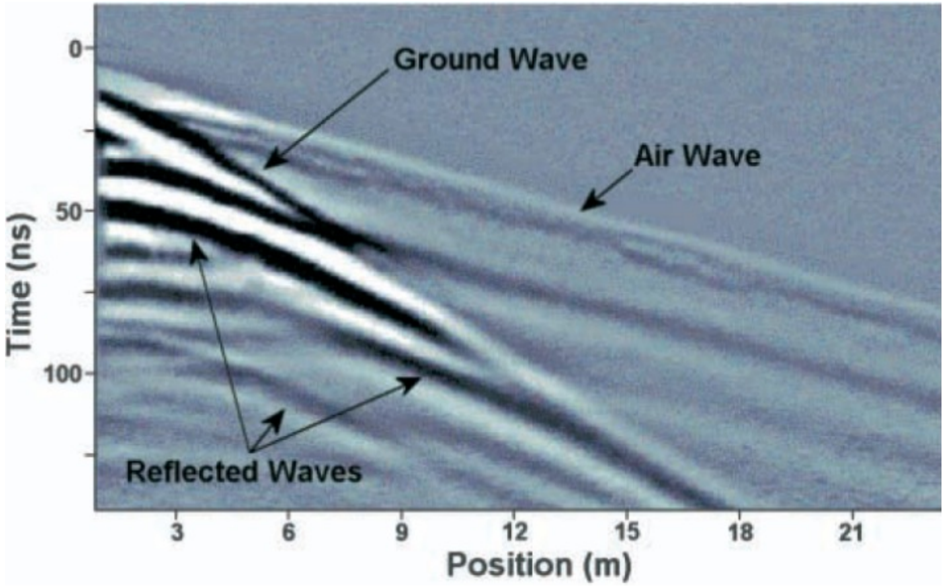
Use of GPR for precision agriculture: soil moisture mapping

- Surface ground wave method



$$v = \frac{x}{t} \qquad \varepsilon_r = \left(\frac{c}{v}\right)^2$$

(Huisman et al., VZJ, 2003)

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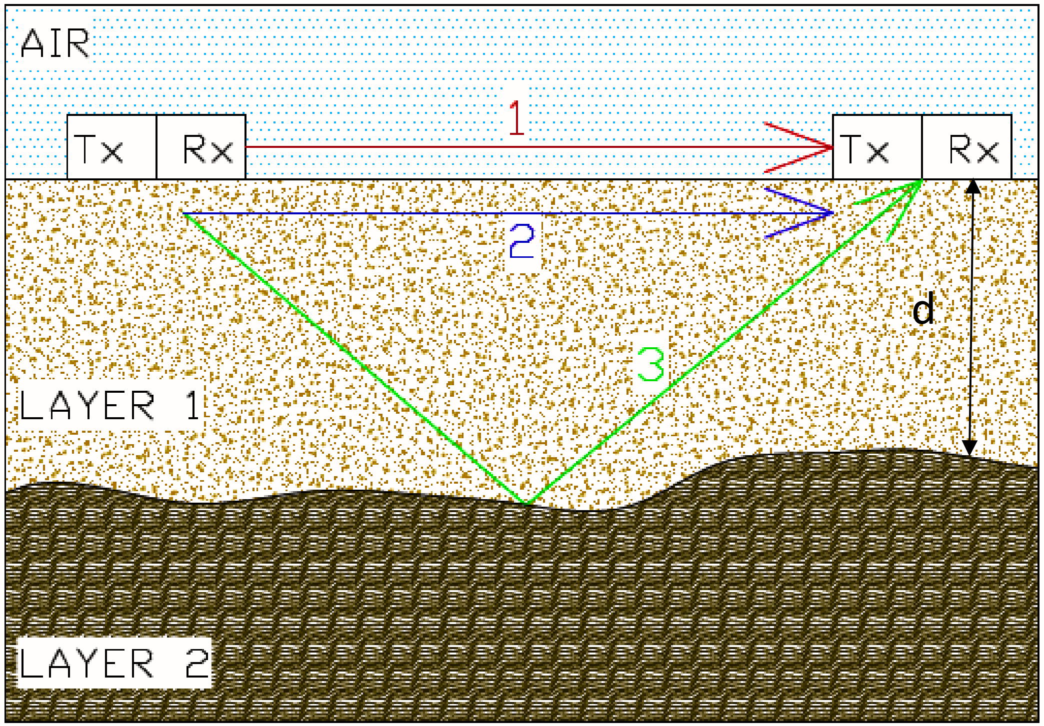
Use of GPR for precision agriculture: soil moisture mapping

- Single offset measurement
  - The depth *d* of the interface should be known.
  - Time lapse measurements permit to monitor changes in water content

$$v_{\text{soil}} = \frac{2\sqrt{d^2 + (0.5a)^2}}{t_{\text{rw}}}$$

$$\varepsilon_r = \left(\frac{c}{v}\right)^2$$



(André et al., Applied Geophysics, 2012)

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Use of GPR for precision agriculture: soil moisture mapping

- Single offset measurement
  - The depth *d* of the interface should be known.
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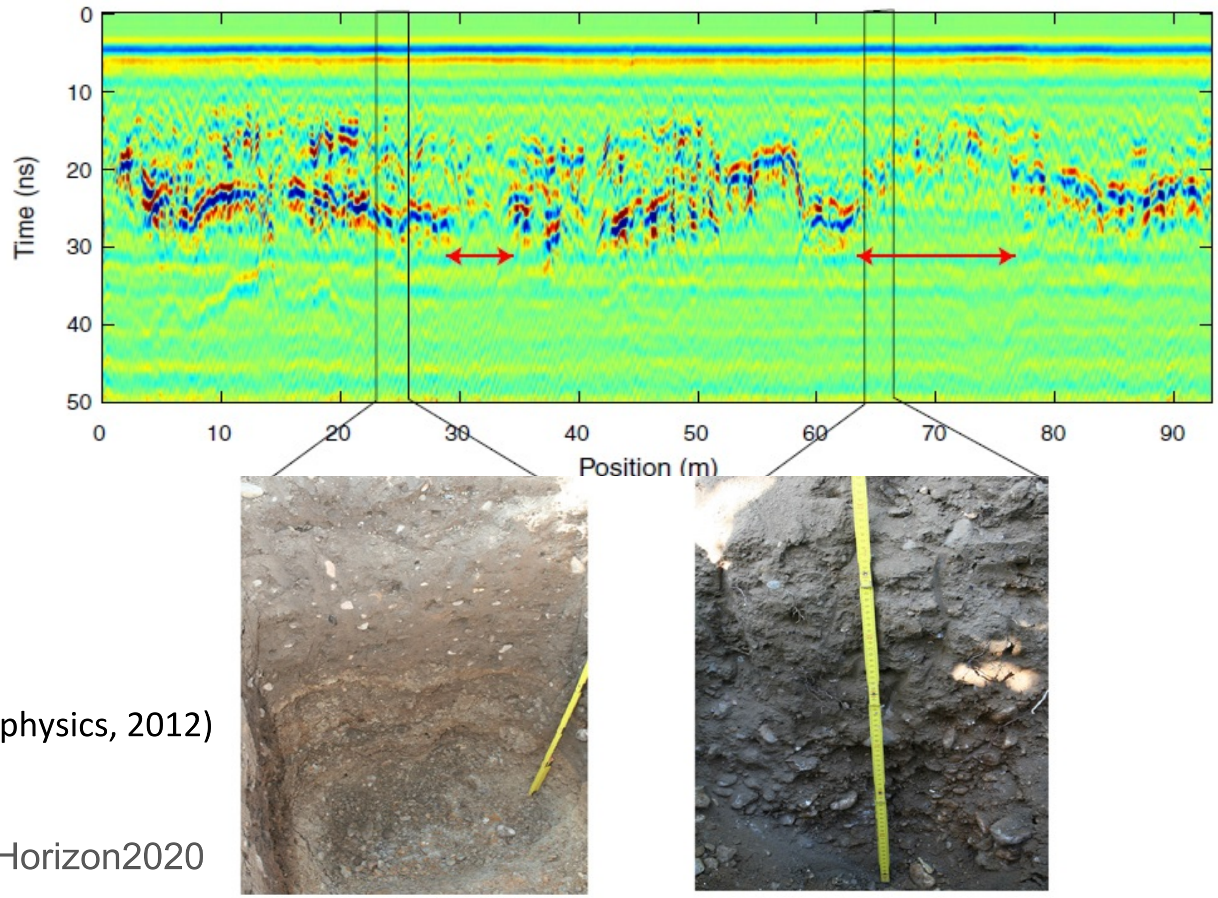

(André et al., Applied Geophysics, 2012)

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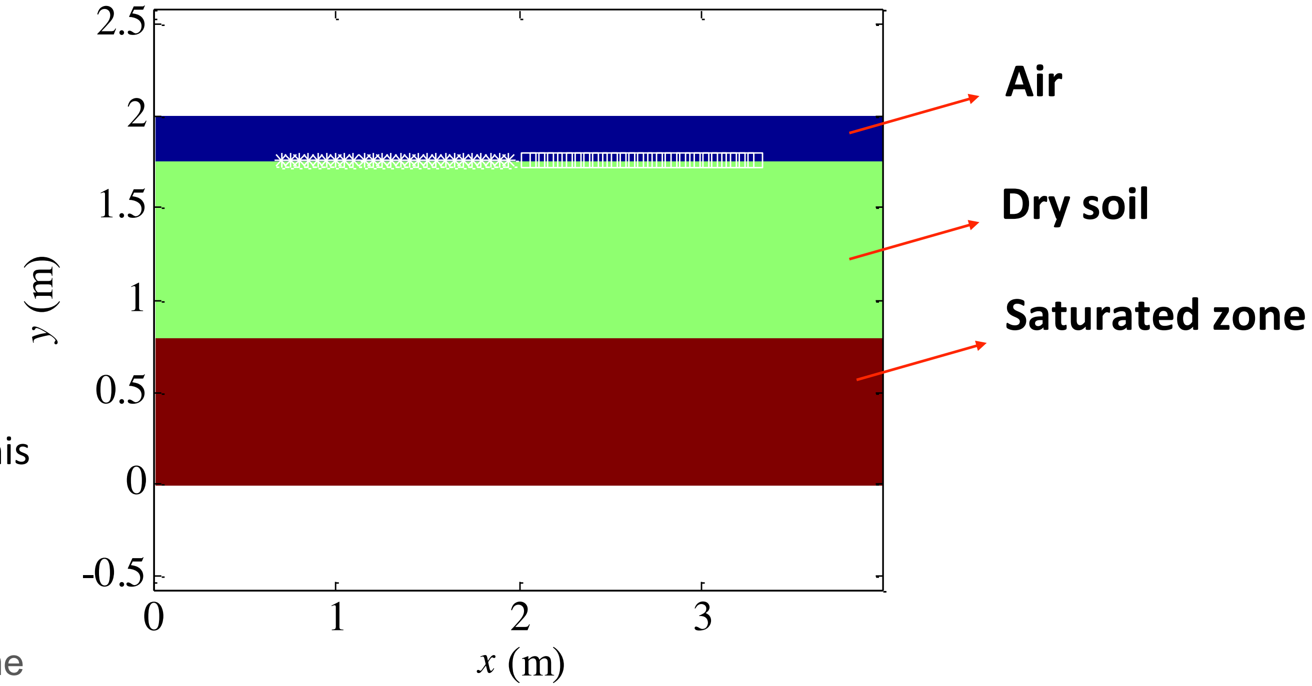
Use of GPR for precision agriculture: soil moisture mapping

- Common mid-point survey (multi-offset measurements)
- Interpretation of GPR data
  - Dielectric permittivity of air
  - Soil surface dielectric permittivity (top dry soil layer)
  - Depth of the water table (saturated zone)



(Capillary rise is neglected in this example by using gprMax)

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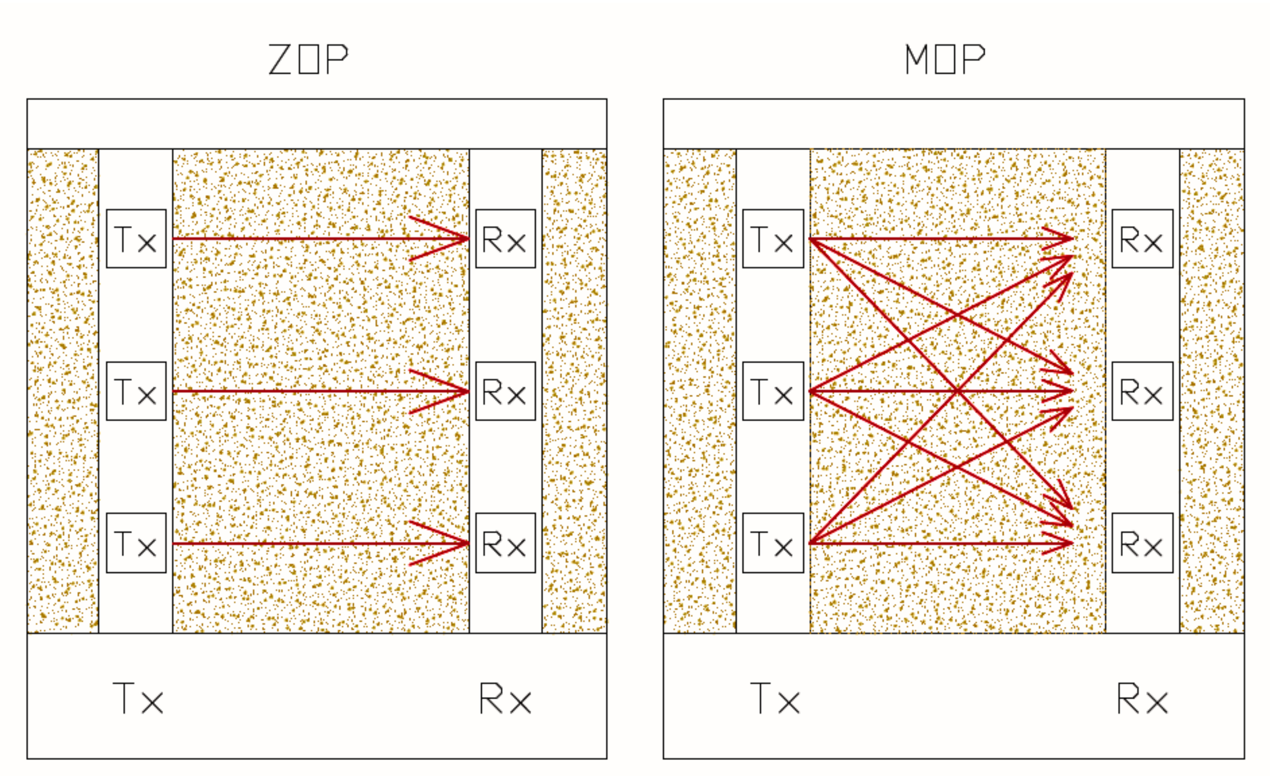
Use of GPR for precision agriculture: soil moisture mapping

- Borehole radar and transmission tomography – special case

Zero offset profile **Multi offset profile**



1D profile **2D tomography**

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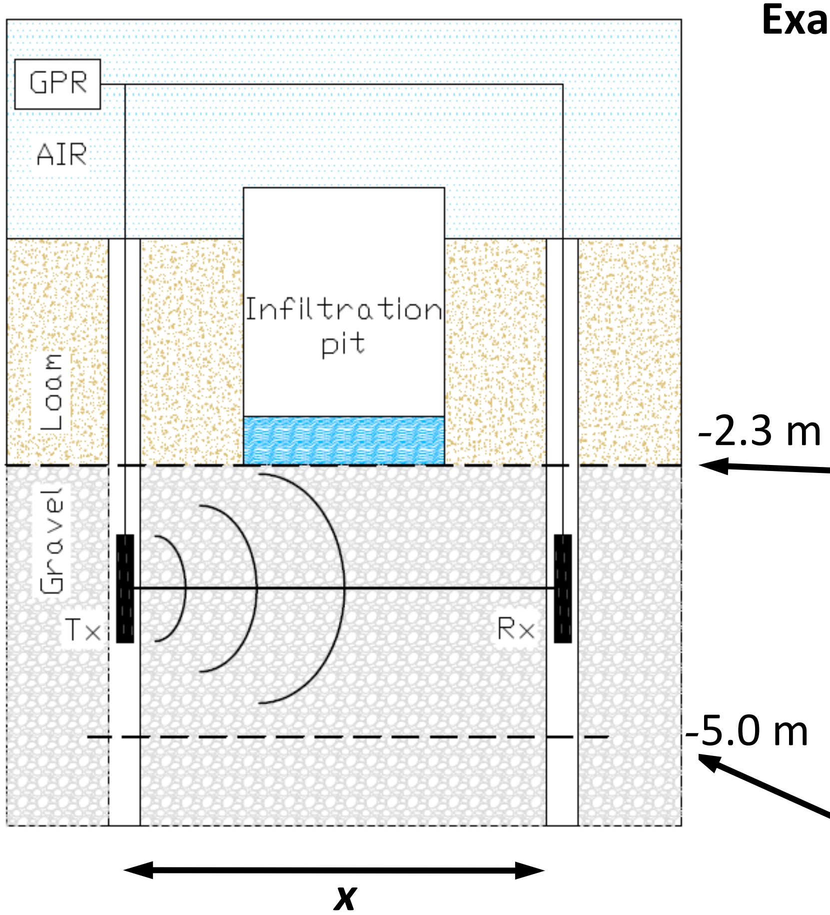
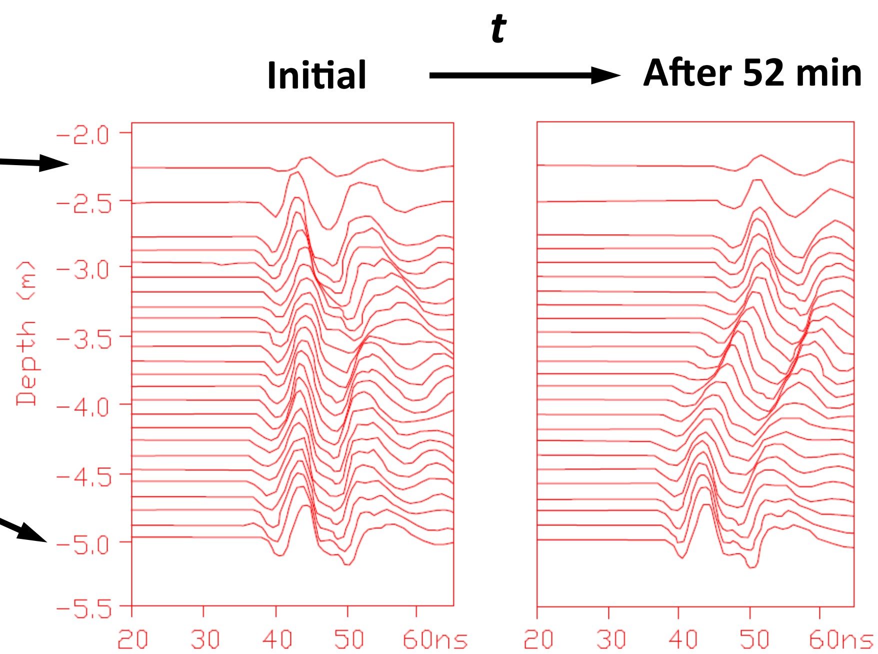
Use of GPR for precision agriculture: soil moisture mapping



Example of 1D profiling

$$v = \frac{x}{t} \qquad \varepsilon_r = \left(\frac{c}{v}\right)^2$$



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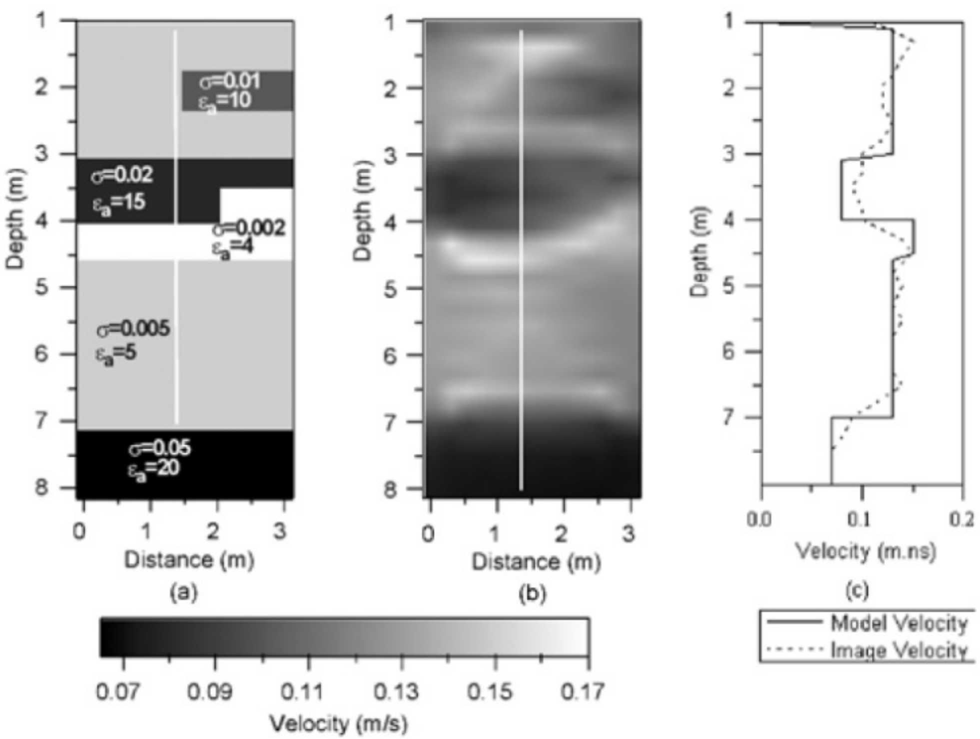
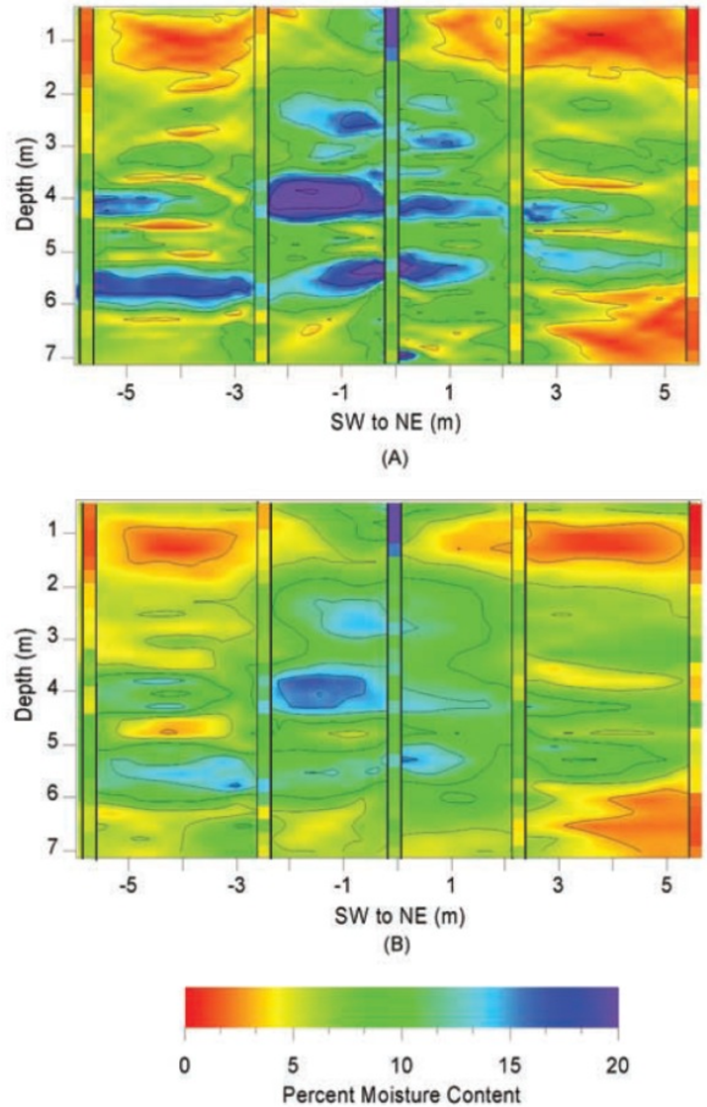
Use of GPR for precision agriculture: soil moisture mapping

Example of 2D tomography

Numerical results



Field results



(Alumbaugh et al., WRR, 2002)

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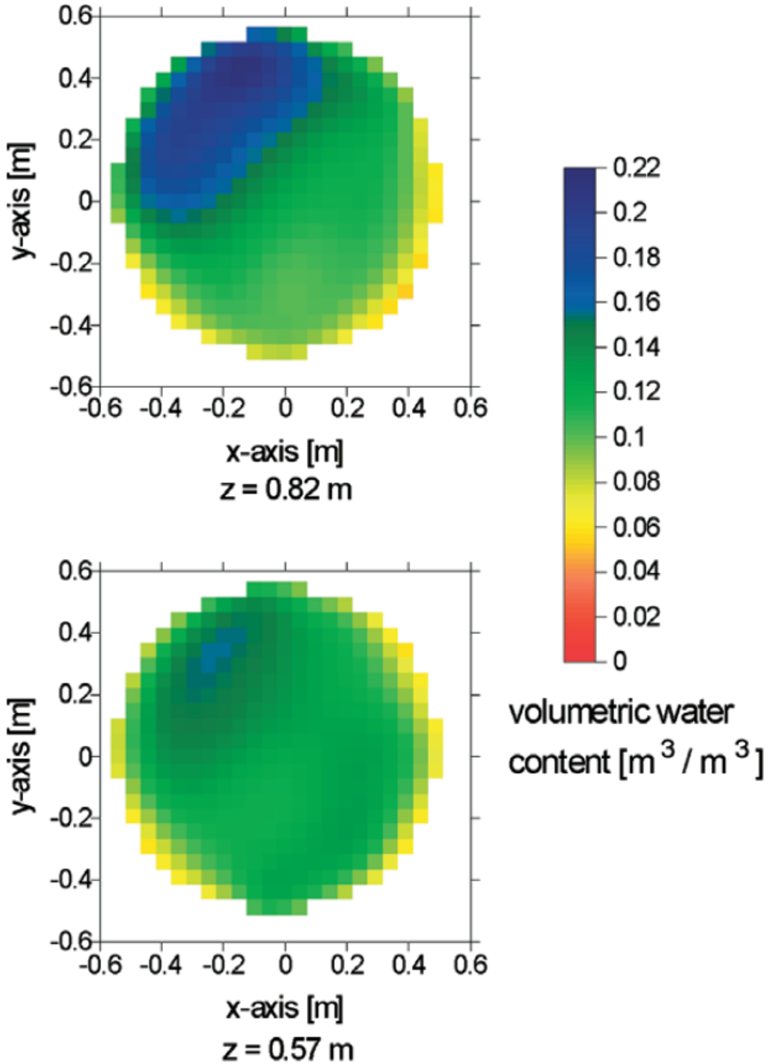
Use of GPR for precision agriculture: soil moisture mapping

Example of 3D tomography



(Schmalholz et al., VZJ, 2003)

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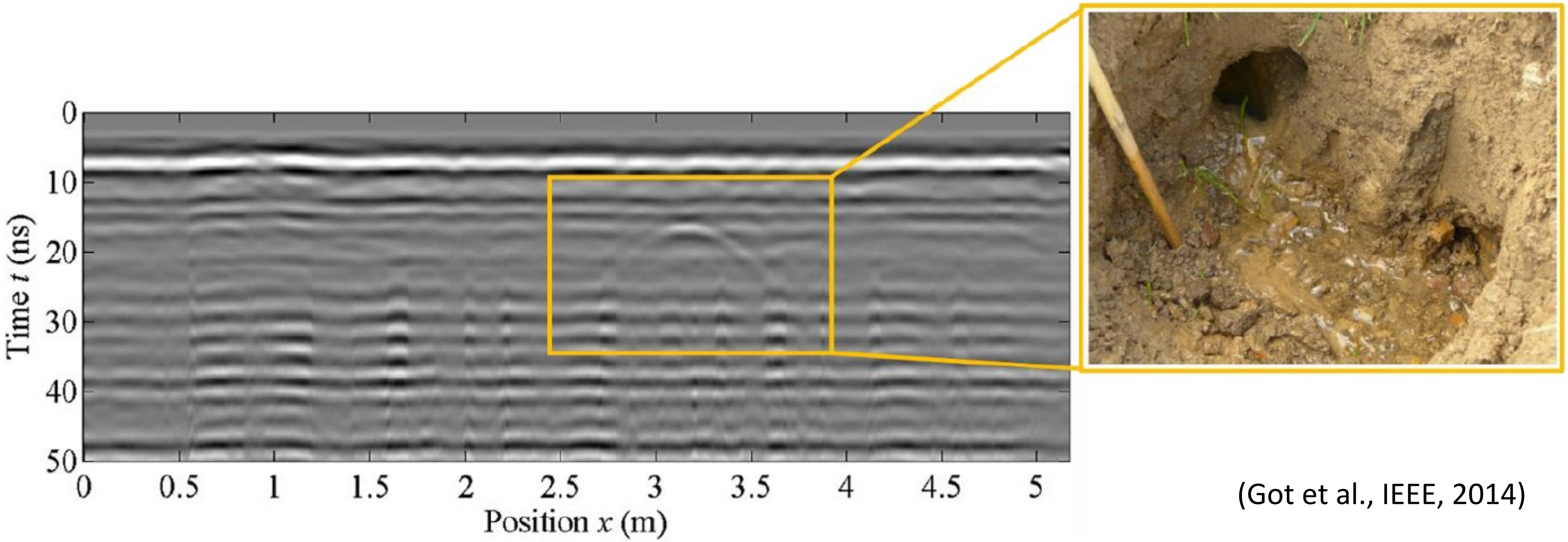
Use of GPR for precision agriculture: soil piping detection

- For GPR detection of natural soil pipes it is advised to use on-ground bowtie antennas with center frequency of about 200 MHz
- Transversal data acquisition has to be performed to see the size of the pipe -> similar to utilities mapping



(Got et al., IEEE, 2014)

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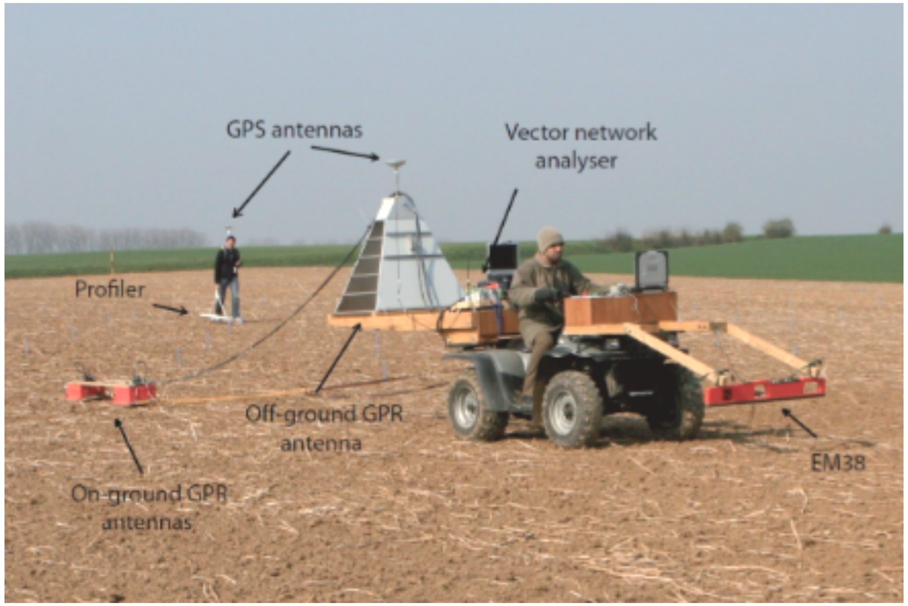
Use of GPR for precision agriculture

- Equipment and Method
  - A combination of on-ground and off-ground antennas is advised.
  - The operating frequency of the antenna should be 0.3-0.8 GHz.
  - In order to map a field with high resolution, the GPR system should be fixed to a vehicle.

- Data presentation
  - Presentation of GPR data is usually carried out in the form of B-Scans and C-Scan horizontal sections corresponding to different depths



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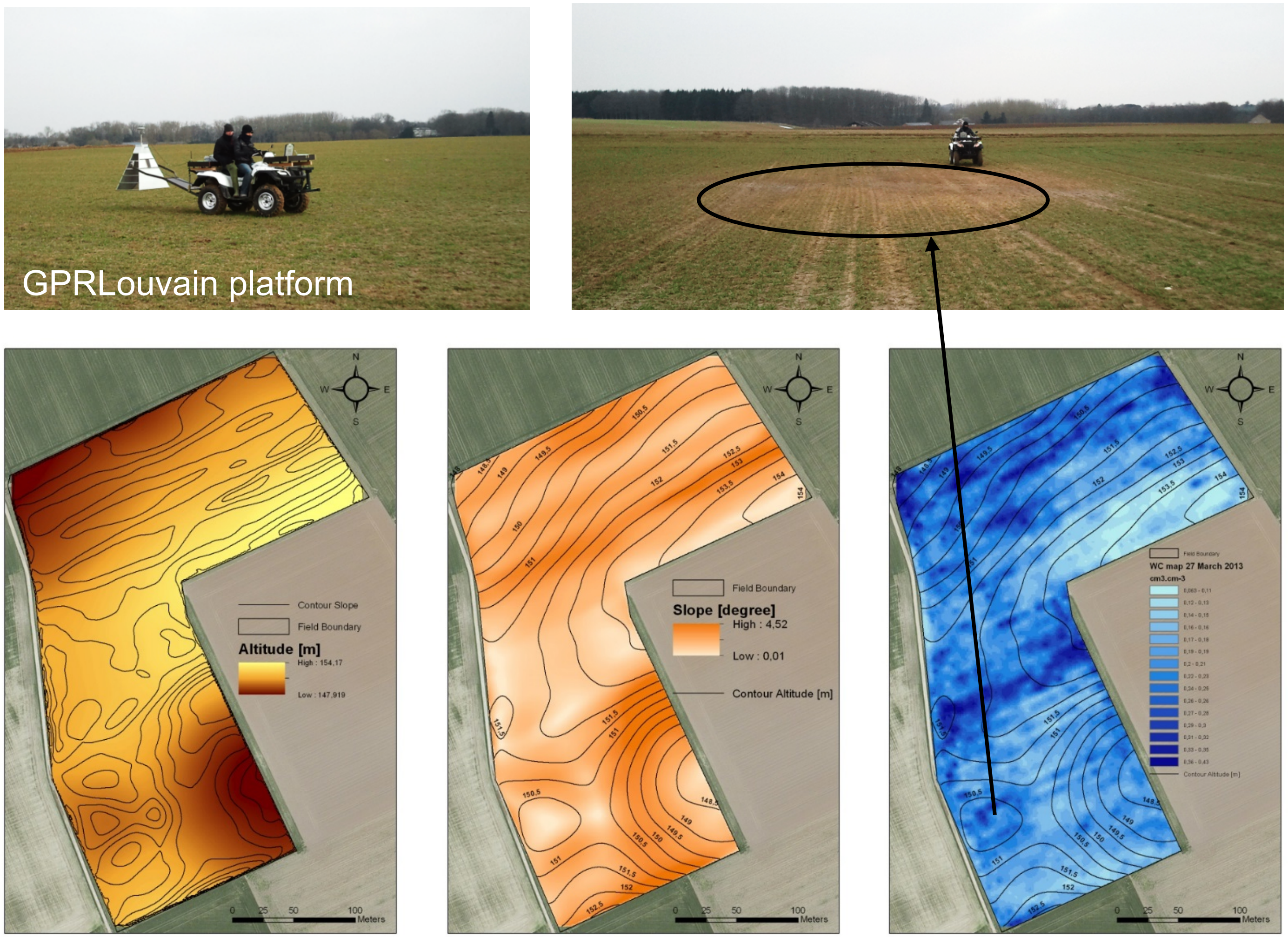
Case Study (agricultural fields)

High-resolution, real-time mapping of soil moisture using full-wave inversion



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References

[1] J. Ježová, L. Mertens, and S. Lambot, "Ground-penetrating radar for observing tree trunks and other cylindrical objects," Construction and Building Materials, vol. 123, pp. 214–225, 2016.

This paper explains basics of the tree trunk inspection with GPR. It talks about the complexity of GPR images obtained over cylindrical objects such as trees or columns. Several types of reflection curves occurring in radargrams are discussed.

[2] I. Rodríguez-Abad, R. Martínez-Sala, F. García-García, R. Capuz-Lladró and R. Díez Barra, "Non-destructive characterization of maritime pine sawn timber dielectric anisotropy by means of GPR," 2011 6th International Workshop on Advanced Ground Penetrating Radar (IWAGPR), Aachen, 2011, pp. 1-5.

In this article, one of the most important properties of wood, moisture, is studied by using GPR and ultrasound tomography. It is possible to evaluate wood moisture by investigating its relative permittivity, which is dependent on the grain direction.

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References

[3] S.A. Al Hagrey, Geophysical imaging of root-zone, trunk, and moisture heterogeneity, J. Exp. Bot. 58 (4) (2007) 839–854.

In this paper, several non-invasive techniques (electrical resistivity, ultrasound and georadar tomography) are used to detect structure deviations in tree trunks and roots. The author discusses the moisture changes as an index of decays in living wood.

[4] S. Lambot, L. Weihermüller, J.A. Huisman, H. Vereecken, M. Vanclooster, E.C. Slob, Analysis of air-launched ground-penetrating radar techniques to measure the soil surface water content, Water Resour. Res. 42 (11) (2006).

In this paper, the authors analyzed the full-wave inverse problem to derive the soil surface permittivity and correlated moisture using far-field GPR. Hypotheses are discussed and objective functions are presented.

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References

[5] J. Minet, P. Bogaert, M. Vanclooster, S. Lambot, Validation of ground penetrating radar full-waveform inversion for field scale soil moisture mapping, J. Hydrol. 424-425 (2012) 112–123.

The authors successfully validated their full-wave inverse modeling technique to map soil moisture using far-field GPR. The origin of the errors was elucidated using geostatistical analyses.

[6] F. Jonard, L. Weihermüller, H. Vereecken, S. Lambot. Accounting for soil surface roughness in the inversion of ultrawideband off-ground GPR signal for soil moisture retrieval. In: Geophysics, Vol. 77, no.1, p. H1-H7 (January-February 2012).

In this paper, the soil moisture estimation quality is tested by using a full-wave radar model with a soil roughness model. Laboratory measurements with several roughness and moisture conditions are performed, to validate the strategy for soil moisture inverse retrieval.

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[7] M. R. Mahmoudzadeh Ardekani, D. C. Jacques and S. Lambot, "A Layered Vegetation Model for GPR Full-Wave Inversion," in IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 9, no. 1, pp. 18-28, Jan. 2016.

This paper deals with the influence of vegetation on the soil moisture evaluation using GPR. The signal is backscattered from the vegetation and the radargram is highly affected. To validate GPR data, TDR probes are used to control soil water content.

[8] F. André, C. van Leeuwen, S. Saussez, R. Van Durmen, P. Bogaert, D. Moghadas, L. de Rességuier, B. Delvaux, H. Vereecken, S.Lambot, High-resolution imaging of a vineyard in south of France using ground-penetrating radar, electromagnetic induction and electrical resistivity tomography, Journal of Applied Geophysics, Volume 78, March 2012, Pages 113-122

In this paper, three technologies (GPR, EMI, ERT) are combined to obtain a high resolution soil moisture map of a vineyard in south of France.

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[9] J. B. Got, P. André, L. Mertens, C. Bielders and S. Lambot, "Soil piping: networks characterization using ground-penetrating radar," Proceedings of the 15th International Conference on Ground Penetrating Radar, Brussels, 2014, pp. 144-148.

This article describes the problem of soil piping, which can highly affect the hydrological properties of environmental areas. The authors used GPR as a promising non-invasive technique to detect the position, size and depth of soil pipes.

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Jana Jezova (jana.jezova@uclouvain.be), received her master degree in civil engineering at the Czech Technical University in Prague, Czech Republic, in 2014. Since the same year she has been a PhD student at the Université catholique de Louvain (UCL), Belgium. She deals with the problem of application of Ground-Penetrating Radar (GPR) for tree trunk non-invasive investigation. She also studies GPR scanning of cylindrical objects and scattering of electromagnetic waves within them. She is a Working Group Member of the COST Action TU1208 "Civil Engineering Applications of Ground Penetrating Radar".

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Sébastien Lambot (sebastien.lambot@uclouvain.be), since 2006, has been a Professor and FNRS research group leader at the Université catholique de Louvain (UCL). His research interests include electromagnetic modelling for Ground-Penetrating Radar (GPR) and electromagnetic induction, inversion of GPR data for non-destructive characterization of soils and materials, hydro-geophysics and remote sensing of the environment.

Prof. Lambot was General Chair of the 3rd International Workshop on Advanced Ground Penetrating Radar in 2005 and General Chair of the 15th International Conference on Ground Penetrating Radar in 2014. He is a Management Committee Member of the COST Action TU1208.

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