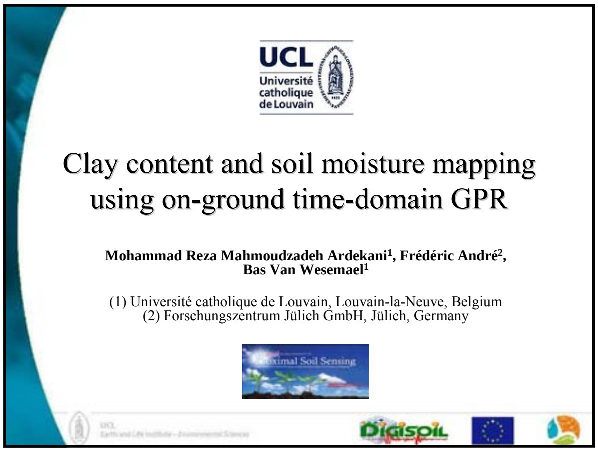
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Clay content and soil moisture mapping using on-ground time-domain GPR
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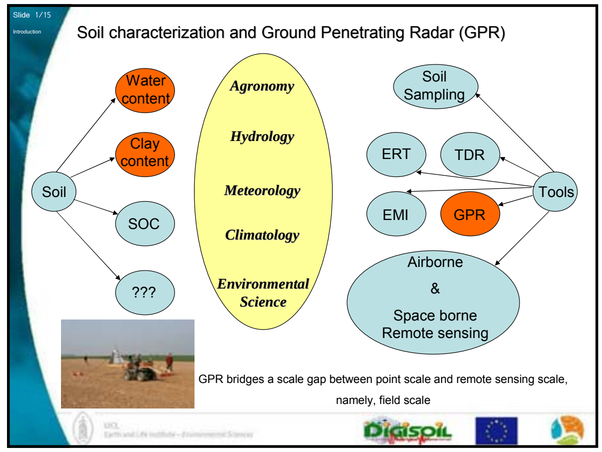
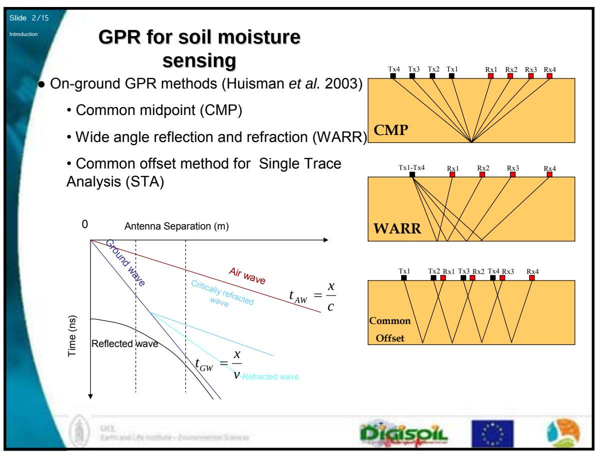
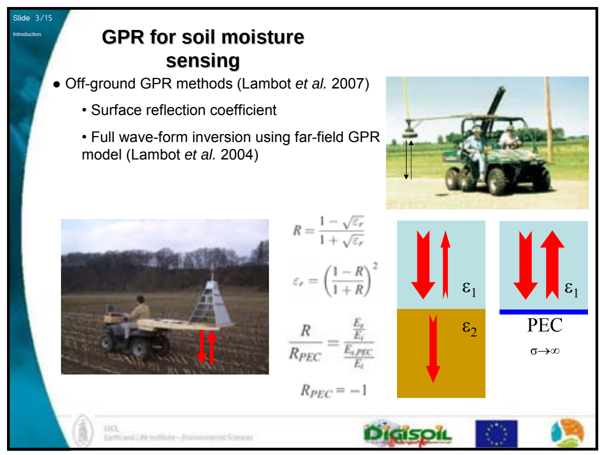
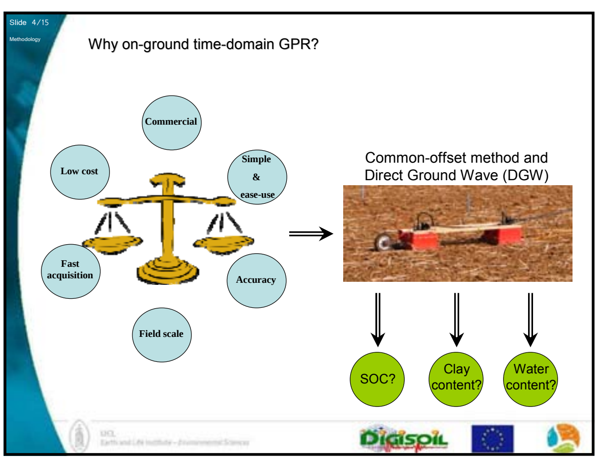
Proximal Soil Sensing


Slide 1/15
Introduction
Soil characterization and Ground Penetrating Radar (GPR)
Soil
Water content
Clay content
SOC
???
Agronomy
Hydrology
Meteorology
Climatology
Environmental Science
Soil Sampling
ERT
TDR
EMI
GPR
Tools
Airborne & Space borne Remote sensing
GPR bridges a scale gap between point scale and remote sensing scale, namely, field scale


Slide 2/15
Introduction
GPR for soil moisture sensing
• On-ground GPR methods (Huisman et al. 2003)
• Common midpoint (CMP)
• Wide angle reflection and refraction (WARR)
• Common offset method for Single Trace Analysis (STA)
Tx4 Tx3 Tx2 Tx1 Rx1 Rx2 Rx3 Rx4
CMP
Tx1-Tx4 Rx1 Rx2 Rx3 Rx4
WARR
Tx1 Tx2 Rx1 Tx3 Rx2 Tx4 Rx3 Rx4
Common Offset
0
Antenna Separation (m)
Time (ns)
Ground wave
Air wave
Critically refracted wave
Reflected wave
Refracted wave
$t_{AW} = \frac{x}{c}$
$t_{GW} = \frac{x}{v}$


Slide 3/15
Introduction
GPR for soil moisture sensing
• Off-ground GPR methods (Lambot et al. 2007)
• Surface reflection coefficient
• Full wave-form inversion using far-field GPR model (Lambot et al. 2004)
$R = \frac{1-\sqrt{\varepsilon_r}}{1+\sqrt{\varepsilon_r}}$
$\varepsilon_r = \left(\frac{1-R}{1+R}\right)^2$
$\frac{R}{R_{PEC}} = \frac{E_r / E_i}{E_{r,PEC} / E_i}$
$R_{PEC} = -1$
ε_1
ε_2
ε_1
PEC
$\sigma \rightarrow \infty$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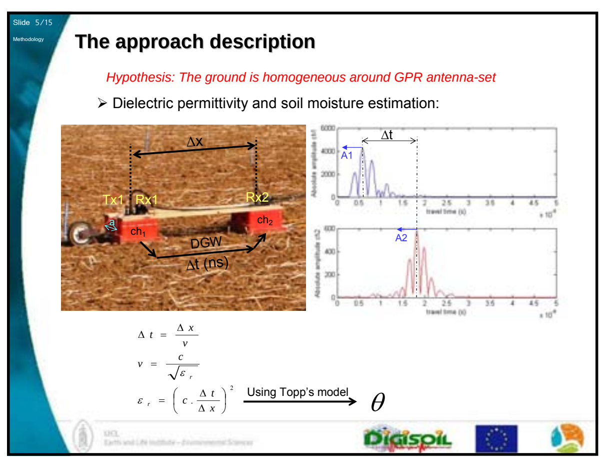
Methodology
Why on-ground time-domain GPR?
Commercial
Low cost
Simple & ease-use
Fast acquisition
Accuracy
Field scale
Common-offset method and Direct Ground Wave (DGW)
SOC?
Clay content?
Water content?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Methodology
The approach description
Hypothesis: The ground is homogeneous around GPR antenna-set
➢ Dielectric permittivity and soil moisture estimation:
Δx
Tx1 Rx1
Rx2
ch_1
ch_2
DGW
Δt (ns)
Δt
A1
A2
$\Delta t = \frac{\Delta x}{v}$
$v = \frac{c}{\sqrt{\varepsilon_r}}$
$\varepsilon_r = \left(c \cdot \frac{\Delta t}{\Delta x}\right)^2$
Using Topp's model
θ

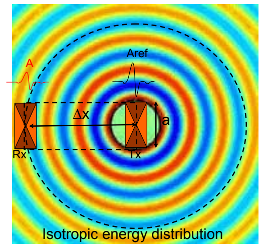
The approach description

Hypothesis: 2D isotropic radiation

➢ Electrical conductivity estimation:

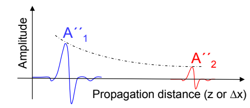
Assuming σ=0:

$$S_c = \pi.\Delta x^2$$
$$S_r = a.\Delta x$$
$$\frac{P_1}{P_2} = \frac{A_{ref}^{\ 2}}{A^{\ 2}} = \frac{S_c}{S_r} = \frac{\pi.\Delta x^2}{a.\Delta x} = \frac{\pi}{a}.\Delta x$$
$$\Rightarrow \frac{A_{ref}}{A} = \sqrt{\frac{\pi}{a}.\Delta x}$$
$$\Rightarrow \frac{A'_1}{A'_2} = \sqrt{\frac{\Delta x_2}{\Delta x_1}}$$



Note: The antenna center frequency is relevant to the antenna dimensions therefore this equation can be approximately used for antenna center frequency.

The approach description



➢ Electrical conductivity estimation:

In existence of σ:

Assuming the simple TEM wave propagation for x-directed electric field in homogeneous medium:

$$E_x = E_{x_0}.e^{-\alpha.z}.\cos(\omega.t - \beta z).\hat{a}_x$$
$$\alpha = \omega\sqrt{\frac{\mu.\varepsilon}{2}(\sqrt{1+(\frac{\sigma}{\omega.\varepsilon})^2} - 1)}$$
$$E \propto Amplitude \Rightarrow e^{-\alpha(\Delta x_2 - \Delta x_1)} = \frac{A''_2}{A''_1}$$
$$A = A'.A'' \Rightarrow \frac{A_2}{A_1} = e^{-\alpha(\Delta x_2 - \Delta x_1)}\sqrt{\frac{\Delta x_1}{\Delta x_2}}$$
$$\Rightarrow \alpha = \frac{-1}{\Delta x_2 - \Delta x_1}\ln(\frac{A_2}{A_1}.\sqrt{\frac{\Delta x_2}{\Delta x_1}})$$
$$\Rightarrow \sigma = \omega.\varepsilon\sqrt{(\frac{2(\frac{\alpha}{\omega})^2}{\mu.\varepsilon}+1)^2 - 1}$$

How mixing the frequency domain equation and time domain information???

The approach description

Hypothesis: Linear relationship between aggregate electrical conductivity and Clay content

➢ Clay content estimation:

Quadratic parallel model: $\sqrt{\sigma_e} = \theta\sqrt{\sigma_w} + (1-\theta)\sqrt{\sigma_{ag}}$

(Tabbagh *et al.* 2006)

Linear model: $\sigma_e = \theta.\sigma_w + (1-\theta)\sigma_{ag}$

Clay content model: $C_{clay}\% = a.\sigma_{ag} + b$

Water conductivity=0.05 S/m

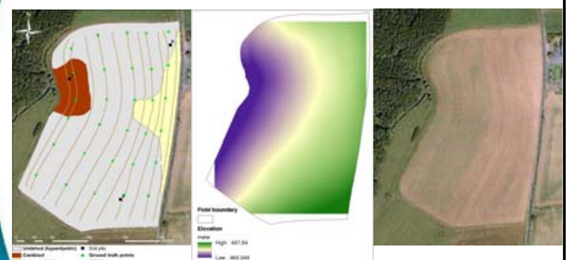
Water content

Apparent conductivity derived by GPR

Aggregate conductivity is assumed to be a function of hydraulic conductivity which is dependent of the capilary size

The study area

➢ A ~5 ha agricaltural field located in the Oësling hills in North part of Grand Duchy of *Laxembourg* with a mean altitude of 480 m.



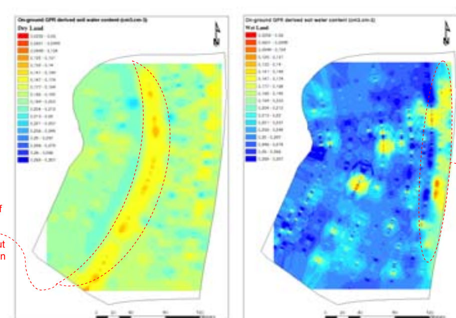
Study field profile | Topographic map derived by dGPS | rom Google map

The ground-truths and the land conditions

- 30 locations entire the field
- 4 different depths (0-10, 10-20, 20-30, and 30-40 cm) for soil moisture validating.
- 2 different depths (0-10, and 20-30 cm) for clay content validation (using Coulter counter, the cost is ~7€ per sample).

Note: because of unforeseen precipitation event, we had 2 different land conditions namely dry and wet. We applied GPR for both conditions but only 3 locations of ground-truths belonged to the dry land and the rest belonged to the wet land.

The water content maps



Because of land slope after long time without precipitation

Because of soil type (Anthrosol)

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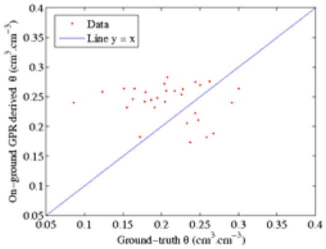
Results

The wet condition water content map validation



- Local variation of water content
- Different characterization scale
- Positioning (note that because of mud the survey wheel did not work and the positioning is estimated manually)

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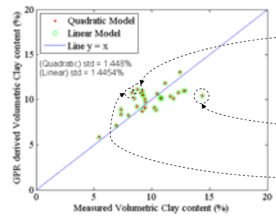
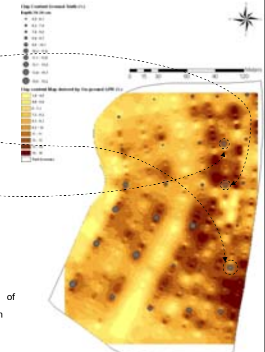
Results

The clay content map and validation





$\lambda_{av} \approx 40$ cm

The ground-truth amounts are derived by averaging of 0-10 and 20-30 cm amounts. The small mismatch can be due to of missing ground-truth value.

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Conclusions

Conclusions

- Both water content maps derived by on-ground GPR are consistent and show the ability of common-offset method for estimating soil water content.
- The DGW penetration depth is about GPR wave-length which is a function of soil moisture and GPR center frequency.
- There is no significant benefit using linear or quadratic parallel model in order to retrieve the aggregate electrical conductivity from the apparent soil electrical conductivity.
- There is a linear relationship between clay content and aggregate electrical conductivity.
- The clay content map derived by GPR satisfies the ground-truths.

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Perspectives

Perspectives

- Evaluating the proposed approach for other GPR antennas with different center frequencies.
- The effect-investigation of different antenna offsets on retrieving the apparent soil electrical conductivity using DGW.
- Modeling the SOC using the aggregate electrical conductivity derived by proposed approach.

Thanks for your attention

To whom it may interest

Also we are applying the proposed approach to model the SOC. If you are interested on this job, for more details contact me via the following Email address:

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