From Soil Measurements to Detector Performance  
—  
How to Predict Soil Influence on EMI and GPR Sensors

Jan Igel\textsuperscript{1}, Sven Altfelder\textsuperscript{2}, Volker Hennings\textsuperscript{2}, Holger Preetz\textsuperscript{1} & Kazunori Takahashi\textsuperscript{1}

\textsuperscript{1}Leibniz Institute for Applied Geophysics, Hannover, Germany

\textsuperscript{2}Federal Institute for Geosciences and Natural Resources, Germany
Factors influencing detector performance for landmine clearance

detector performance

detector technique

human factor

weather

soil

vegetation

man-made clutter

target
Soil influence

Common detector tests

- often performed on artificial substrates (sandbox)
- adequate to develop and optimise new detector techniques
- not adequate to determine realistic detector performance
Soil influence on EMI and GPR sensors

Common detector tests
- often performed on artificial substrates (sandbox)
- adequate to develop and optimise new detector techniques
- not adequate to determine realistic detector performance

Natural field conditions
- much more complicated than homogeneous substrates
- natural soil has layers, stones, vegetation, inhomogeneities...
- test should be carried out in the field or at least in test sites with natural soils
Soil influence

GPR measurements on 3 different soils, but with the same 5 targets

Which are the soil properties that influence landmine detectors?
How can these properties be investigated?
How can detector performance be predicted?
GPR measurements on 3 different soils, but with the same 5 targets

- Which are the soil properties that influence landmine detectors?
- How can these properties be investigated?
- How can detector performance be predicted?
Detection techniques and soil properties

**Metal detector (MD), EM induction**
- magnetic susceptibility $\kappa$
- electric conductivity $\sigma$

**Ground-penetrating radar (GPR), EM wave propagation**
- dielectric permittivity $\varepsilon$
- electric conductivity $\sigma$

**Magnetic susceptibility**
- mineralogy
- bulk density
- stone content ...

**Electric conductivity**
- texture
- salinity
- water content ...

**Dielectric permittivity**
- water content
- bulk density
- texture ...

- absolute values
- frequency dependence $\rightarrow$ lab-measurements
- spatial variability $\rightarrow$ field-measurements
Detection techniques and soil properties

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## Detection techniques and soil properties

### Metal detector (MD), EM induction
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### Ground-penetrating radar (GPR), EM wave propagation
- Dielectric permittivity $\varepsilon$
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### Magnetic susceptibility
- Mineralogy
- Bulk density
- Stone content ...

### Electric conductivity
- Texture
- Salinity
- Water content ...

### Dielectric permittivity
- Water content
- Bulk density
- Texture ...

- Absolute values
- Frequency dependence $\rightarrow$ lab-measurements
- Spatial variability $\rightarrow$ field-measurements
## Magnetic minerals

<table>
<thead>
<tr>
<th>Mineral/Material</th>
<th>Chemical notation</th>
<th>Susceptibility ((10^{-3} \text{ SI}))</th>
<th>Origin</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ferromagnetic</strong></td>
<td></td>
<td></td>
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<tr>
<td>Iron</td>
<td>Fe</td>
<td>2 180 400</td>
<td>anthropogenic</td>
</tr>
<tr>
<td>Cobalt</td>
<td>Co</td>
<td>1 815 600</td>
<td>anthropogenic</td>
</tr>
<tr>
<td>Nickel</td>
<td>Ni</td>
<td>612 800</td>
<td>anthropogenic</td>
</tr>
<tr>
<td><strong>ferrimagnetic</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnetite</td>
<td>Fe(_3)O(_4)</td>
<td>2 000 – 5 800</td>
<td>lithogenic, biogenic</td>
</tr>
<tr>
<td>Titanomagnetite</td>
<td>Fe(_3)O(_4) – Fe(_2)TiO(_4)</td>
<td>1 310 – 1 450</td>
<td>lithogenic</td>
</tr>
<tr>
<td>Maghemite</td>
<td>(\gamma)Fe(_2)O(_3)</td>
<td>2 000 – 5 800</td>
<td>pedogenic</td>
</tr>
<tr>
<td>Pyrrhotite</td>
<td>Fe(_7)S(_8)</td>
<td>2 300</td>
<td>lithogenic</td>
</tr>
<tr>
<td><strong>antiferromagnetic</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hematite</td>
<td>(\alpha)Fe(_2)O(_3)</td>
<td>3 – 9</td>
<td>pedogenic</td>
</tr>
<tr>
<td>Goethite</td>
<td>(\alpha)FeO(_{2+})</td>
<td>1 – 4</td>
<td>pedogenic</td>
</tr>
</tbody>
</table>
Frequency-dependent susceptibility

Laterite from basaltic rock (SEM)

Magnetite has wide grain-size spectrum

Superparamagnetism

Susceptibility 30 Hz – 10 kHz

Heterogeneity & GPR

Title

Introduction

Susceptibility & EMI

AMEREM, Ottawa 2010

J. Igel et al., LIAG Hannover

Soil influence on EMI and GPR sensors
Laterite from basaltic rock (SEM)

Magnetite has wide grain-size spectrum

Susceptibility 30 Hz – 10 kHz

absolute/relative frequency dependence:

\[ \Delta \kappa = \kappa_{LF} - \kappa_{HF} \]

\[ \kappa_{FD} = \frac{(\kappa_{LF} - \kappa_{HF})}{\kappa_{LF}} \]
Study on magnetic properties of tropical soils

Samples of BGR archive

- ≈ 600 laterite samples
- 15 countries of the tropical belt
- 6 groups of parent rock materials
  - ultrabasic
  - basic/intermediate
  - acid
  - clay/clayslate
  - phyllite
  - sandstone
- different degree of weathering
  - unweathered rock
  - weathered rock
  - subsoil
  - topsoil
Absolute susceptibility of tropical soils

Histogram

Influence on EMI sensors: neutral → very severe
(Classification due to CEN Workshop Agreement, 2006)
Absolute susceptibility of tropical soils

Influence on EMI sensors: neutral $\rightarrow$ very severe
(Classification due to CEN Workshop Agreement, 2006)
Influence on EMI sensors: neutral → very severe
(Classification due to Billings, 2004 & CEN Workshop Agreement, 2008)
Frequency-dependent susceptibility of tropical soils

Influence of parent material

- ultrabasic
- basic/int.
- acid
- clay/~slate
- phyllite
- sandstone

Influence of weathering

Influence on EMI sensors: neutral → very severe
(Classification due to Billings, 2004 & CEN Workshop Agreement, 2008)

Degree of weathering:
- topsoil
- subsoil
- weathered rock
- unweathered rock
### Classification system

<table>
<thead>
<tr>
<th>Parent material</th>
<th>Regardless weathering</th>
<th>unw. rock</th>
<th>Degree of weathering</th>
<th>weath. rock</th>
<th>subsoil</th>
<th>topsoil</th>
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</thead>
<tbody>
<tr>
<td>ultrabasic</td>
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<td>■■</td>
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<tr>
<td>basic/intermediate</td>
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<td>■■</td>
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<tr>
<td>acid</td>
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<td>■■</td>
<td>■■</td>
<td>■■</td>
<td>■■</td>
</tr>
<tr>
<td>clay/clay-slate</td>
<td></td>
<td>■■</td>
<td>■□</td>
<td>■□</td>
<td>■□</td>
<td>■□</td>
</tr>
<tr>
<td>phyllite</td>
<td></td>
<td>■□</td>
<td>–</td>
<td>■□</td>
<td>■□</td>
<td>■□</td>
</tr>
<tr>
<td>sandstone</td>
<td></td>
<td>■□</td>
<td>■□</td>
<td>■□</td>
<td>■□</td>
<td>■□</td>
</tr>
</tbody>
</table>

- median, 90% quantile
- ■ neutral
- ■■ moderate
- ■ severe
- ■■ very severe
- – no data
- □ only few data

Regardless

Degree of weathering

- unw. rock
- weath. rock
- subsoil
- topsoil
Case study: Angola
Case study: Angola

Classification System

<table>
<thead>
<tr>
<th>Parent material</th>
<th>Regardless</th>
<th>Strong</th>
<th>Moderate</th>
<th>Weak</th>
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</thead>
<tbody>
<tr>
<td>Ultrabasic</td>
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<tr>
<td>Andesite</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Clay/loam soil</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phyllite</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Siltstone</td>
<td></td>
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</table>

Soil map (FAO)  
Detector performance
Looking at different scales

Regional scale

- generalised information
- most likelihood value
Looking at different scales

Regional scale

- generalised information
- most likelihood value

Field scale

- small-scale variability
  - influence on ground compensation of EMI sensors
  - influence on GPR
Natural soil shows heterogeneous water distribution

\( \varepsilon \) and \( \sigma \) depend on water content

GPR is based on EM wave propagation and influenced by \( \varepsilon \) and \( \sigma \)

Small-scale heterogeneity causes "geologic noise" in GPR data
GPR and soil heterogeneity

- natural soil shows heterogeneous water distribution
- $\varepsilon$ and $\sigma$ depend on water content
- GPR is based on EM wave propagation and influenced by $\varepsilon$ and $\sigma$
- small-scale heterogeneity causes "geologic noise" in GPR data
Determining spatial variability in field

**Geophysical technique**

**Electric resistivity tomography (ERT)**

**GPR groundwave mapping**

**Example on sandy grassland**

**Electric conductivity $\sigma$**

![Electric conductivity graph](image)

**Dielectric permittivity $\varepsilon_r$**

![Dielectric permittivity graph](image)
Analysing heterogeneity

Procedure

1. high-resolution measurement on representative area
2. geostatistical analysis
   - density function: \( \rightarrow \) how often a value occurs
   - variogram: \( \rightarrow \) spatial correlation
3. model fit
4. generation of random media
5. FD-calculation of EM wave propagation

Geophysical measurement
Analysing heterogeneity

Procedure

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   - density function: → how often a value occurs
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Density function and variogram

![Density function and variogram graph]
Analysing heterogeneity

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Geostatistical model
Analysing heterogeneity

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Spatial distribution:
in situ and simulated

in situ

statistical simulation
Analysing heterogeneity

Procedure

1. high-resolution measurement on representative area
2. geostatistical analysis
   - density function: → how often a value occurs
   - variogram: → spatial correlation
3. model fit
4. generation of random media
5. FD-calculation of EM wave propagation
   → realistic synthetic GPR data
   → S/N ratio (geologic noise)
Influence of heterogeneity on GPR performance (FD calculation)

Model: $\varepsilon_r$ variable, $\sigma = \text{const.}$
Irrigation experiment

Experimental setup
- sandy soil with grass
- landmine in 10 cm depth
- irrigate dry soil until saturation
- GPR B-scan measured every 2 min

Before irrigation
($\varepsilon_r = 4.0, \theta_v = 5.5\%$)

Irrigation stopped
($\varepsilon_r = 20.8, \theta_v = 35.7\%$)

5 hours after irrigation
($\varepsilon_r = 12.8, \theta_v = 24.0\%$)

18 hours after irrigation
($\varepsilon_r = 11.2, \theta_v = 21.1\%$)
Irrigation experiment

**Experimental setup**
- sandy soil with grass
- landmine in 10 cm depth
- irrigate dry soil until saturation
- GPR B-scan measured every 2 min
  → mine signature changes
  → geologic noise changes

**Before irrigation**
- \( \varepsilon_r = 4.0, \theta_v = 5.5 \% \)

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**18 hours after irrigation**
- \( \varepsilon_r = 11.2, \theta_v = 21.1 \% \)

Relative permittivity = 4.1
Volumetric water content = 5.8 \%
Irrigation experiment: Can we model geological noise?

Analysing noise
- extract noise signal
- model assumption: dielectric sphere
- Mie-scattering theory
- good fit of modeled and measured noise
ITEP dual-sensor test, Germany 2009

Three soils

- sandy soil
  \( \varepsilon_r = 5 \pm 0.2 \)
- loamy laterite
  \( \varepsilon_r = 15 \pm 2.5 \)
- stony humus
  \( \varepsilon_r = 20 \pm 4 \)

Permittivity measurements (TDR)
ITEP dual-sensor test, Germany 2009

Three soils
- sandy soil \( \varepsilon_r = 5 \pm 0.2 \)
- loamy laterite \( \varepsilon_r = 15 \pm 2.5 \)
- stony humus \( \varepsilon_r = 20 \pm 4 \)

GPR performance, 5 landmine targets

FAR reduction
how much FAR of EMI reduced by additional GPR

POD loss
how many mines falsely rejected by additional GPR
ITEP dual-sensor test, Germany 2009

Three soils
- sandy soil \( \varepsilon_r = 5 \pm 0.2 \)
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Test result: metal detector vs. dual sensor

- FAR reduction
  how much FAR of EMI reduced by additional GPR
- POD loss
  how many mines falsely rejected by additional GPR

Test result graph:
- sandy soil
- loamy laterite
- stony humus

Graph data:
- FAR reduction (%)
- POD loss (%)

- Sandy soil: FAR reduction is high, POD loss is low.
- Loamy laterite: FAR reduction is moderate, POD loss is moderate.
- Stony humus: FAR reduction is low, POD loss is high.

AMEREM, Ottawa 2010
J. Igel et al., LIAG Hannover
Soil influence on EMI and GPR sensors 19/20
Conclusion

- Magnetic properties of 600 tropical soil samples:
  - more than 1/3 of the soils have severe and very severe impact
  - parent rock and weathering have influence

- Classification system:
  - absolute and frequency dependent susceptibility
  - geological maps → detector performance

- Typical spatial variability of the investigated soils:

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<th>Correlation length</th>
<th>Distribution</th>
<th>Cause of variability</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa$</td>
<td>m</td>
<td>normal</td>
<td>stones, bulk density</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>sub-m</td>
<td>lognormal</td>
<td>water content</td>
</tr>
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- Influence of heterogeneity on landmine detection can be quantified by:
  - field measurements + geostatistics + simulations.

- Electric conductivity has lower impact on GPR than permittivity.
Magnetic properties of 600 tropical soil samples:
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