A numerical study on using guided GPR waves along metallic cylinders in boreholes for permittivity soundings

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17th International Conference on GPR
June 18, 2018
The guided waves method

- Volumetric water-content $\Theta_V$ distribution in vadose zone relevant for hydrological processes.
The Guided-Waves Method

- **GWM** ⇒ travel-times $t_s$ → interval velocities $v_i$ → $\epsilon_r$ → $\Theta_V$
The Guided-Waves Method

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The Guided Waves Method

guided wave
multiples
The Guided Waves Method
The Guided Waves Method

- **$v_i$**: Depth [m] vs. Vel. [m/ns]
- **$\varepsilon_r$**: Depth [m] vs. $\varepsilon_r$ [ ]
- **$\Theta_V$**: Depth [m] vs. $\Theta_V$ [%]

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Research objectives

1) Assess a sensible volume

2) Accuracy of $\varepsilon_r$ measurements with/without a plastic borehole casing.

3) Vertical resolution
We build a complex 3D antenna instead of, e.g., a point source to:

- Include influence of shielded bow-tie antenna on signal
- Include coupling between antenna and metallic waveguide
3D antenna model

3D model (sliced) of the full antenna. PEC = Perfect Electric Conductor; PCB = Printed Circuit Board; HDPE = High-Density Polyethylene.
Optimizing the material parameters

Reflected wavelet from a metal surface in air, measured and simulated.
1) Field distribution around the waveguide

General model setup, ground with variable $\varepsilon_r$. 

Ground $\varepsilon_r = 6$, $\sigma = 0$
1) Field distribution around the waveguide
1) Field distribution around the waveguide
1) Field distribution around the waveguide

![Diagram showing field distribution around the waveguide at t=8 ns]
1) Field distribution around the waveguide
1) Field distribution around the waveguide
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![Diagram showing field distribution around a waveguide](image)

- **X-axis [m]**
- **Y-axis [m]**
- **Z-axis [m]**

Graph showing field distribution at t=28 ns:

- **Y-axis [m]**
- **Z-axis [m]**

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1) Field distribution around the waveguide
1) Field distribution around the waveguide

- **Procedure:**
  1) simulate same model for \( \varepsilon_r = 3, 9, 20, 36 \)
  2) take horizontal slices at 3 depths at max. amplitude of guided wave
1) Field distribution around the waveguide

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  1) simulate same model for $\varepsilon_r = 3, 9, 20, 36$
  2) take horizontal slices at 3 depths at max. amplitude of guided wave

- **Result:**
  - For a 400 MHz antenna, $1/e$ amplitude drop for all models at $= 4.1 \text{ cm}$
2) Influence of a plastic borehole casing on $\varepsilon_r$ measurements

- For water, the $\varepsilon_r$ measurements show a gradual increase with depth, with simulations (red) and measurements (blue) matching closely.

- For air, the $\varepsilon_r$ measurements remain constant with depth, showing a small variation in simulations (red) and measurements (blue).

![Graphs showing $\varepsilon_r$ vs depth for water and air with simulations and measurements, highlighting the influence of borehole casing.]
2) Influence of a plastic borehole casing on $\varepsilon_r$ measurements

Modeling setup.
2) Influence of a plastic borehole casing on $\varepsilon_r$ measurements

**Procedure:**

1) simulate same model for $\varepsilon_r = 9, 20, 36, 60$, for plastic casing widths: 1, 2, 4 mm

2) evaluate offset

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Cross-section of metal waveguide with 1 mm casing wall.
2) Influence of a plastic borehole casing on $\varepsilon_r$ measurements

Cross-section of metal waveguide with 1 mm casing wall.
2) Influence of a plastic borehole casing on $\varepsilon_r$ measurements

Cross-section of metal waveguide with 1 mm casing wall.
3) Vertical resolution

![Diagram showing vertical resolution in a borehole with different media densities.](image)

- $\varepsilon_r = 6$
- $\varepsilon_r = 20$

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3) Vertical resolution

\[ \varepsilon_r = 6 \]

\[ \varepsilon_r = 20 \]

\[ \varepsilon_r = 6 \]
3) Vertical resolution

- t [ns]
- Depth [m]
- v [m/ns]
- $\varepsilon_r$ [ ]

- Background removal
- Subtracted last trace
- Subtracted average of 10 traces
3) Vertical resolution

![Graph showing vertical resolution](image-url)
Conclusions

GWM good for high resolution velocity measurements in soils

2) *Assess a sensible volume*: The EM field is distributed symmetrically around waveguide.
   • Independent of $\varepsilon_r$, the $1/e$ amplitude drop $\approx 4.1\, \text{cm} \rightarrow$ sensible volume.

3) *Influence of plastic casing*: A plastic borehole casing around waveguide causes a considerable reduction in calculated $\varepsilon_r$.
   $\rightarrow$ Needs to be accounted for, is rectifiable.

4) *Vertical resolution*: Simulations show that sharp media boundaries are identifiable by $\approx 5\, \text{cm}$, and capillary transition zones are identifiable almost perfectly.