Radar Tunnel Detection

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Challenges and Conclusions

- Finding tunnels along border is hard:
  - Lots of terrain to cover
  - Variable depth
  - Randomly varying rough ground surface
  - Unknown soil dielectric constant
  - Lossy (moist) soils obscure signals
  - Attended sensors are expensive, unattended sensors are targets
- There is hope:
  - Tunnels have distinctive feature of long aspect ratio
  - Tunnels are filled with known target material (air)
  - Airborne SL-SAR can scan region quickly
  - Underground focusing (UF) is essential for detection
- UF-SL-SAR imaging is compelling for Mexican and Middle Eastern borders

Here's Why…

Problem formulation

- Underground tunnels present both military and homeland security threats:
  - Transit routes for trafficking drugs, people and weapons
  - Detonation access under high security facilities
  - Avoid security checkpoints (especially on the borders)

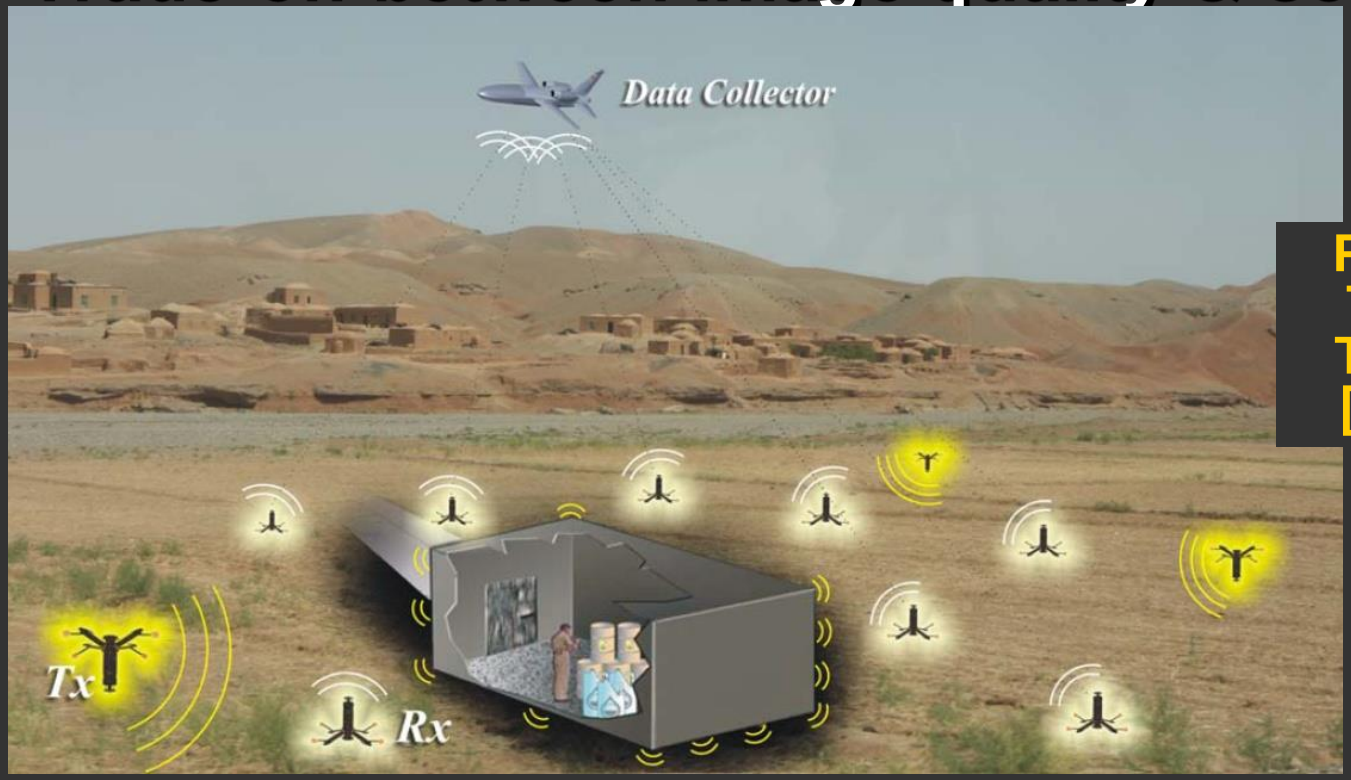
Near Otay Messa, CA (Sandy H, Getty Images 2006)

Height: 1.5 – 2 m
Width: 0.5 – 1 m
Length: 0.1 – 10 km

Tijuana, Mexico (David Maung, AP, 2004)

Current methods

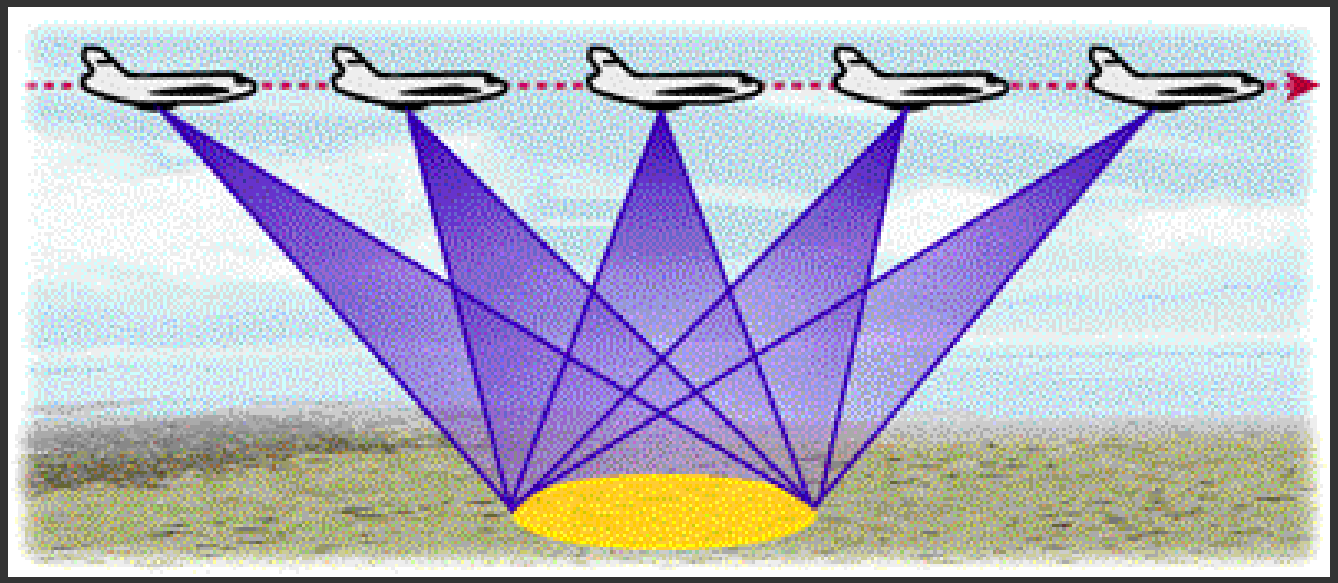
- Most of the currently proposed solutions rely on land-based Ground Penetrating Radar (GPR)
  - Time consuming
  - Expensive
- Trade-off between image quality & scanning time



Radio Frequency Tomography for Tunnel Detection [Lo Monte 2010]

Why Spotlight-SAR?

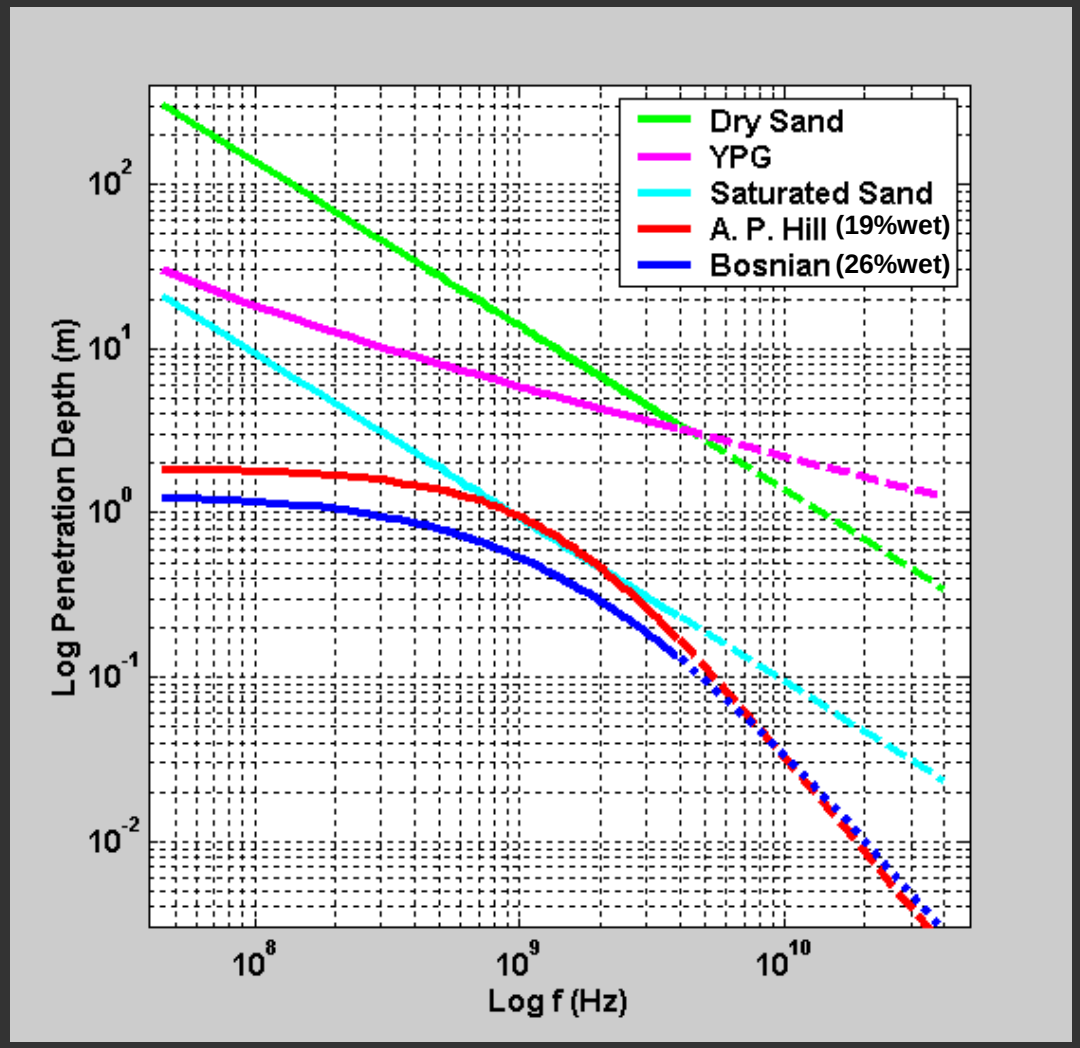
- Synthetically focus for narrow illumination spots
- Generate high resolution images
- Scans large regions in short amount of time



Spotlight SAR [Natural Resources Canada 2005]

System configuration and challenges

- **Penetration Depth v. Frequency for various dielectric materials**



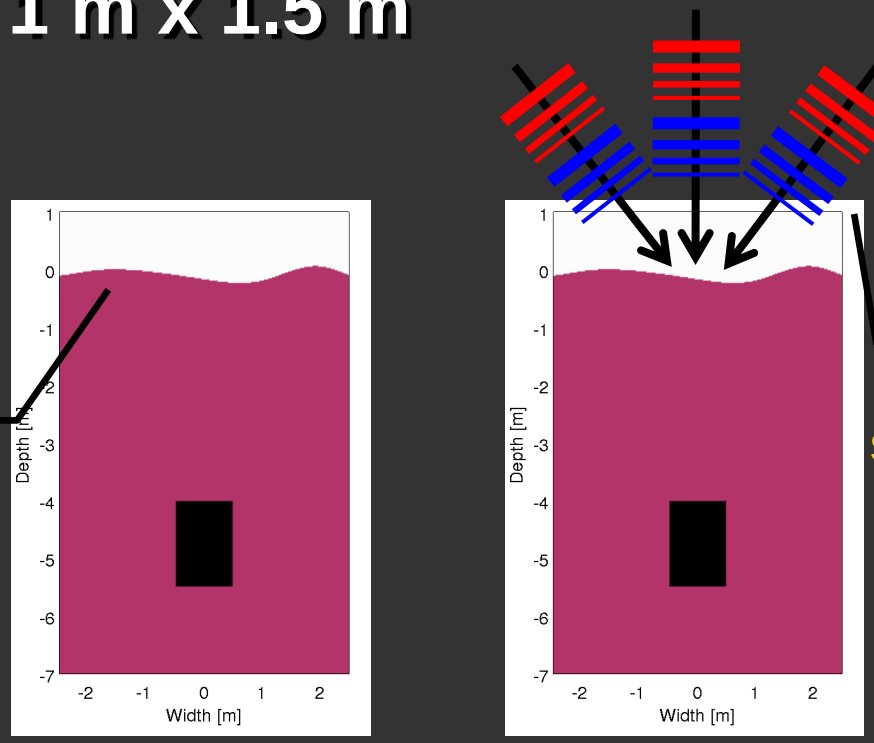
Penetration Depth d_{10}

= Distance for the power to drop by a factor of 10 (-10 dB)

Simulation configuration

- Multiple angles and frequencies for higher resolution:
  - 128 frequencies from 50 MHz to 550 MHz
  - 19 angles from -45 degrees to 45 degrees
- Parametrize permittivity
- Tunnel: 1 m x 1.5 m

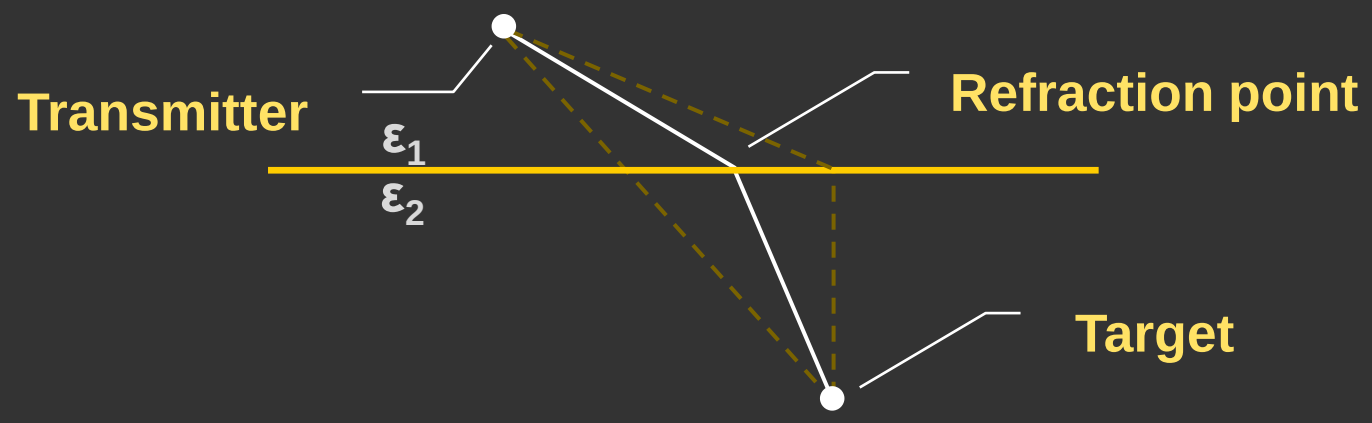
Parameter:
roughness height



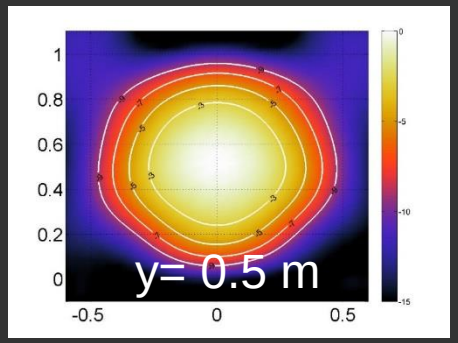
Several angles
and
several frequencies

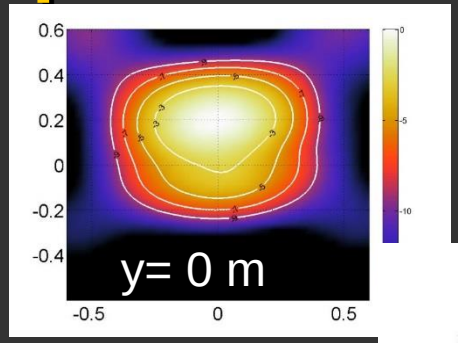
Underground Focusing Considerations

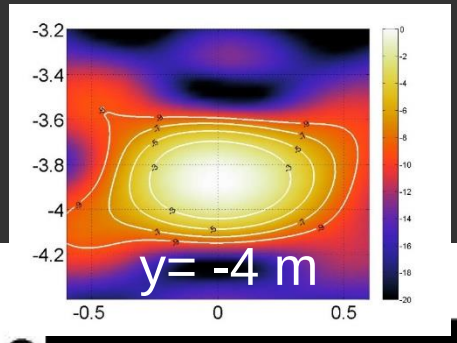
- Enhances Spotlight – SAR capabilities
- Takes into account wave refraction assuming a flat surface
- Needs estimation of soil characteristics
- Image quality and tunnel detectability depend on soil properties
- Underground media variation presents challenges



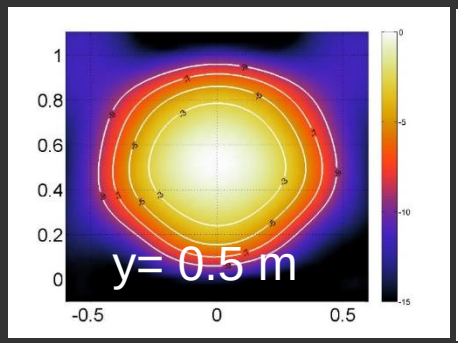
Non-dispersive sandy soil resolution: focal spot size

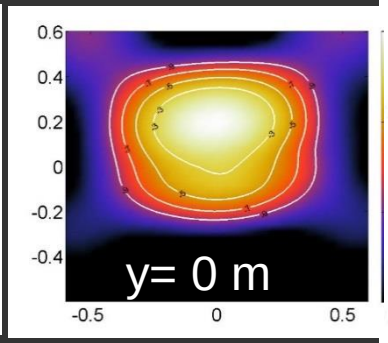


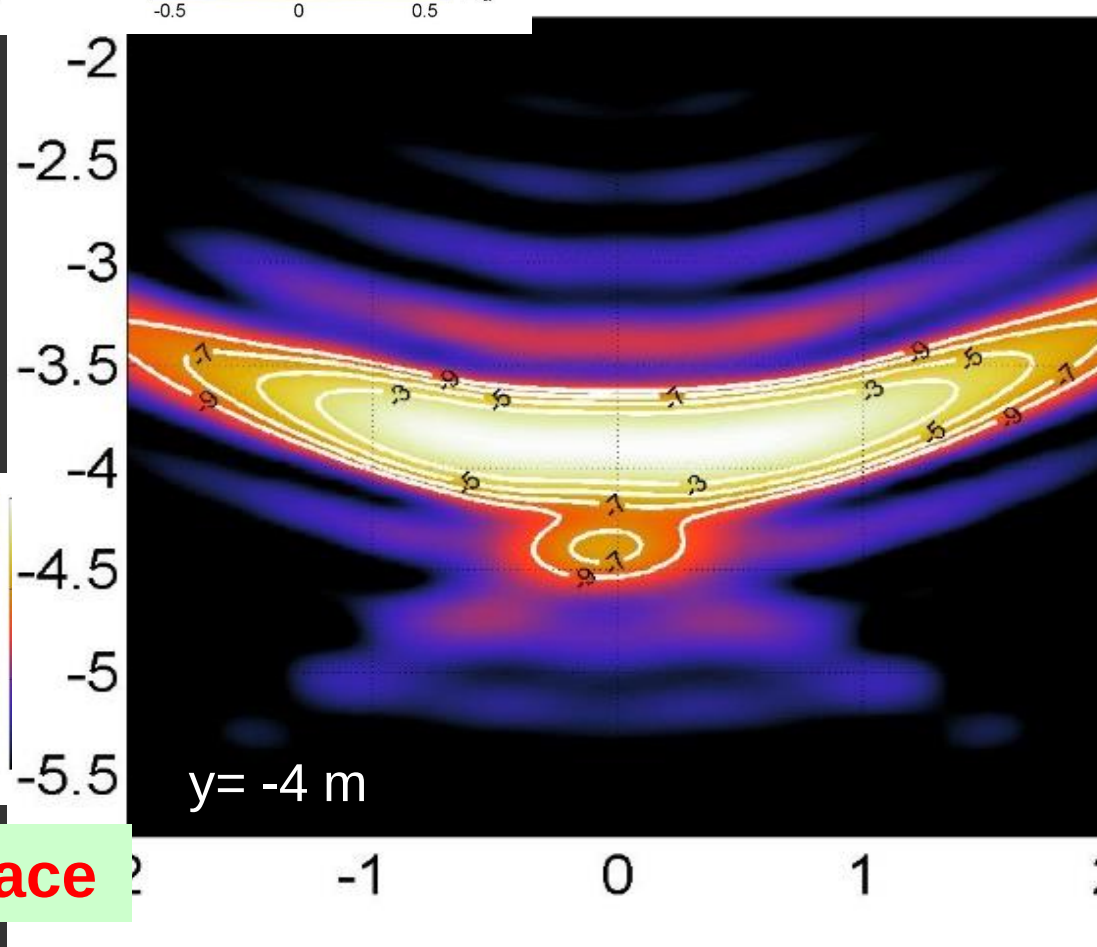




Refraction focusing at underground point



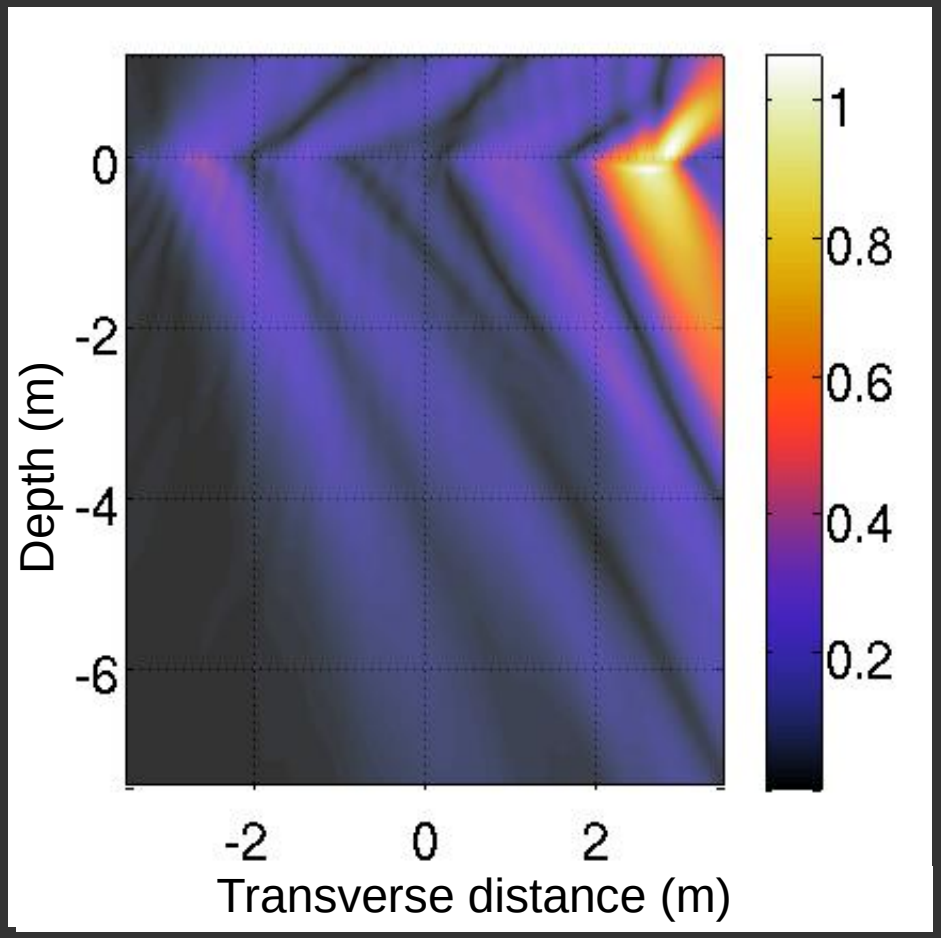




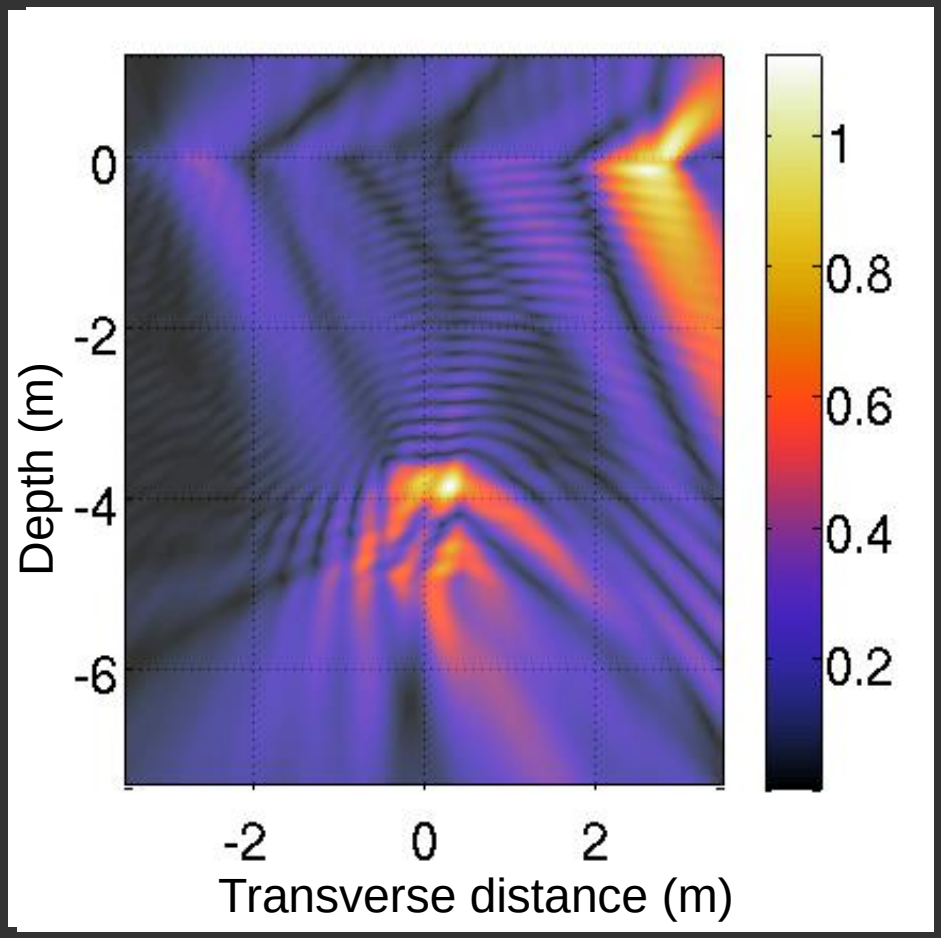
Focusing at point on surface

Field Scattered by Rough Surface Imperfections / Tunnel: 550 MHz , -45 deg.

Magnitude Scattered No Tunnel



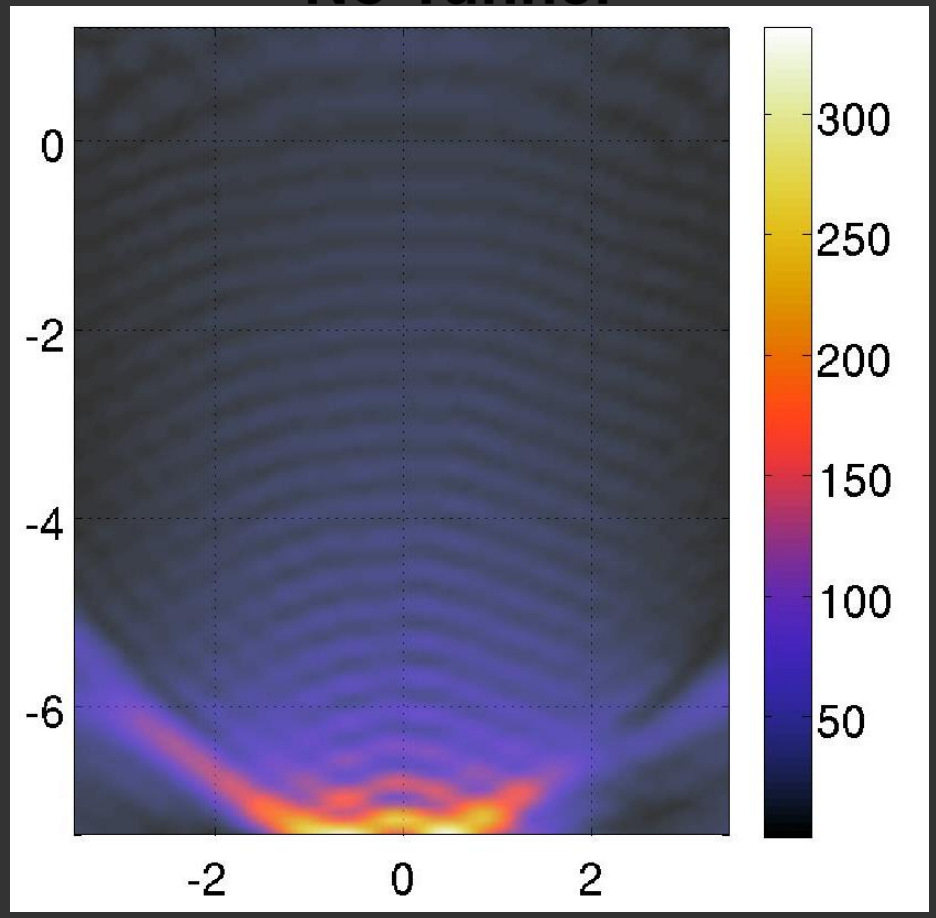
Magnitude Scattered Tunnel



Range focusing dry sand: total field

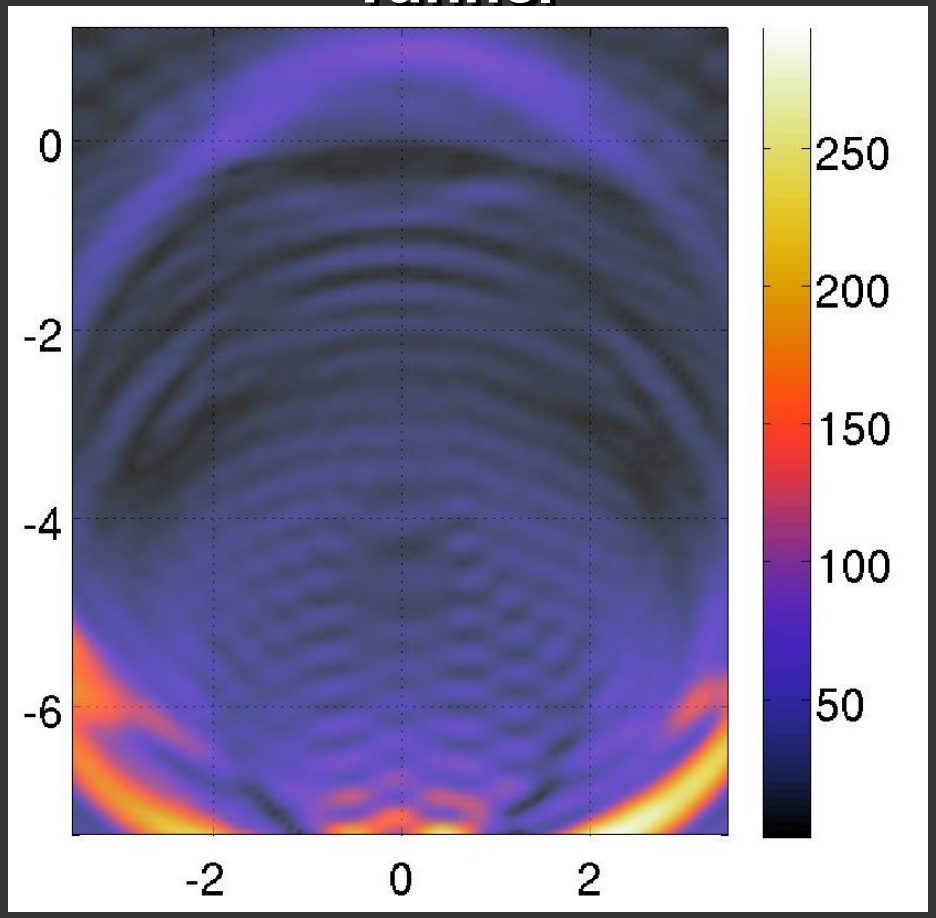
- From 0.5 m to -9 m

Magnitude Total field
No Tunnel



Focused at -8 m

Magnitude Total field
Tunnel

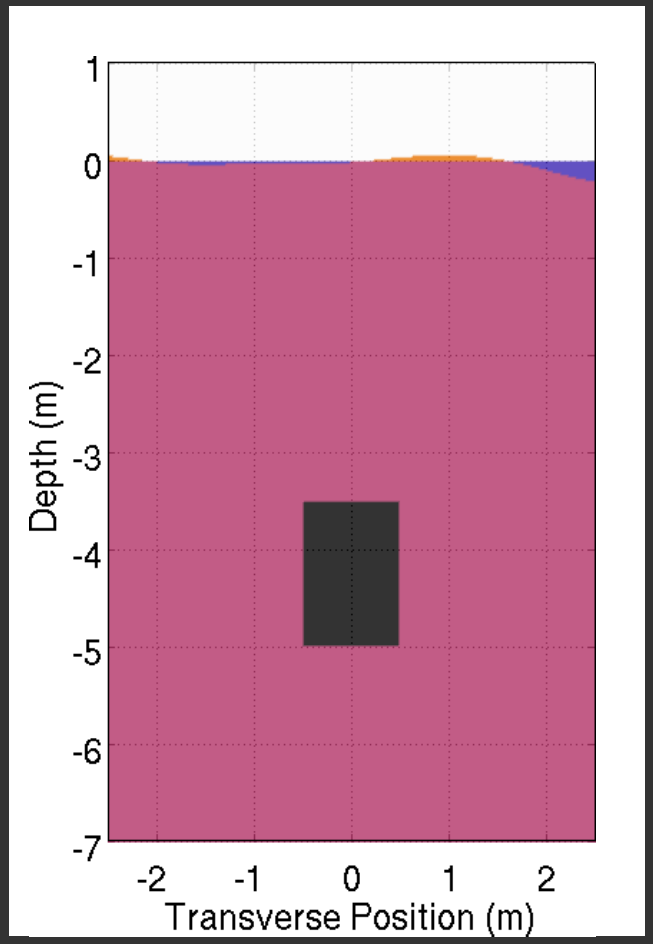


Focused at -8 m

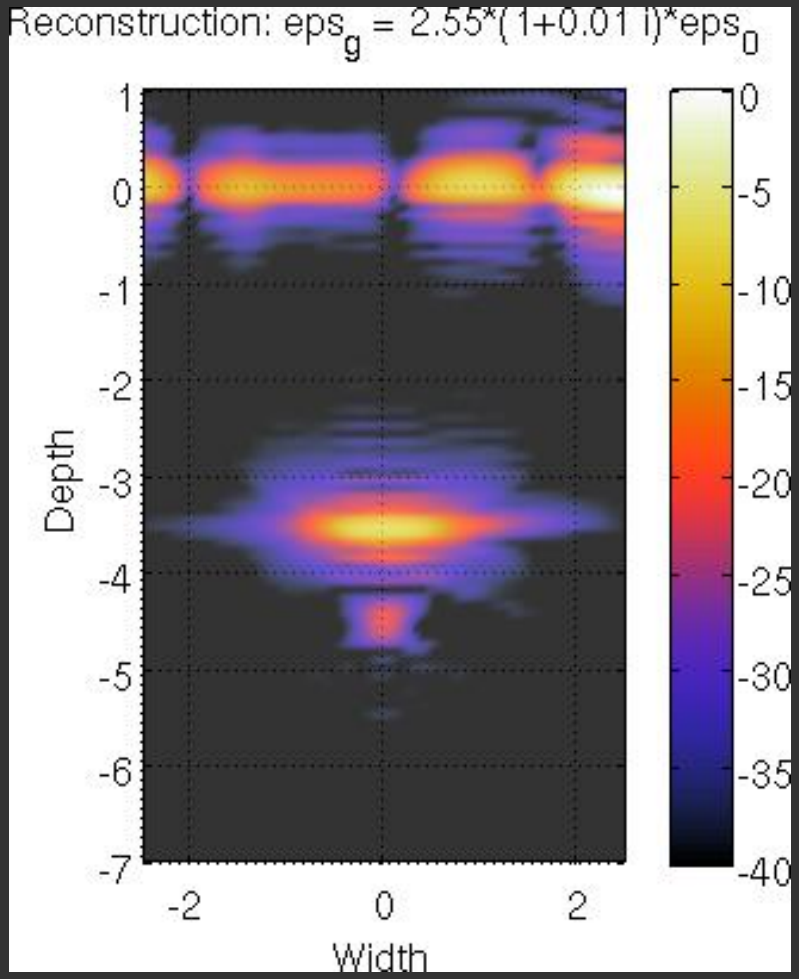
Nominal Image Reconstruction

- Magnitude of scattered field [dB scale]

Original geometry



Tunnel



Wavenumber Estimation

- Case I: Non-dispersive dry clay soil
  - Simulation: $\varepsilon = 8\,\varepsilon_0\,(1+0.01\,i\,)$
  - Imaging: parameter sweep

    $\varepsilon_r = [1,3,4, 6, 8, 10, 12, 14]$
  - Roughness height sweep:

    $R = [0.1\ 0.2\ 0.3\ 0.4\ 0.5\ 0.6]$

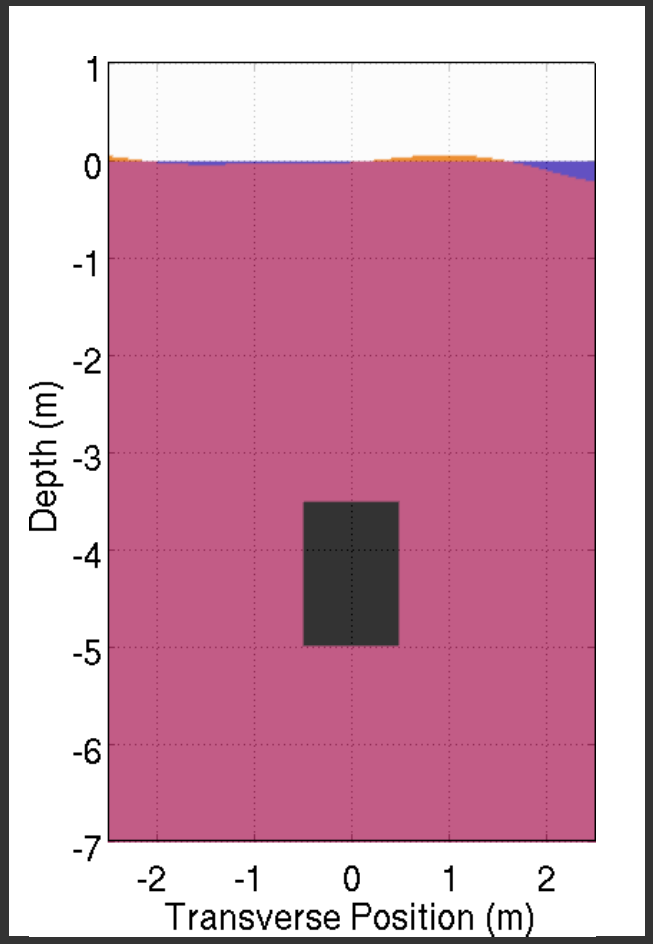
- Case II: Lossy clay loam soil
  - Simulation: ε = A.P. Hill firing point
  - Imaging: parameter sweep

Case I: Non-dispersive dry clay soil Imaging with permittivity sweep

Image reconstruction with $\varepsilon_r = 1$

- Magnitude of scattered field [dB scale]

Original geometry



Tunnel

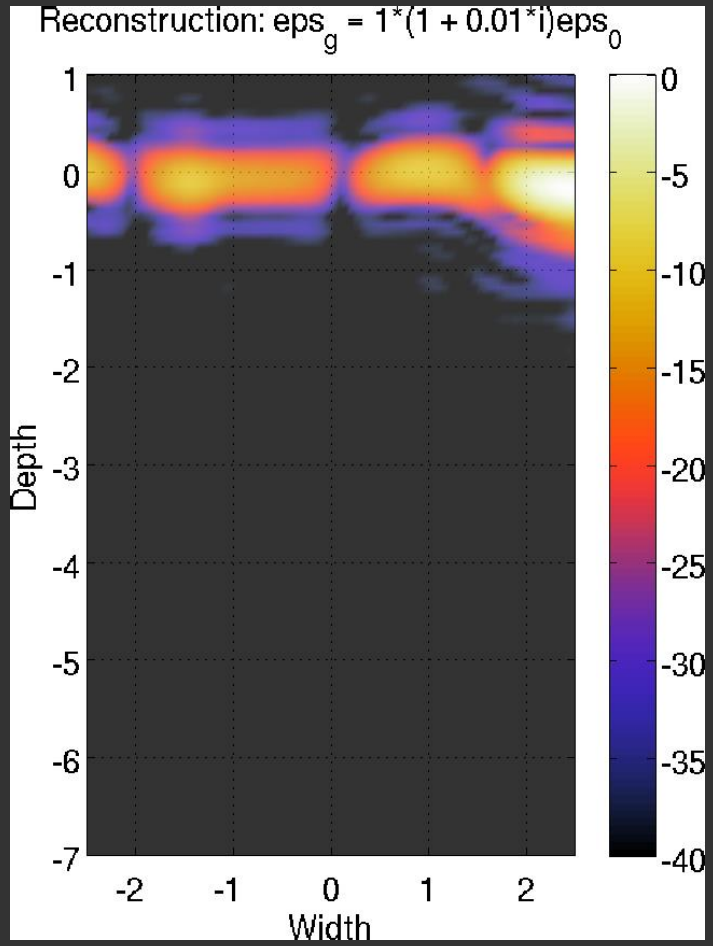
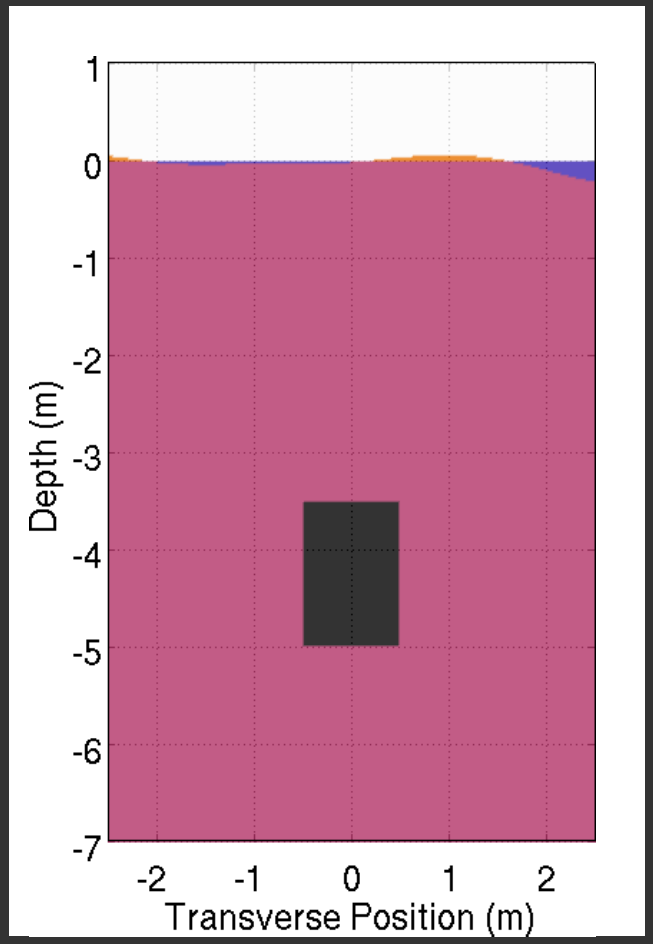


Image reconstruction with $\varepsilon_r = 3$

- Magnitude of scattered field [dB scale]

Original geometry



Tunnel

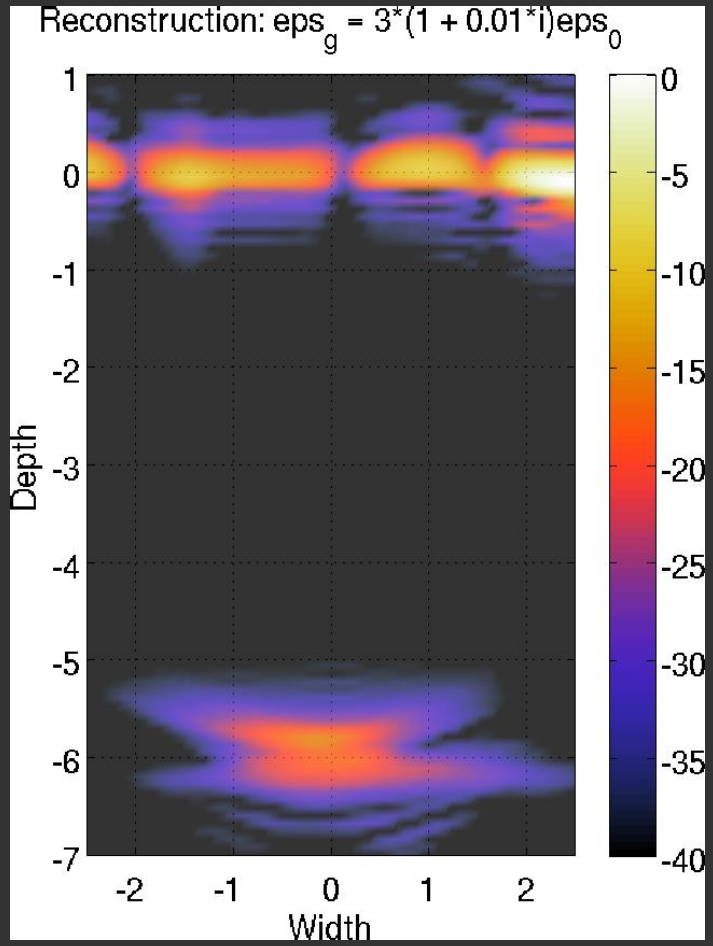
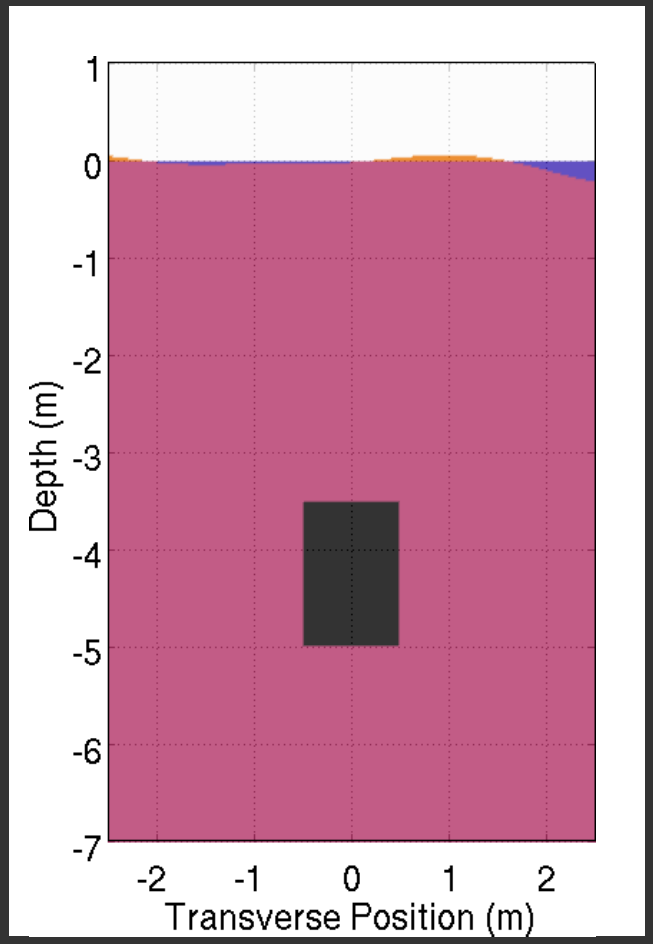


Image reconstruction with $\varepsilon_r = 4$

- Magnitude of scattered field [dB scale]

Original geometry



Tunnel

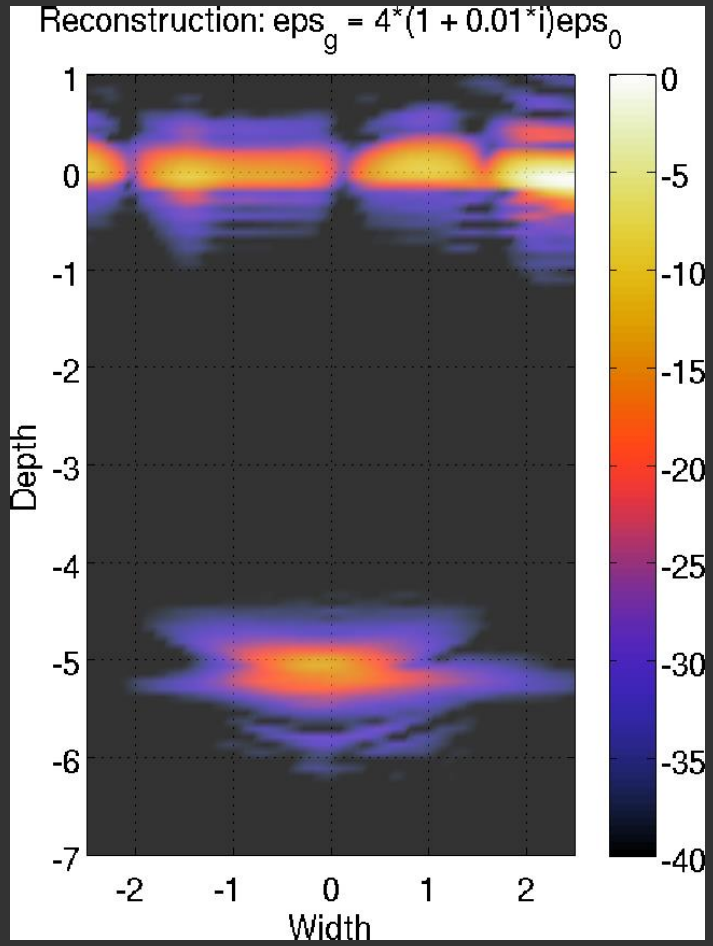
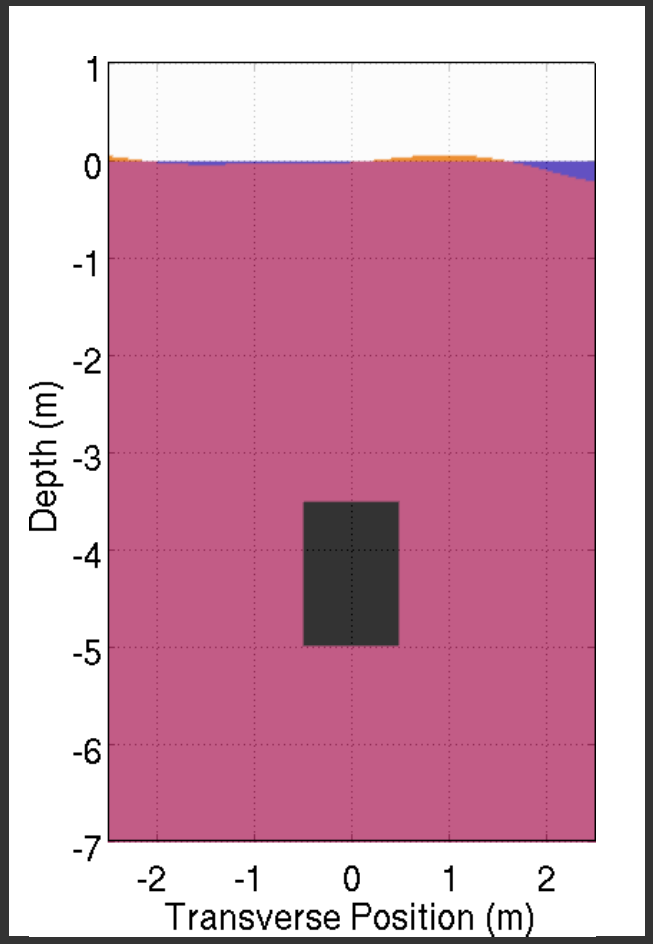


Image reconstruction with $\varepsilon_r = 6$

- Magnitude of scattered field [dB scale]

Original geometry



Tunnel

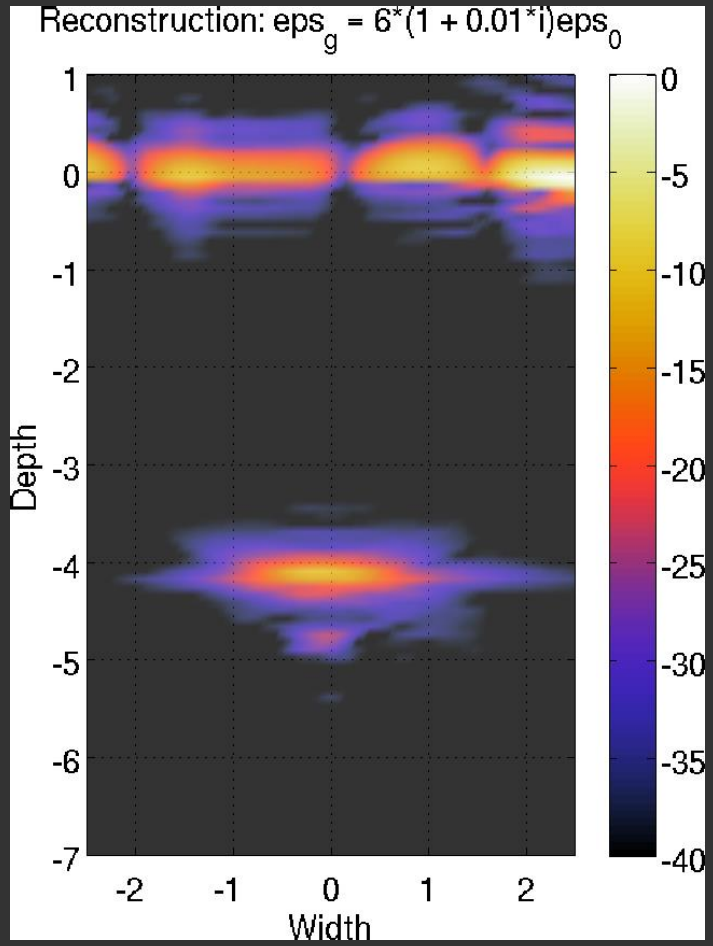
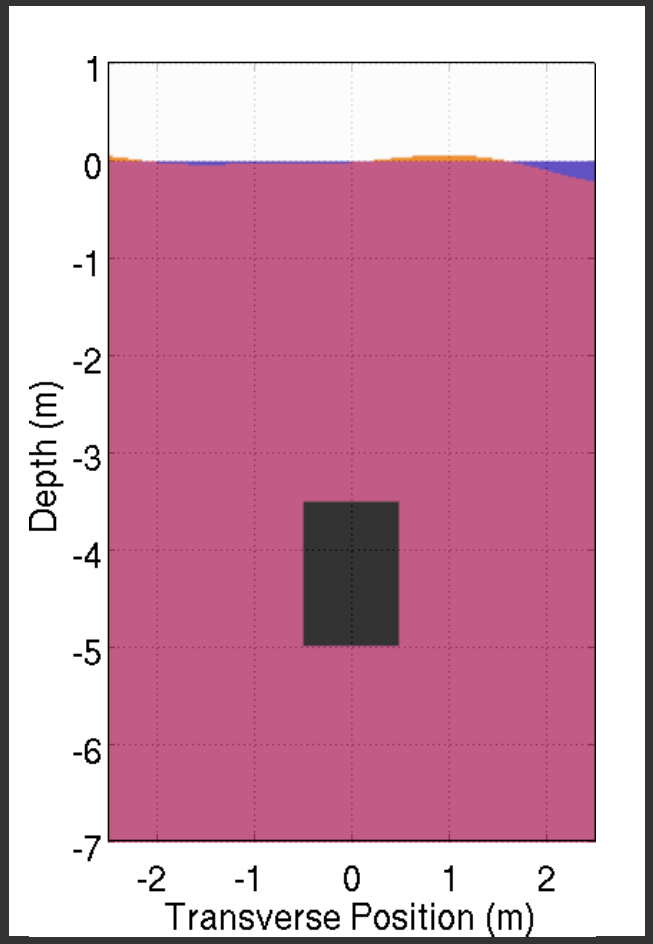


Image reconstruction with $\varepsilon_r = 8$

- Magnitude of scattered field [dB scale]

Original geometry



Tunnel

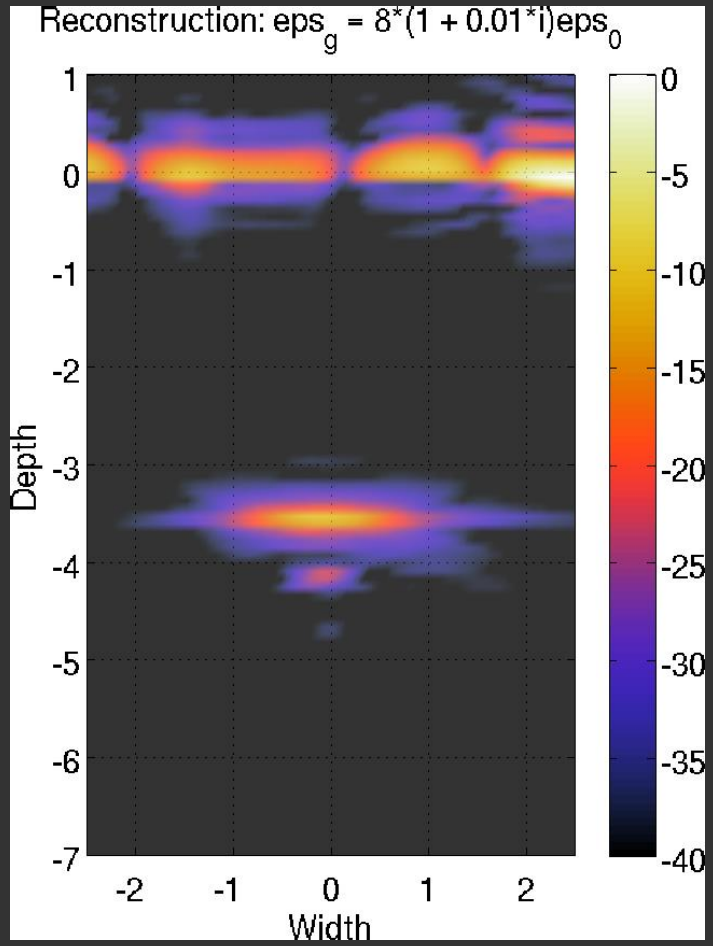
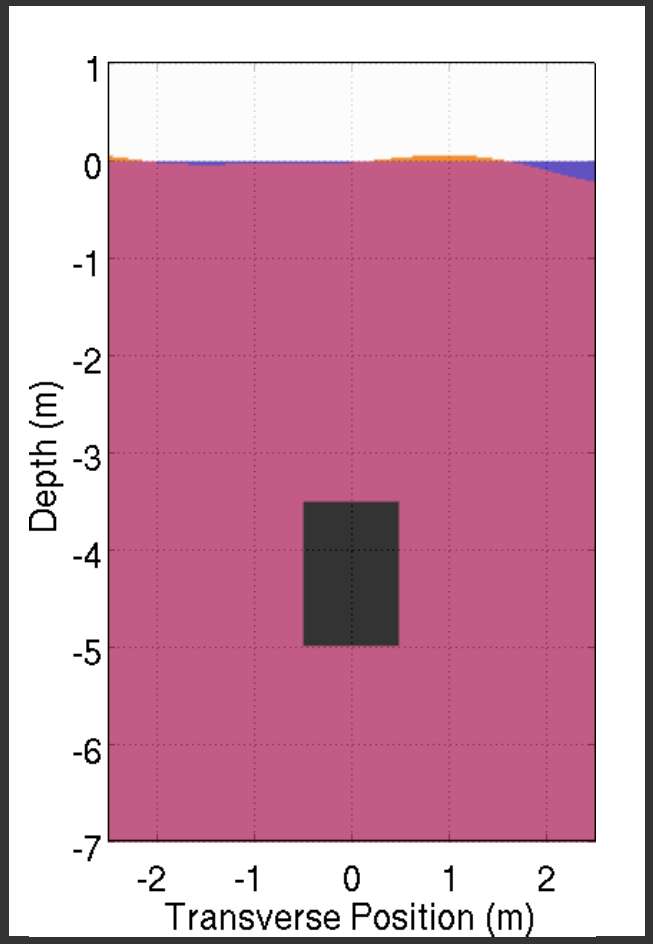


Image reconstruction with $\varepsilon_r = 10$

- Magnitude of scattered field [dB scale]

Original geometry



Tunnel

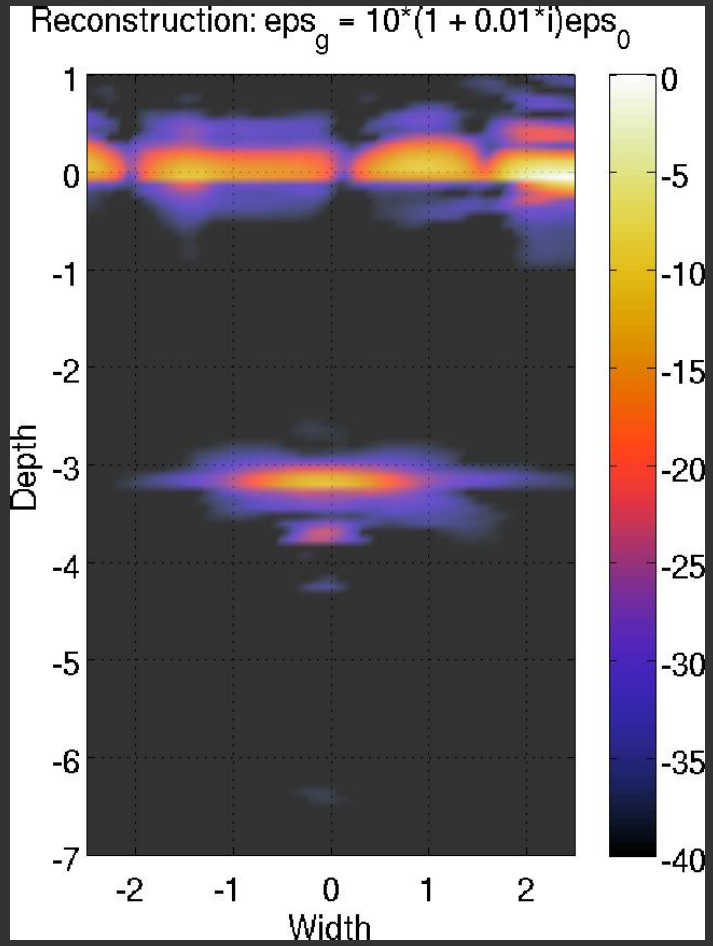
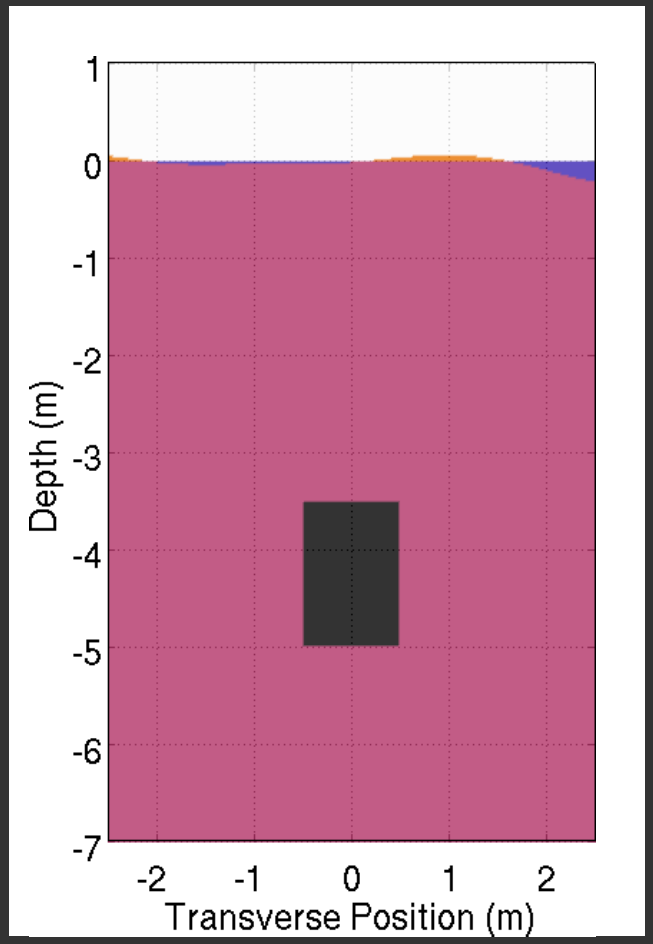


Image reconstruction with $\varepsilon_r = 12$

- Magnitude of scattered field [dB scale]

Original geometry



Tunnel

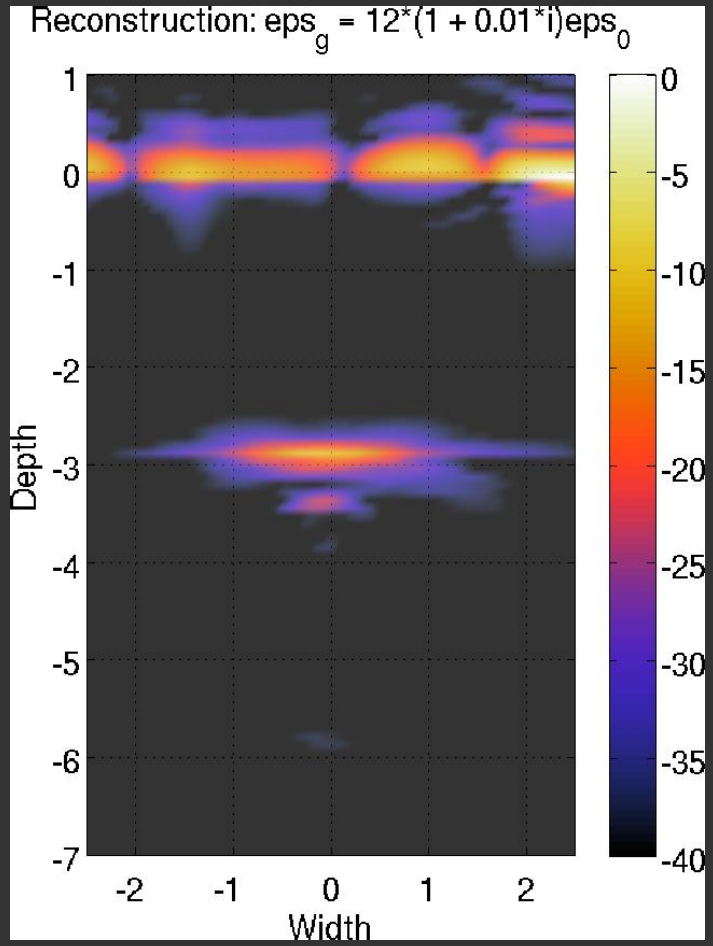
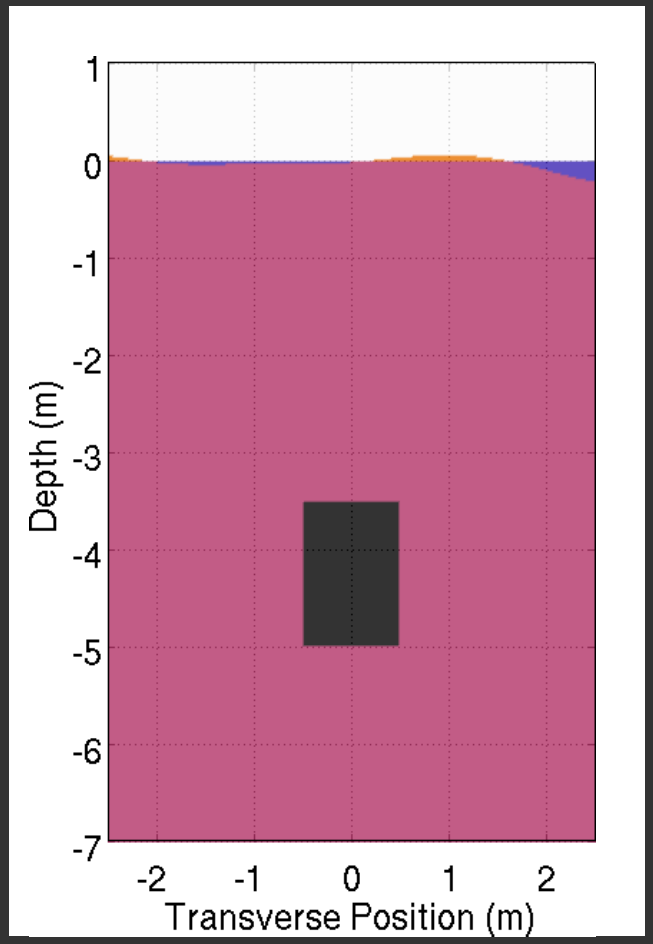


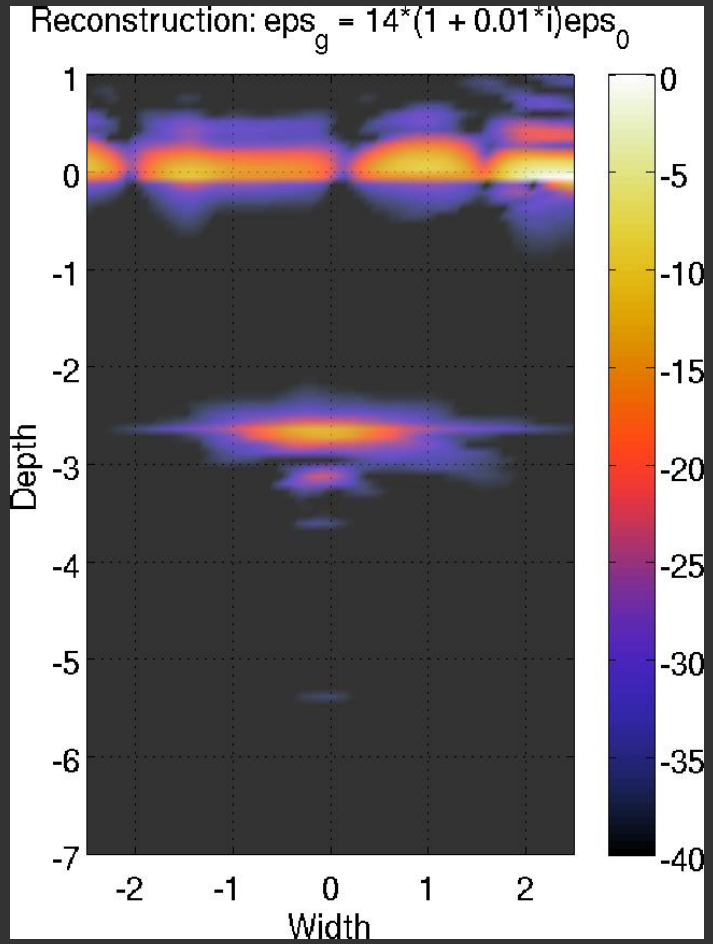
Image reconstruction with $\varepsilon_r = 14$

- Magnitude of scattered field [dB scale]

Original geometry



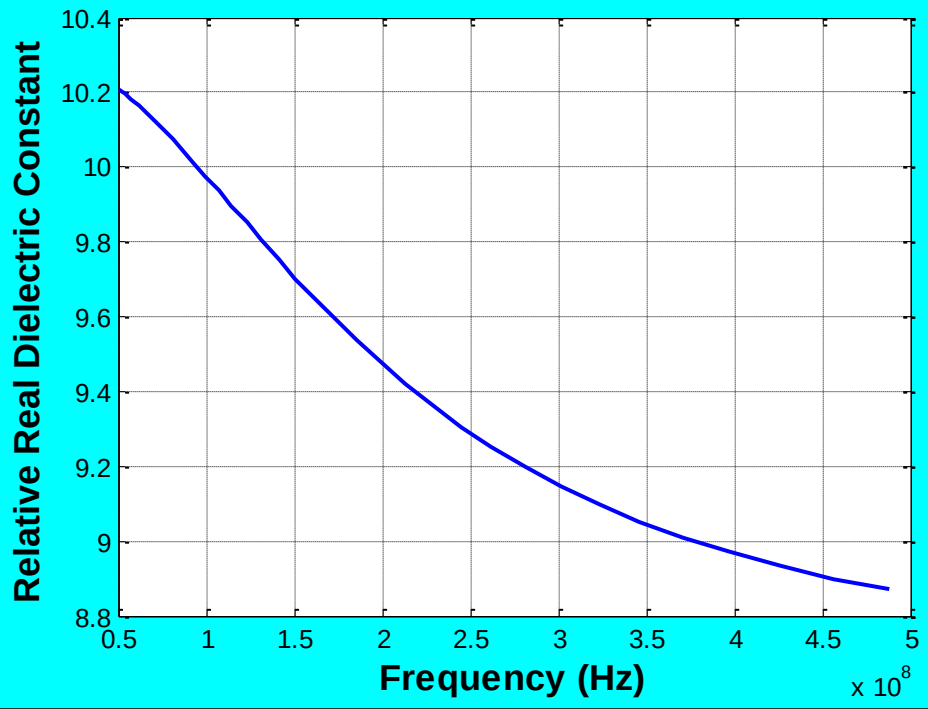
Tunnel

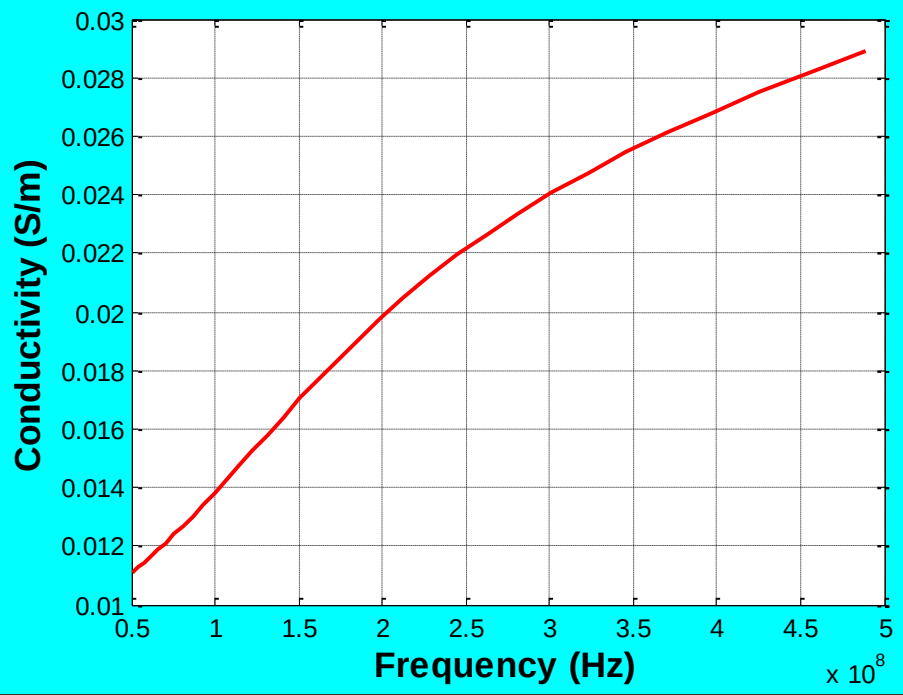


Case II: Lossy clay loam soil Imaging with permittivity sweep

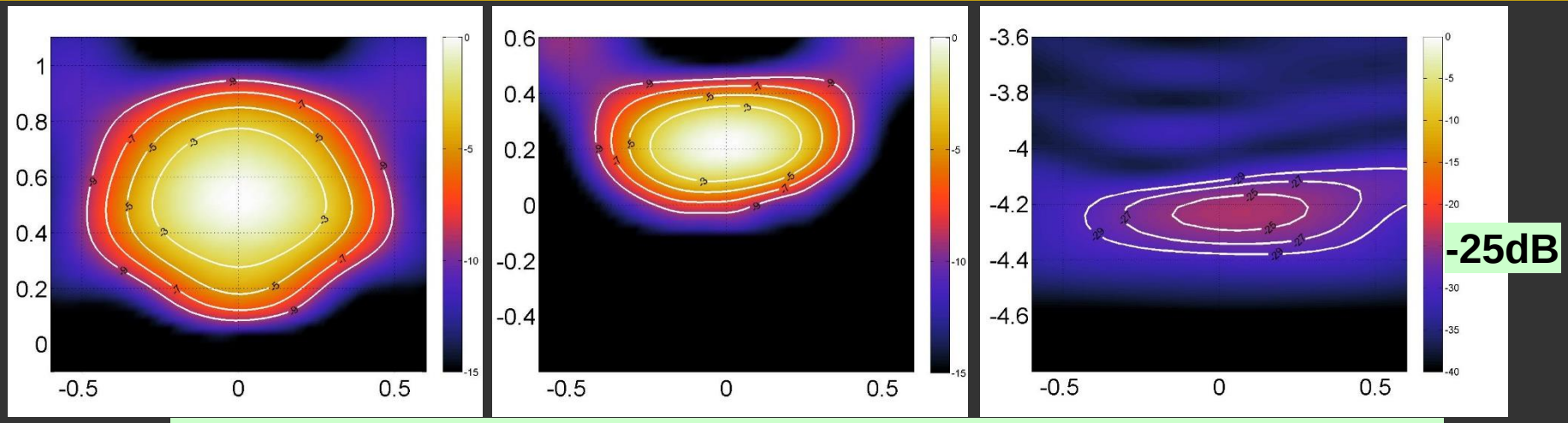
Lossy, dispersive clay loam soil

Average $\epsilon = \epsilon_0(9.2 - j8.7)$





Dispersive clay loam soil

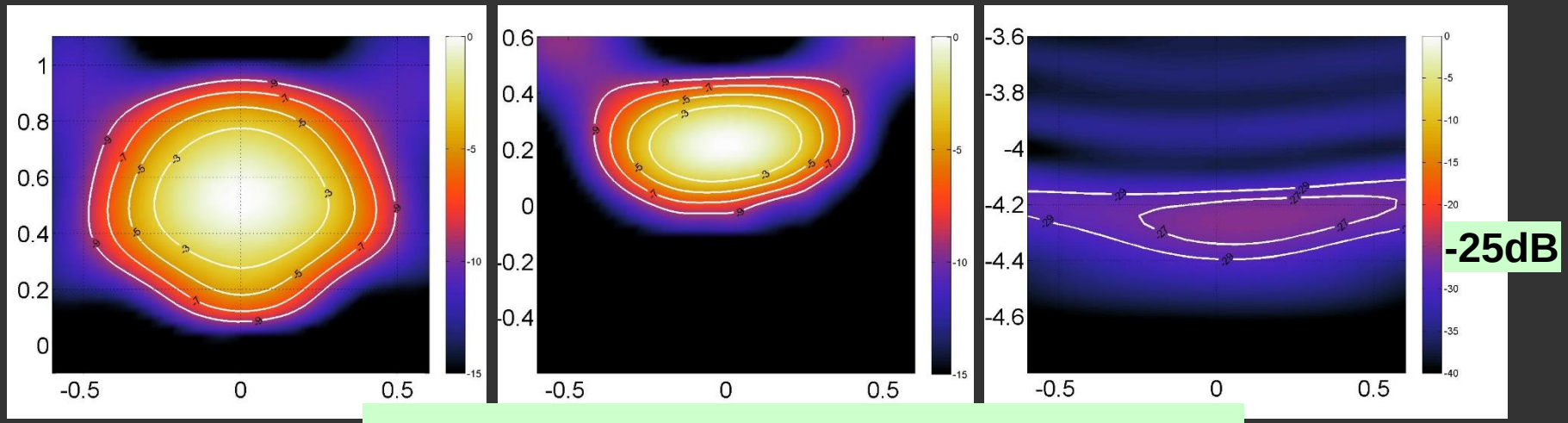


Refraction focusing at underground point

y= 0.5 m

y= 0 m

y= -4 m



Focusing at point on surface

Image reconstruction: $\varepsilon = 0.1\ \varepsilon_{hill}$

- Magnitude of scattered field [dB scale]

Original geometry **Reconstruction** **Tunnel response**

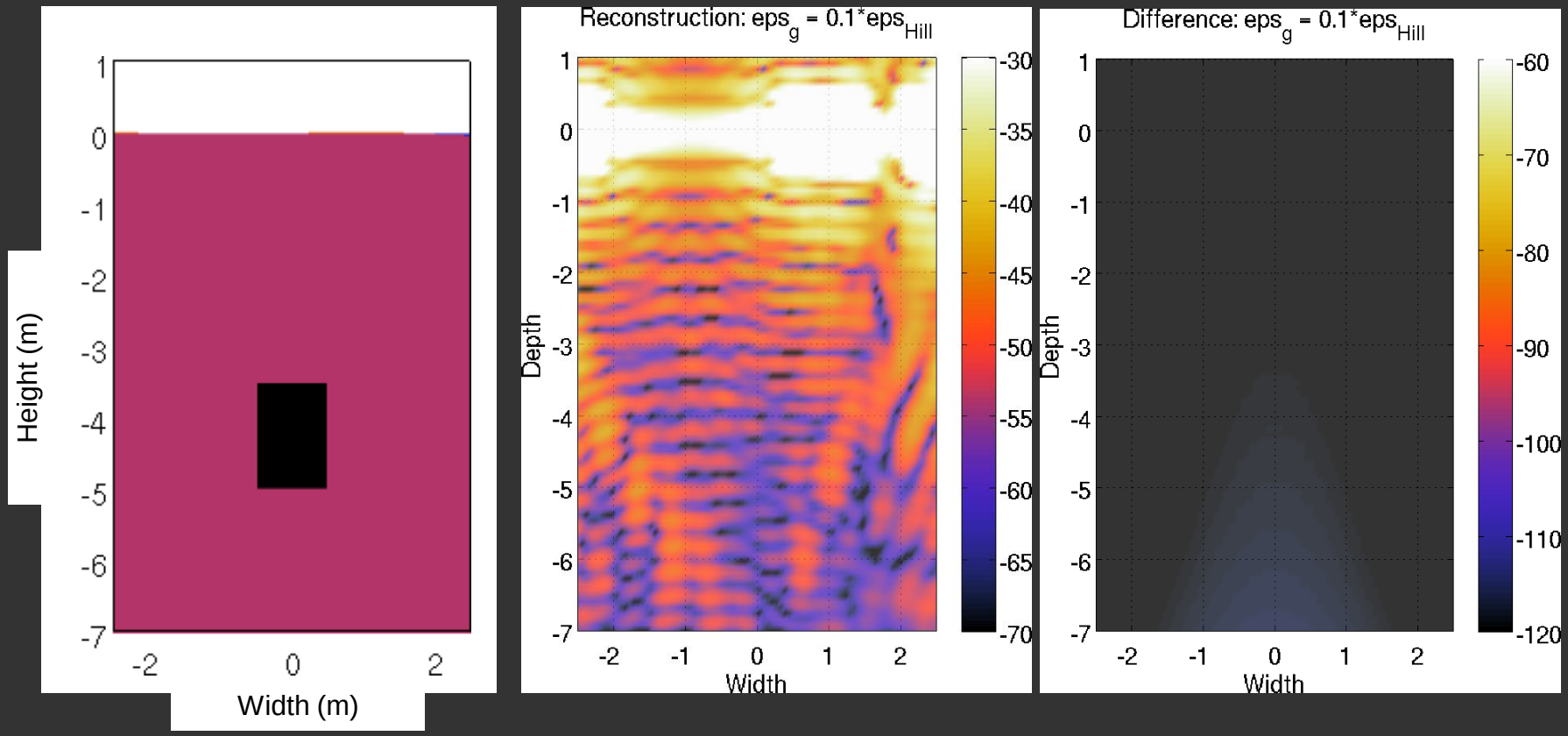


Image reconstruction: $\varepsilon = 0.3\ \varepsilon_{hill}$

- Magnitude of scattered field [dB scale]

Original geometry **Reconstruction** **Tunnel response**

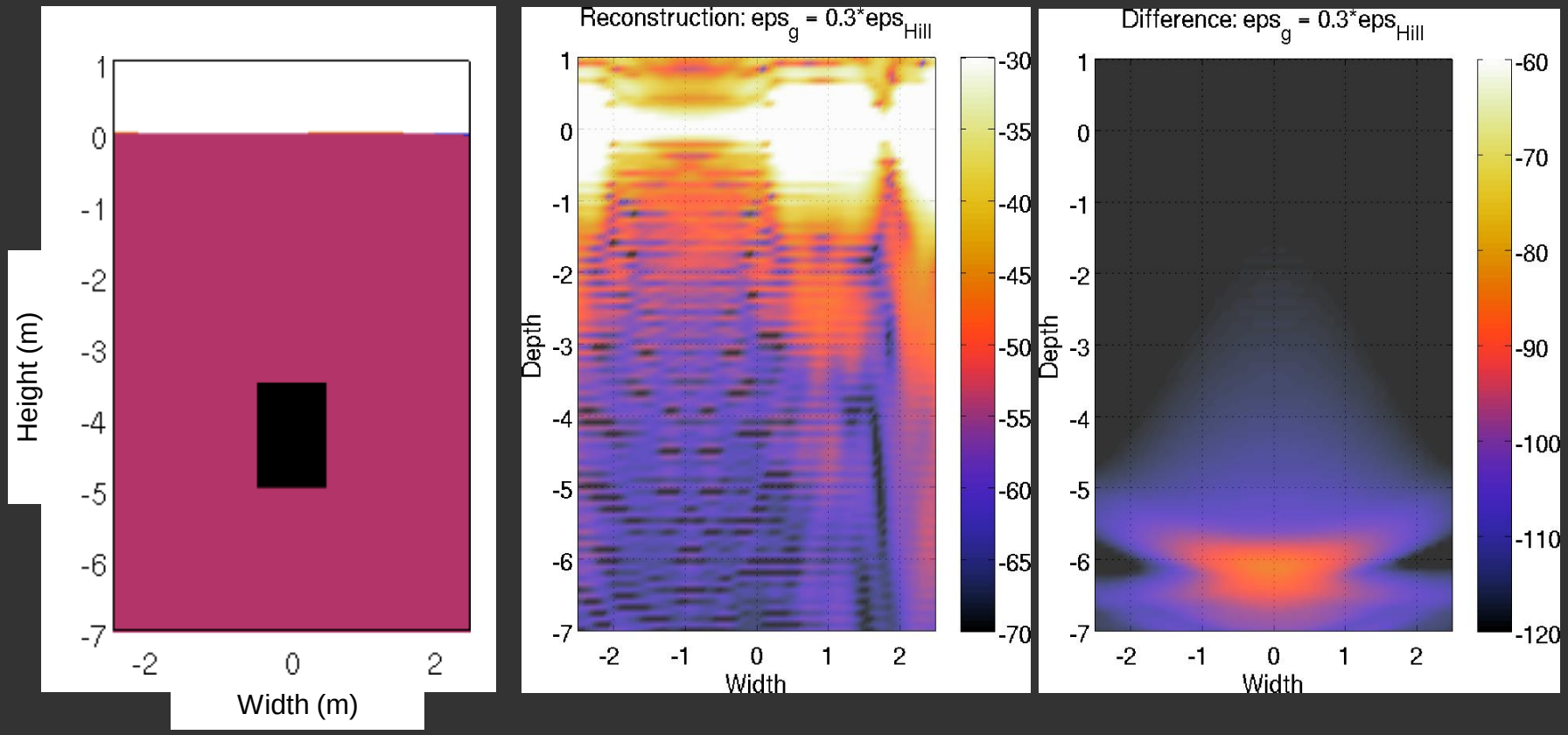


Image reconstruction: $\varepsilon = 0.8\ \varepsilon_{hill}$

- **Magnitude of scattered field [dB scale]**

Original geometry **Reconstruction** **Tunnel response**

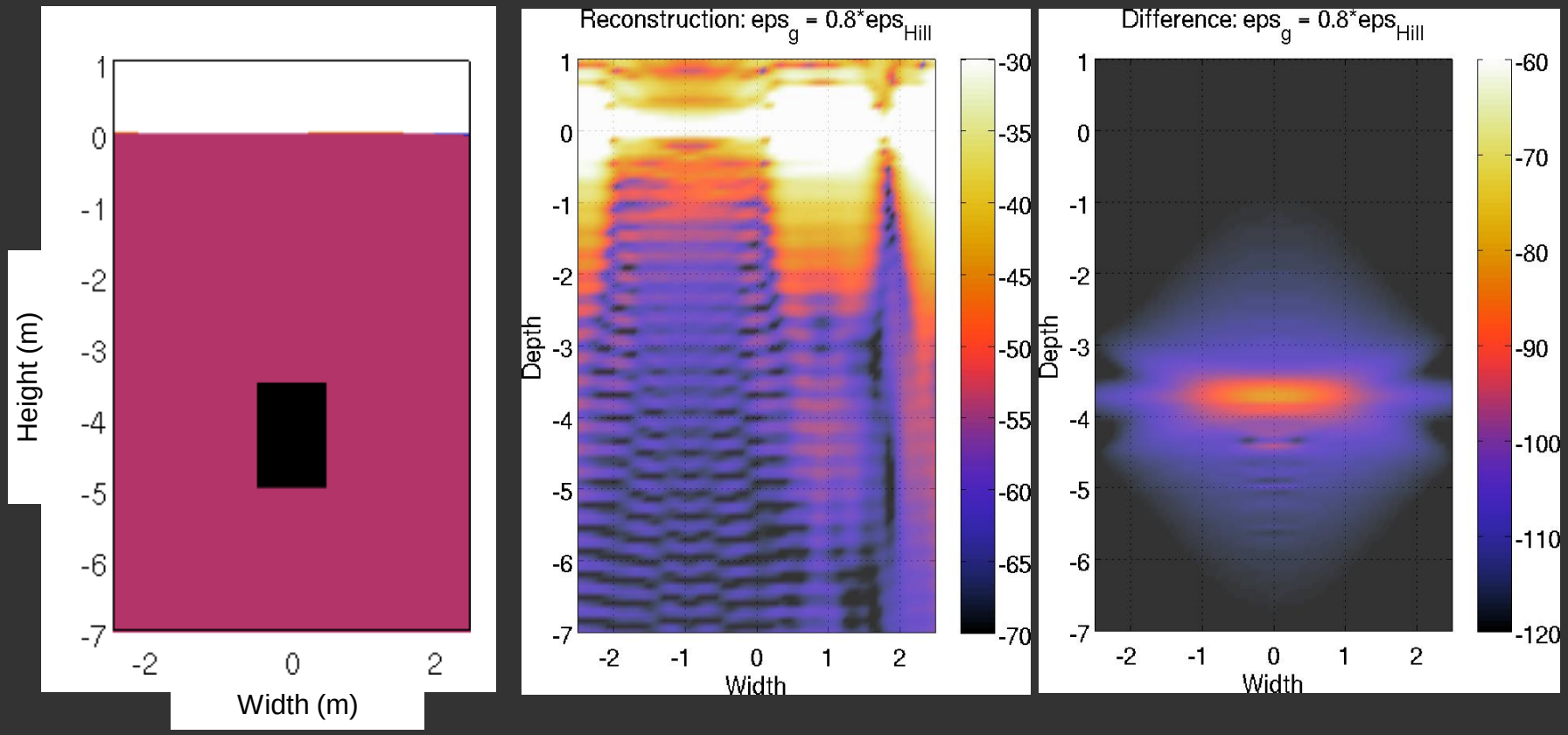


Image reconstruction: $\varepsilon = 1\ \varepsilon_{hill}$

- **Magnitude of scattered field [dB scale]**

Original geometry **Reconstruction** **Tunnel response**

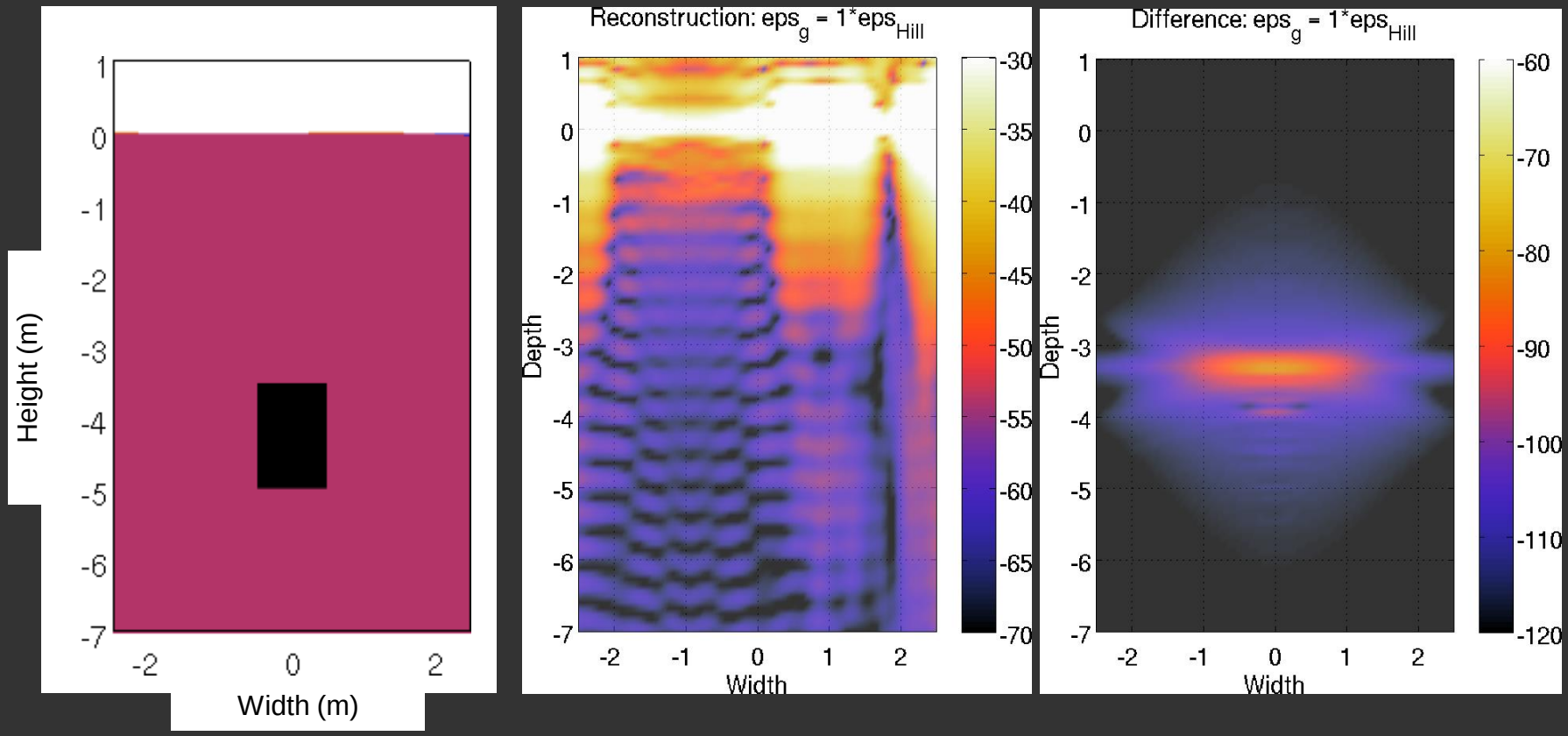


Image reconstruction: $\varepsilon = 2\,\varepsilon_{hill}$

- **Magnitude of scattered field [dB scale]**

Original geometry **Reconstruction** **Tunnel response**

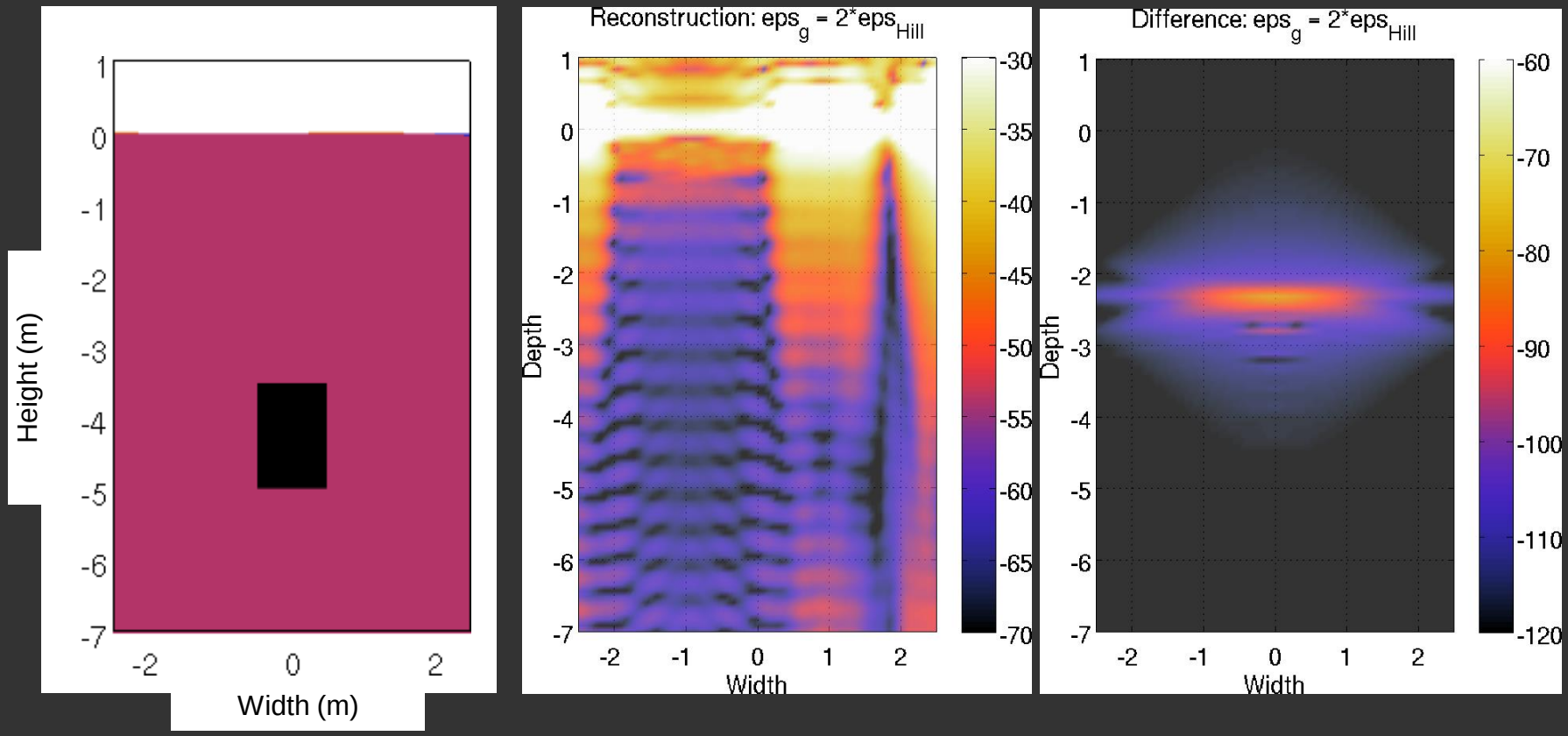


Image reconstruction: $\varepsilon = 4\,\varepsilon_{hill}$

- **Magnitude of scattered field [dB scale]**

Original geometry **Reconstruction** **Tunnel response**

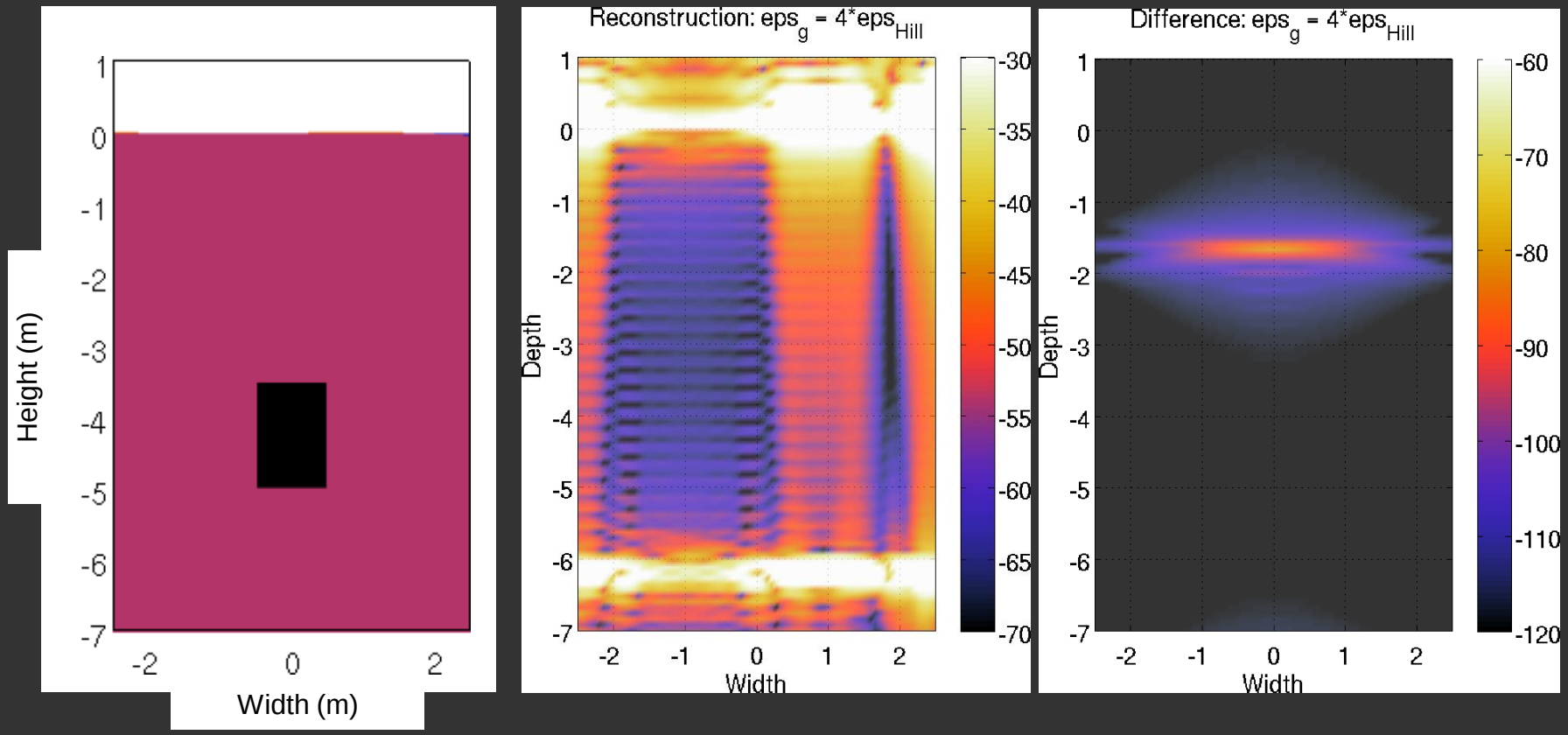


Image reconstruction: $\varepsilon = 8\ \varepsilon_{hill}$

- **Magnitude of scattered field [dB scale]**

Original geometry **Reconstruction** **Tunnel response**

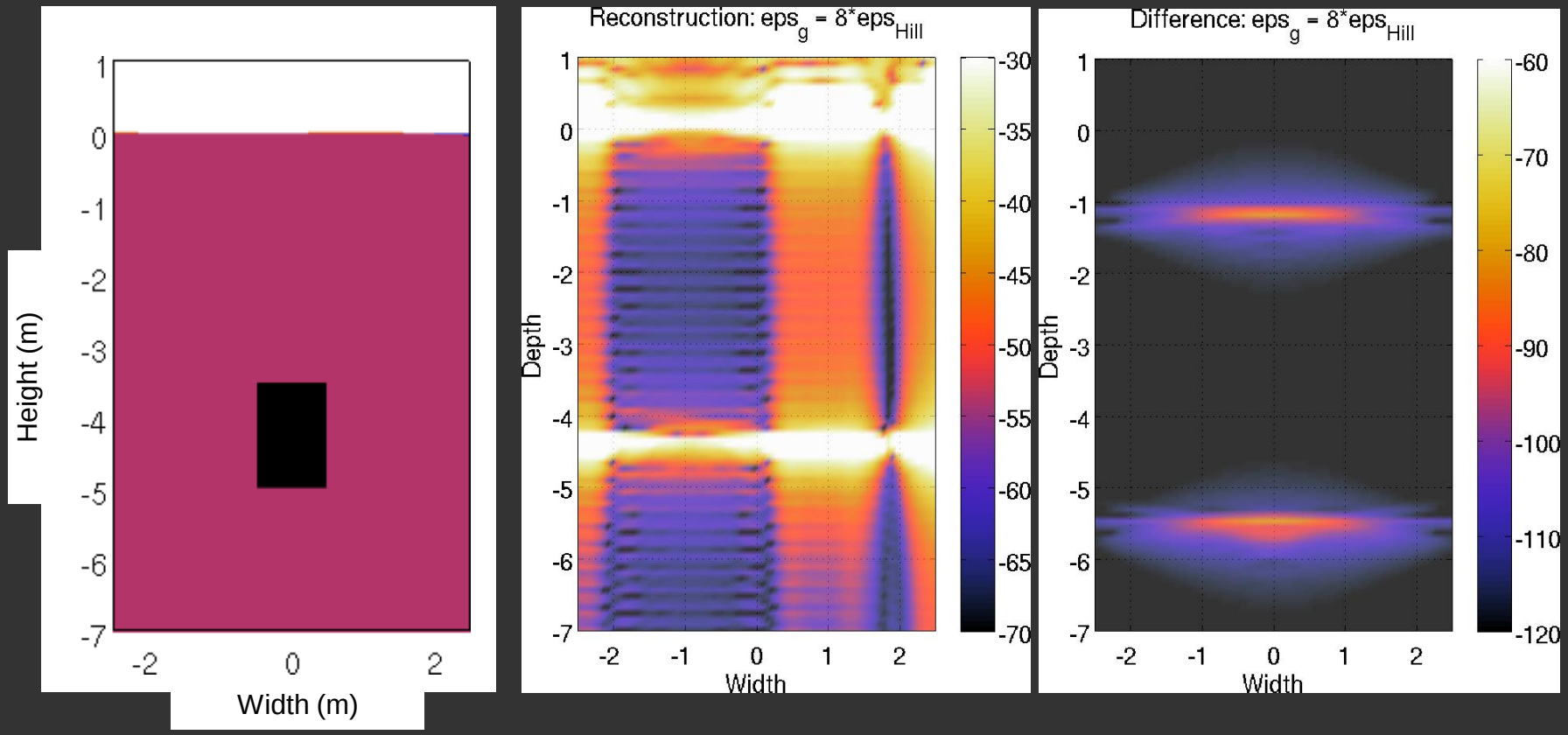
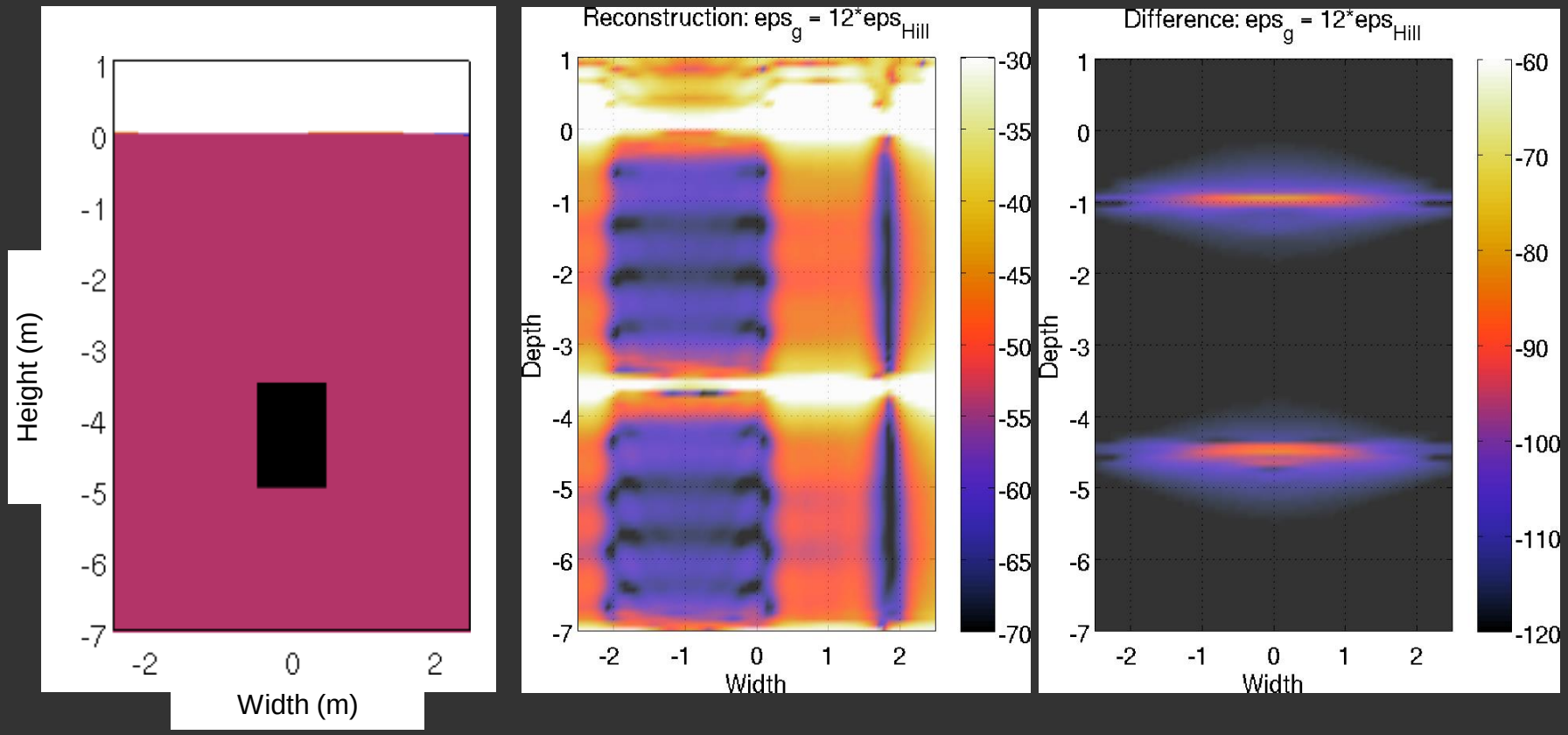


Image reconstruction: $\varepsilon = 12\ \varepsilon_{hill}$

- **Magnitude of scattered field [dB scale]**

Original geometry **Reconstruction** **Tunnel response**



Roughness sweep: dry sandy soil

$$\varepsilon = 2.55\ \varepsilon_0\ (1+0.01\ i\ )$$

Image reconstruction: R_{height} = 0.1 m

- Magnitude of scattered field [dB scale]

Original geometry **Tunnel** **Background**

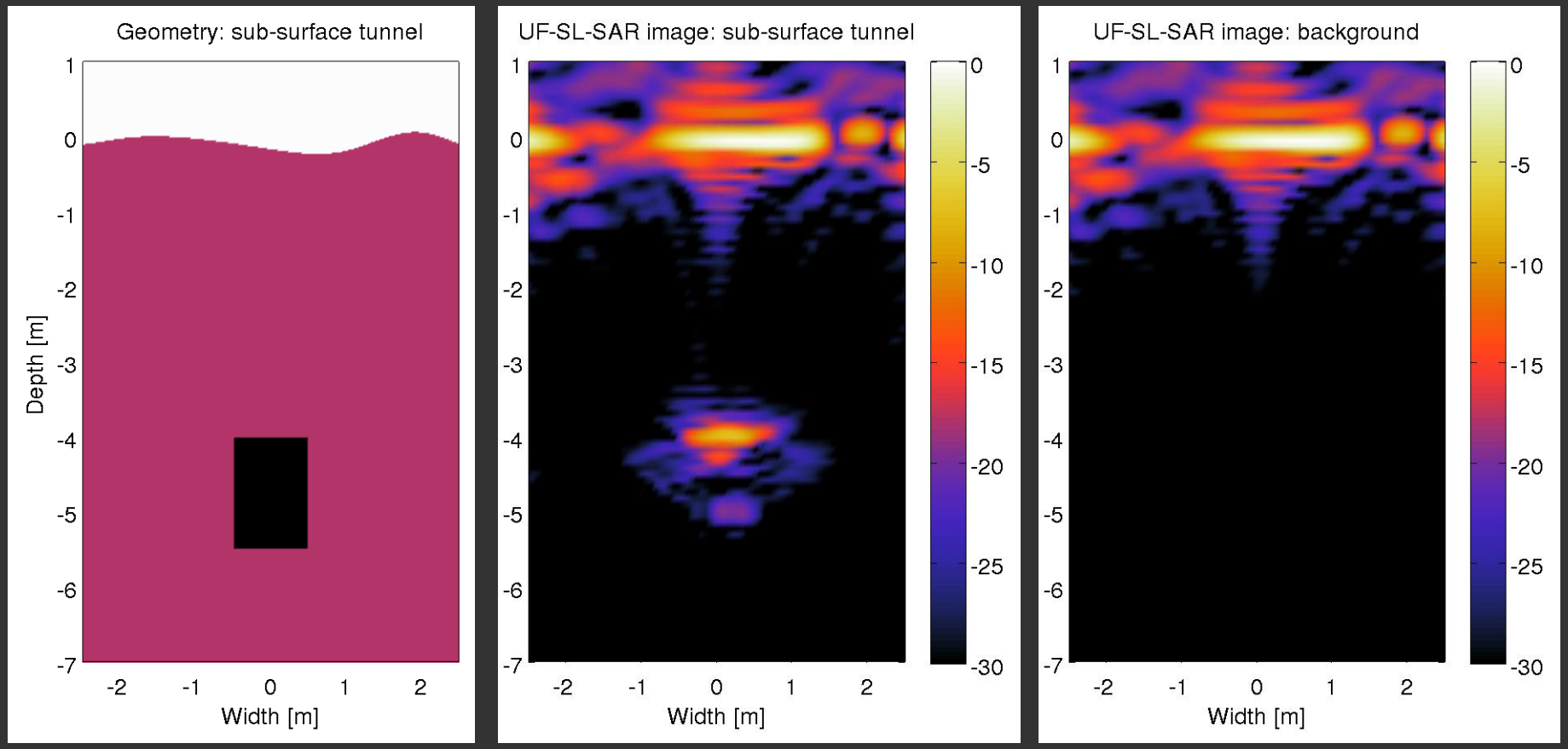


Image reconstruction: R_{height} = 0.2 m

- Magnitude of scattered field [dB scale]

Original geometry **Tunnel** **Background**

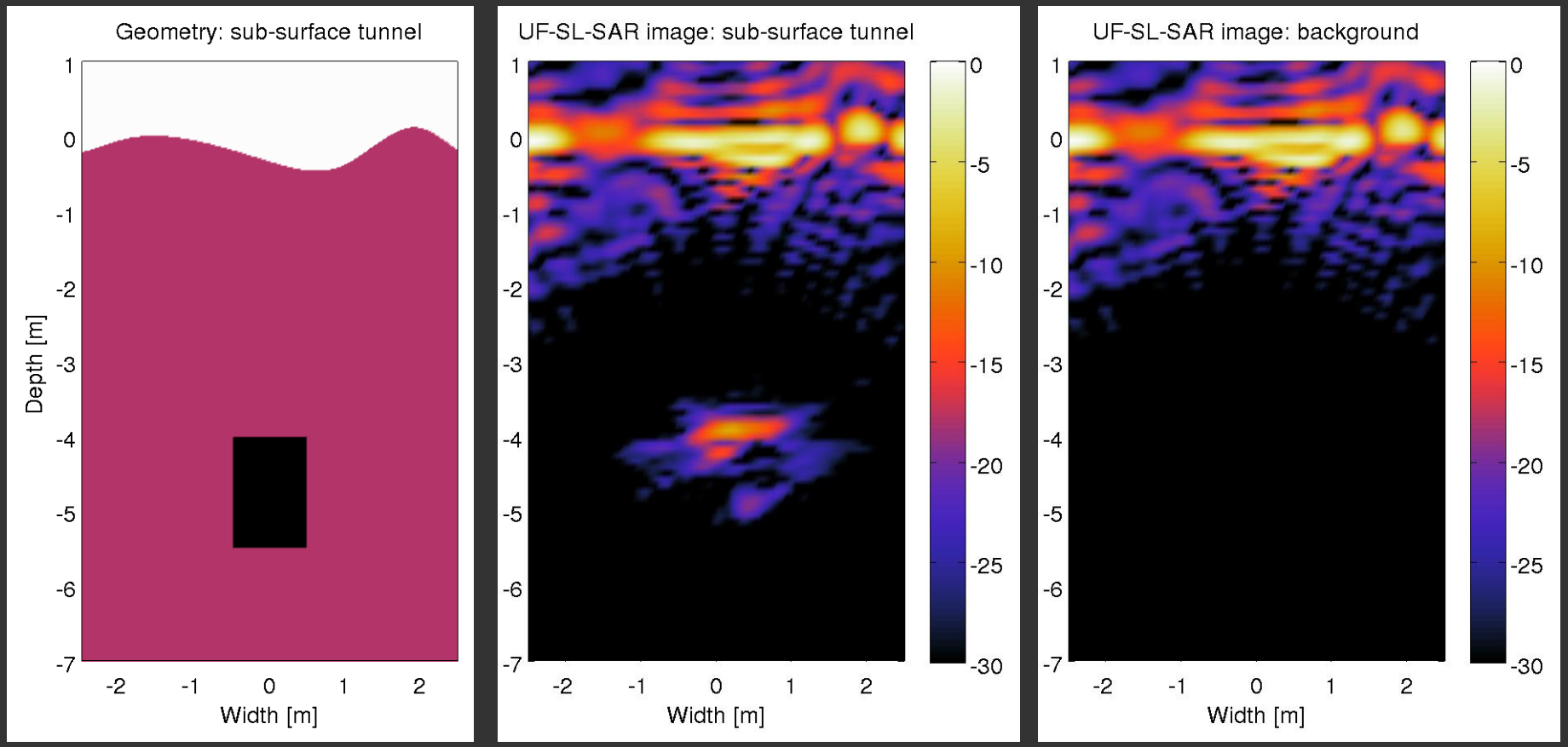


Image reconstruction: R_{height} = 0.3 m

- Magnitude of scattered field [dB scale]

Original geometry **Tunnel** **Background**

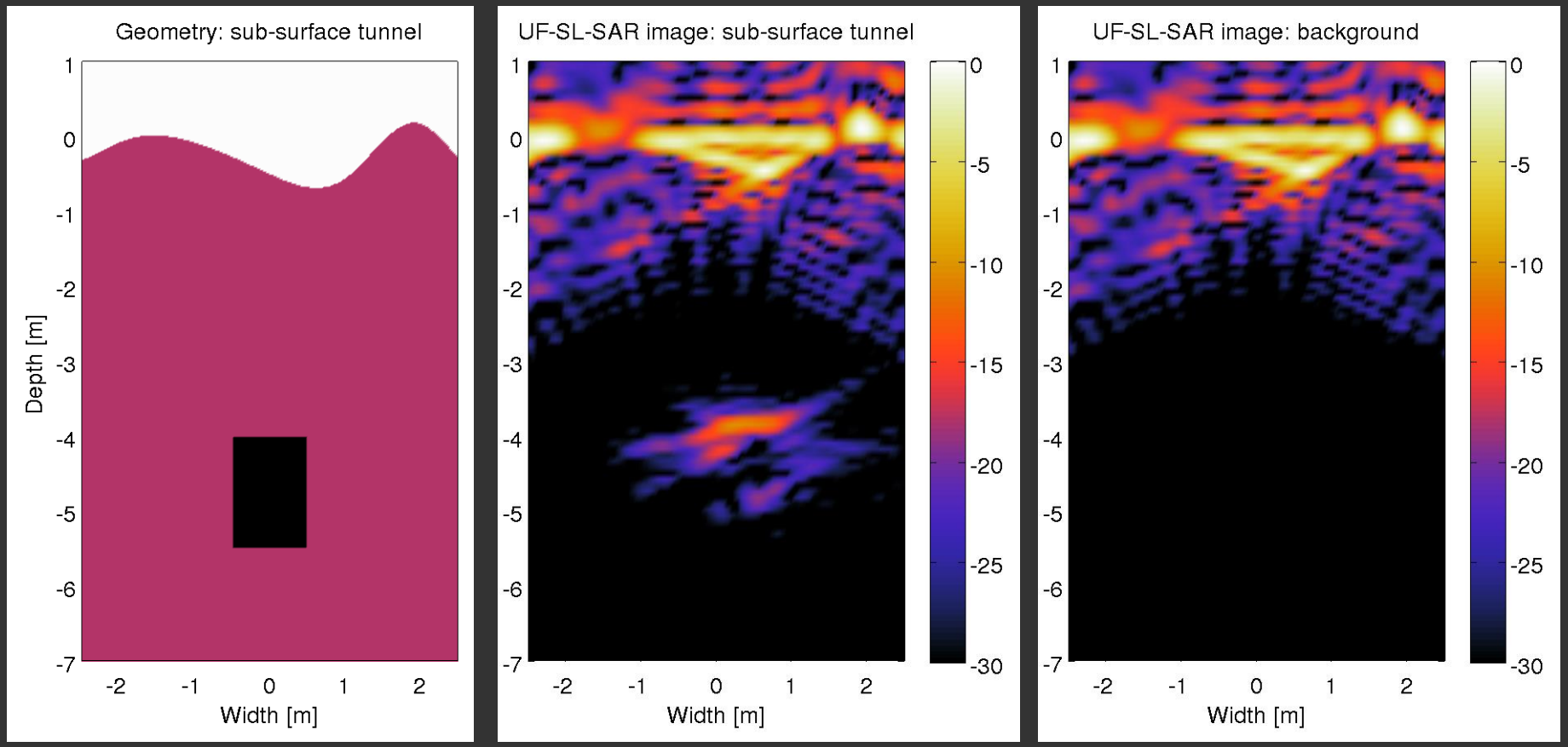


Image reconstruction: R_{height} = 0.4 m

- Magnitude of scattered field [dB scale]

Original geometry **Tunnel** **Background**

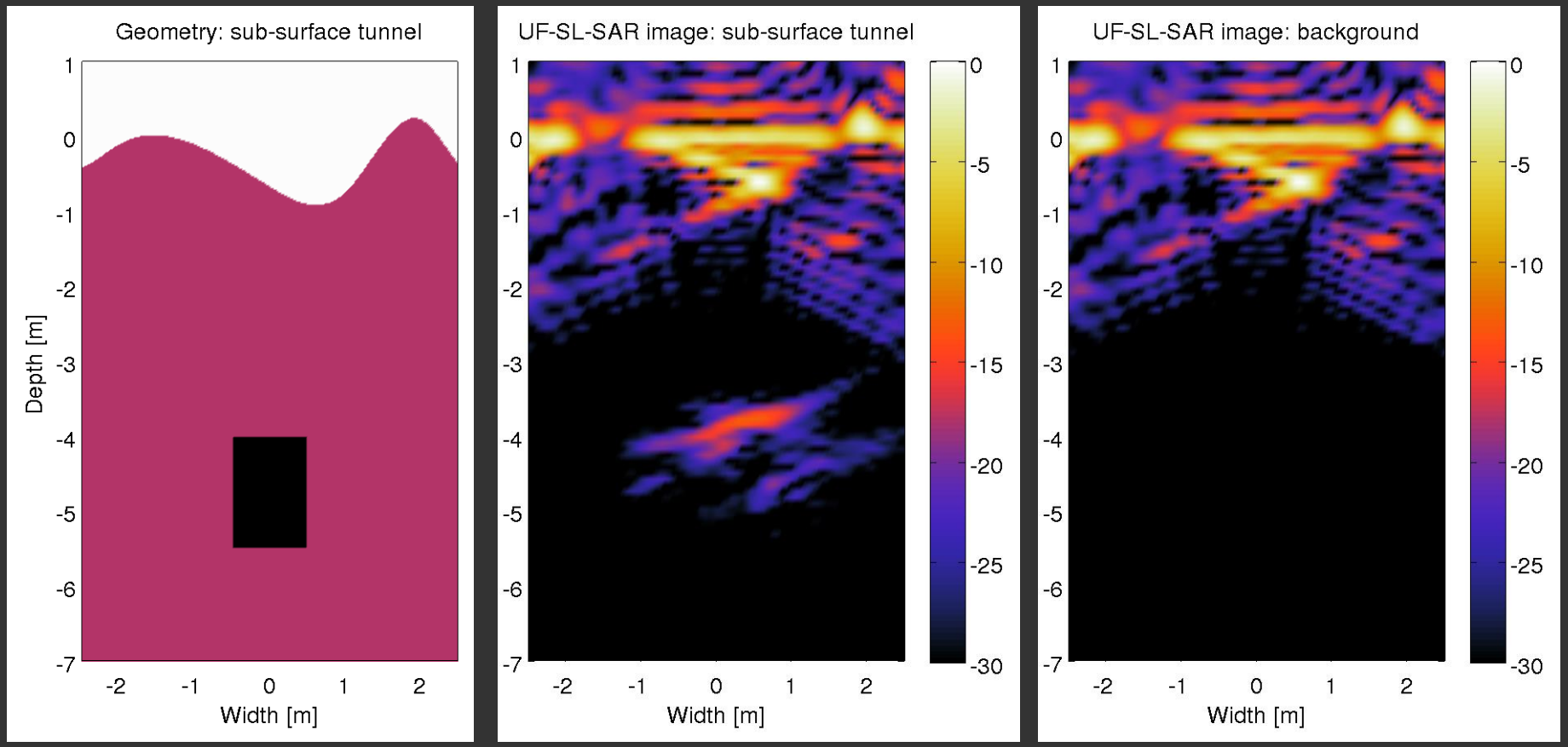


Image reconstruction: R_{height} = 0.5 m

- Magnitude of scattered field [dB scale]

Original geometry **Tunnel** **Background**

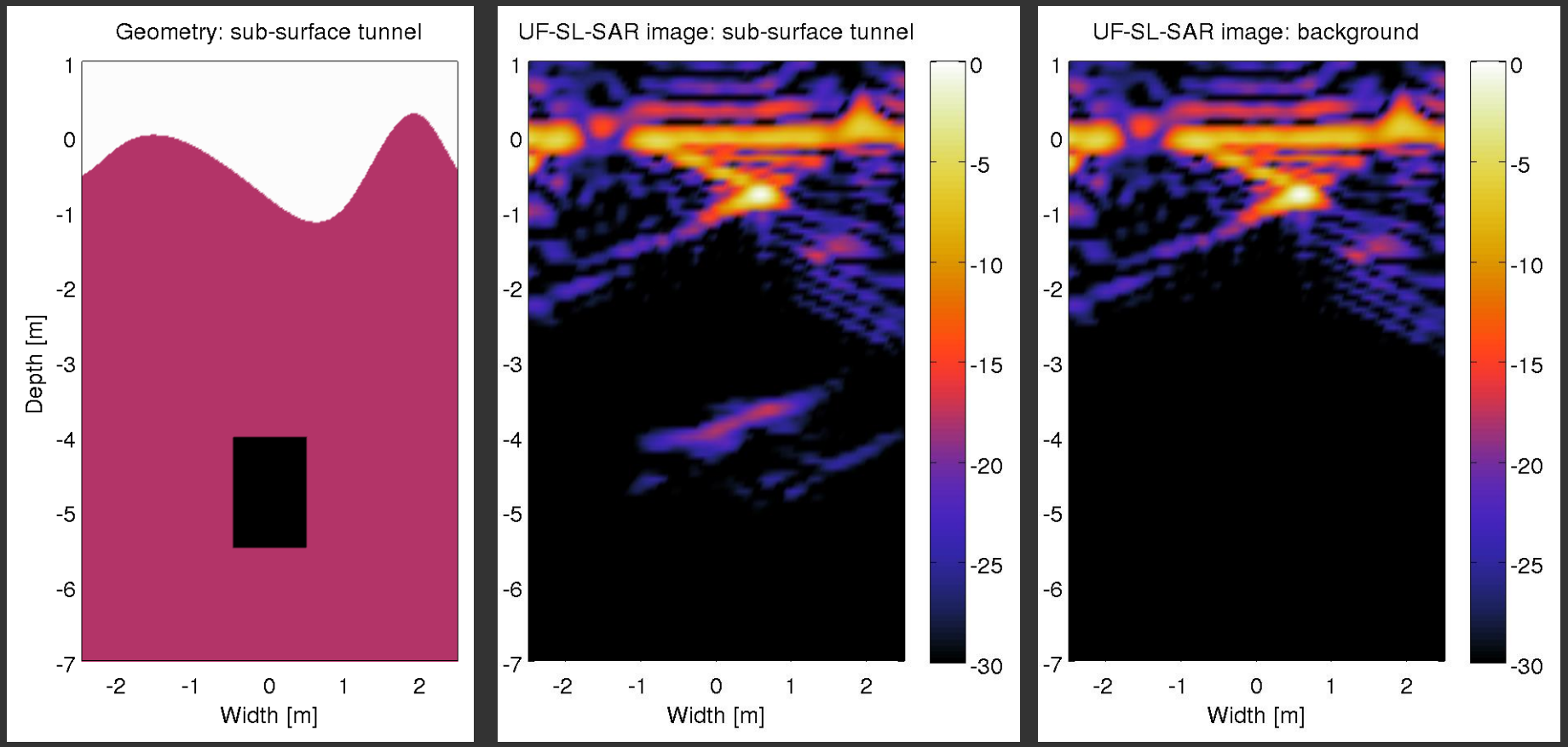
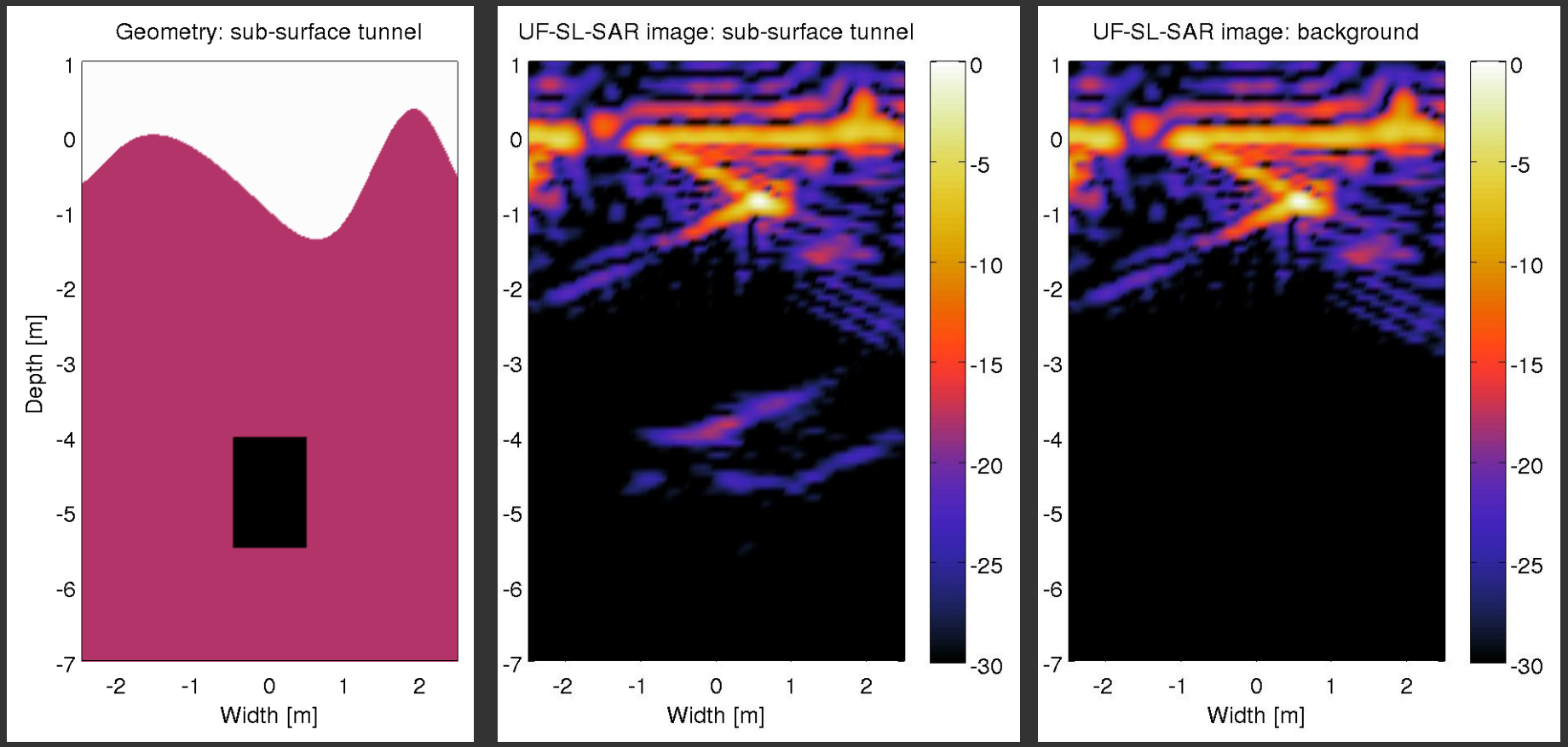


Image reconstruction: R_{height} = 0.6 m

- Magnitude of scattered field [dB scale]

Original geometry | **Tunnel** | **Background**



Conclusions -- 1

Underground Focusing Spotlight Synthetic Aperture Radar for low-loss soils (deserts):

- Successful detection on non-dispersive sandy soil until surface roughness exceeds 0.5 m (for correlation length of 1 m)
- Sufficiently high wave number estimate provides accurate tunnel detection
  - Wrong prediction of tunnel depth
  - Partial reconstruction of surface

Conclusions -- 2

Underground Focusing Spotlight Synthetic Aperture Radar for lossy soils:

- Unsuccessful tunnel detection even with minimal surface roughness
- Soil loss reduces target signal below surface clutter levels
- Not suitable for tunnel detection with UF-SL-SAR

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