Improving Ground Penetrating Radar Imaging in High Loss Environments

David L. Wright and Michael H. Powers
U.S. Geological Survey
Denver, CO

Gary R. Olhoeft
Department of Geophysics
Colorado School of Mines
Golden, CO

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EMSP Environmental Management Science Program

Why the interest in GPR?

- Radar energy responds to detailed changes in the physical and chemical properties of the subsurface.
- Surface GPR can provide a non-invasive look at subsurface features.
- Cost effective to image large subsurface volumes with sub-meter scale resolution.
- Effectiveness varies with local conditions.

Relevant DOE Uses of GPR

- Vadose zone characterization

  (e.g. Knight and others in 2002 EMSP workshop.)
  - Moisture content
  - Geologic controls on contaminant migration
- Buried waste, structures, and utilities
- Contaminant plumes
- Engineered barrier integrity (surface and borehole GPR)

Causes of GPR failure

- Electrically conductive earth materials, such as clay, cause rapid GPR signal loss and can severely limit depth of penetration.
- Scattering losses always reduce signal with distance and limit depth of penetration even in resistive earth.
- Lateral changes in surface conditions can obscure deeper features.
- Resolution decreases with depth
- System response varies as surface materials vary such that absolute calibration is not available so specific interpretations become unlikely or impossible.

Methods to Improve GPR imaging

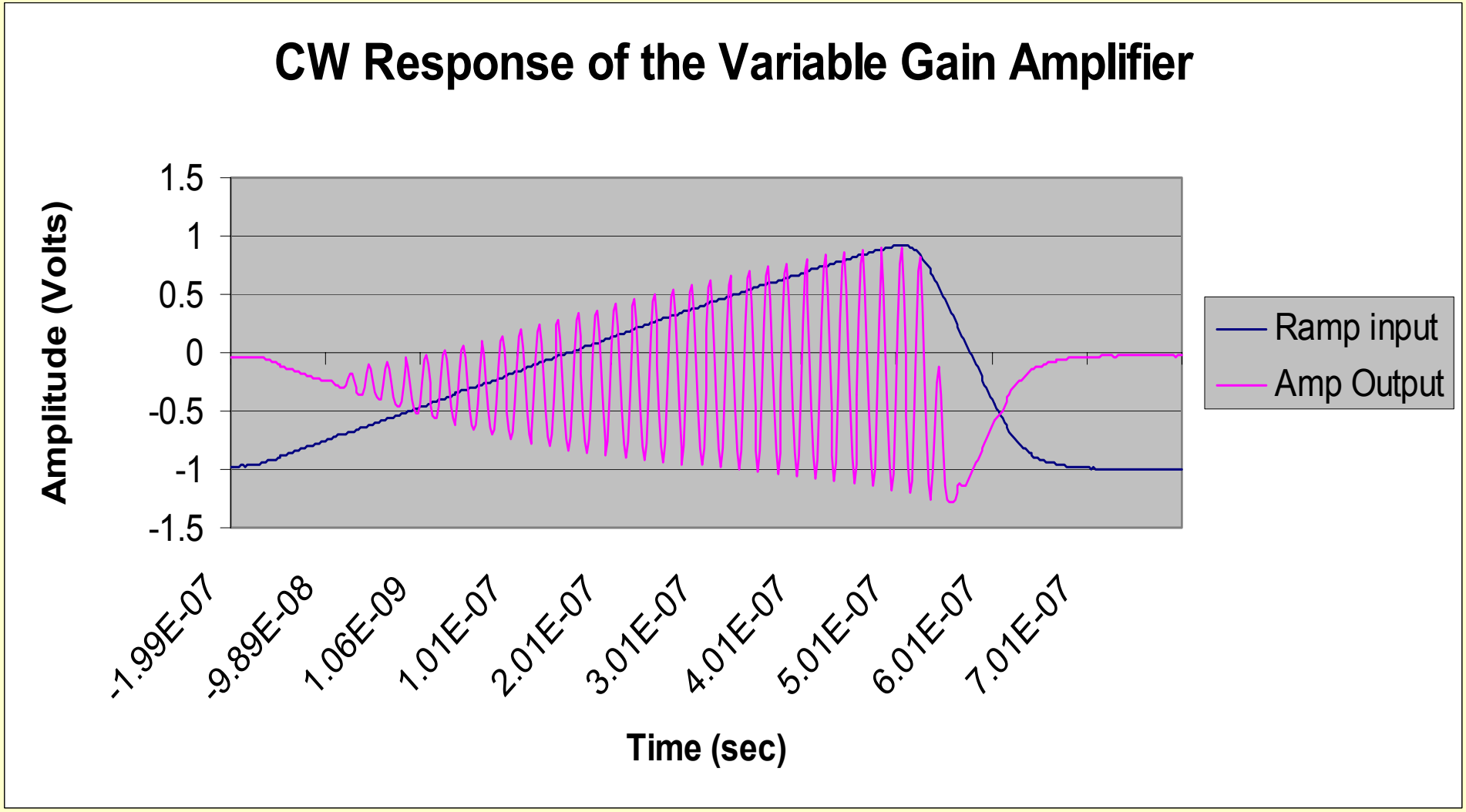
Hardware/Software

- Increase transmitter power (FCC and NTIA regulations set limits on this pathway).
- Select the frequency (depth vs. resolution).
- Increase the receiver sensitivity.
- Antenna design, arrays, polarization, calibration.
- Processing, e.g. deconvolution and migration, using calibrated antenna response to remove near-surface variations in deeper data and improve resolution with depth.

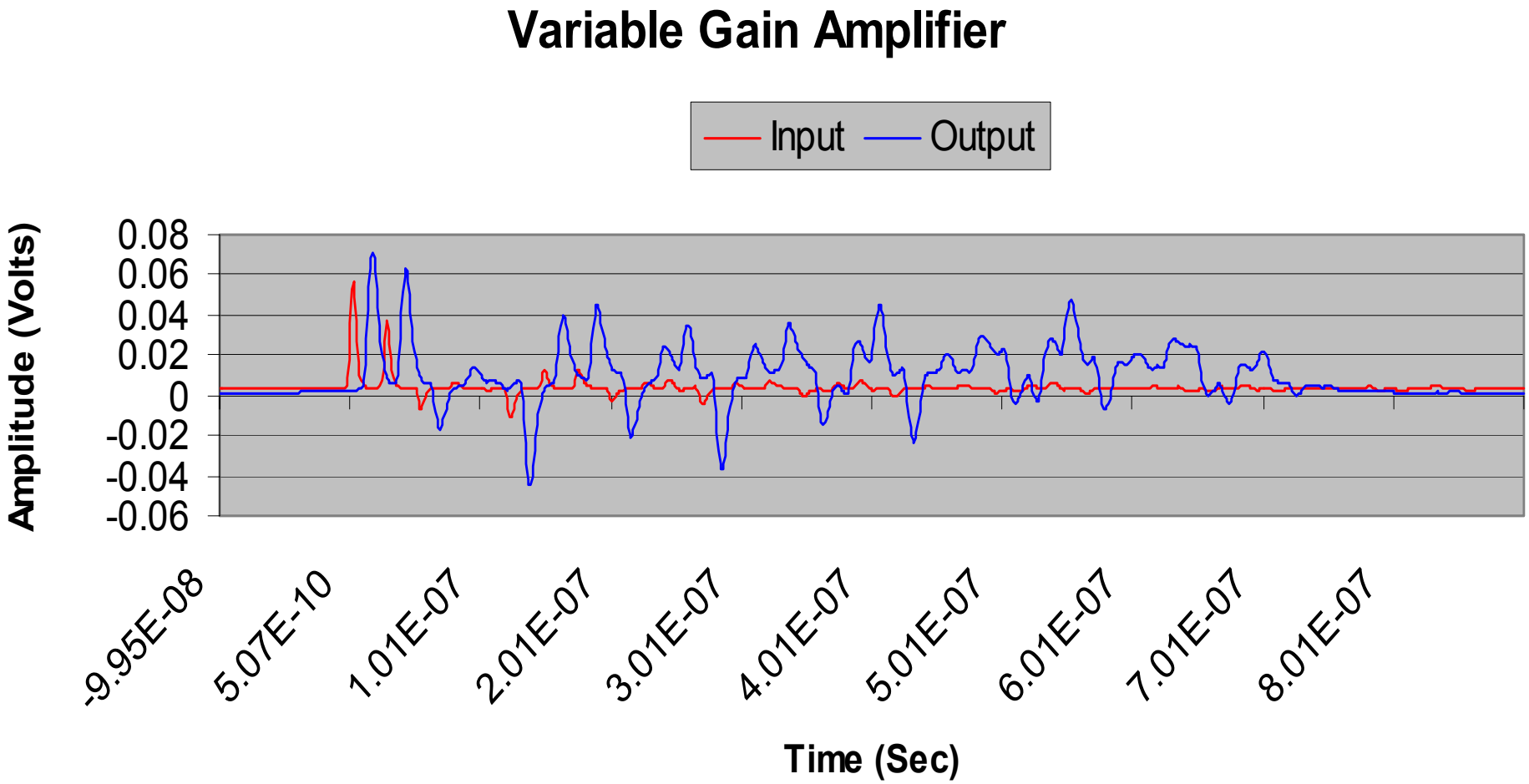
Increasing receiver sensitivity

- Waveform Averaging -- Signal to noise ratio (S/N) improvement (in dB) is $10\log_{10}(n)$ where "n" is the number of summed waveforms.
  - Waveform averaging after digitizing sampled signal. Many commercial systems do this. Slower than real-time digitization.
  - Waveform averaging of digitized RF signal (no sampling) Faster, so potential improvement in S/N ratio can be greater. However, fast RF digitizers have fewer bits, so RF signal conditioning is needed to achieve maximum benefit.
- Signal Conditioning -- Amplify weaker signals more than strong signals.
  - Sensitivity time control (STC) or logarithmic amplifier
  - Some commercial systems do STC after sampling, but we will do STC directly on the RF signal, or use a logarithmic amplifier.

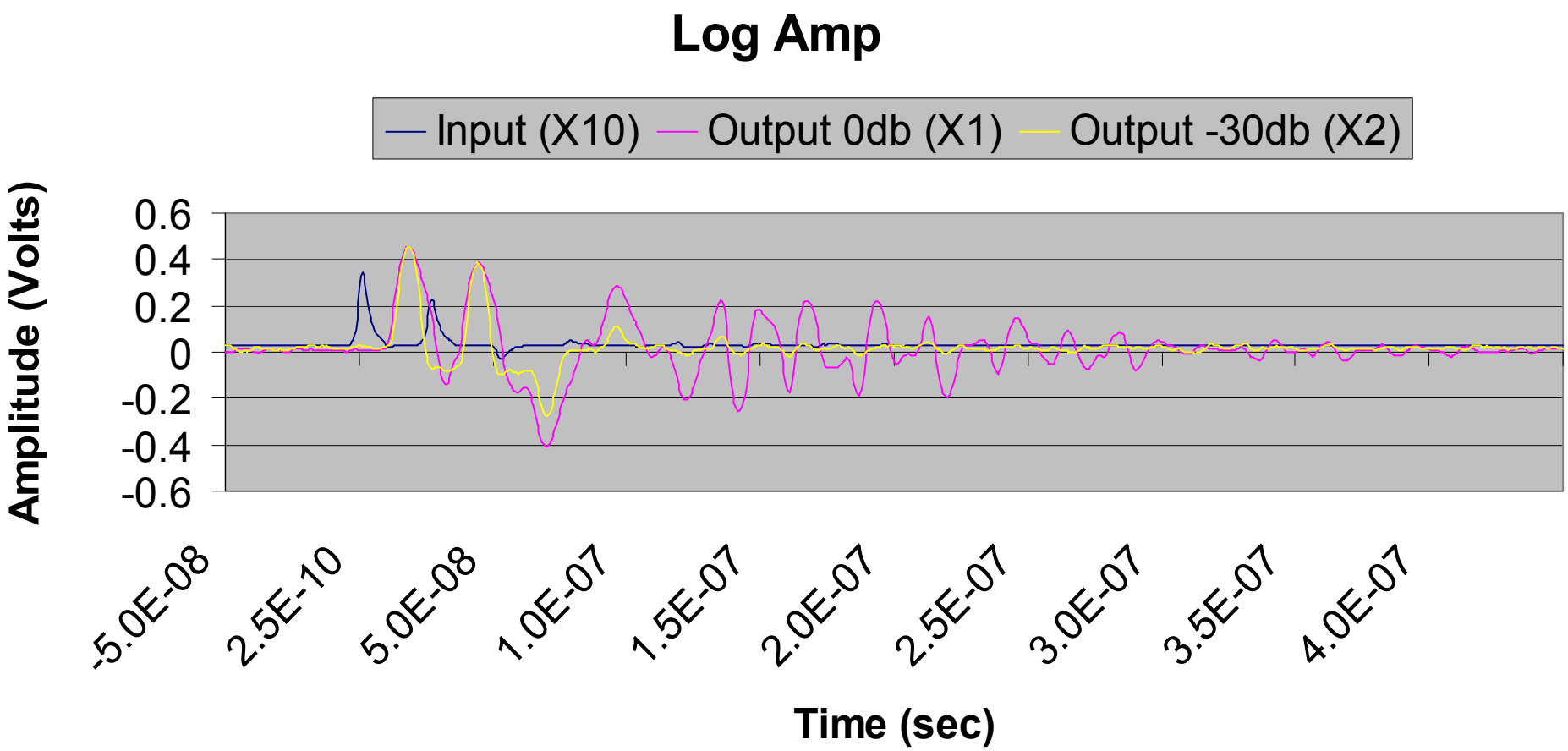
This slide shows the result of passing a constant amplitude continuous wave (CW) signal through an amplifier whose gain increases with time (STC).



This slide shows experimental data resulting from passing a train of decreasing amplitude pulses through an amplifier whose gain is increasing with time.



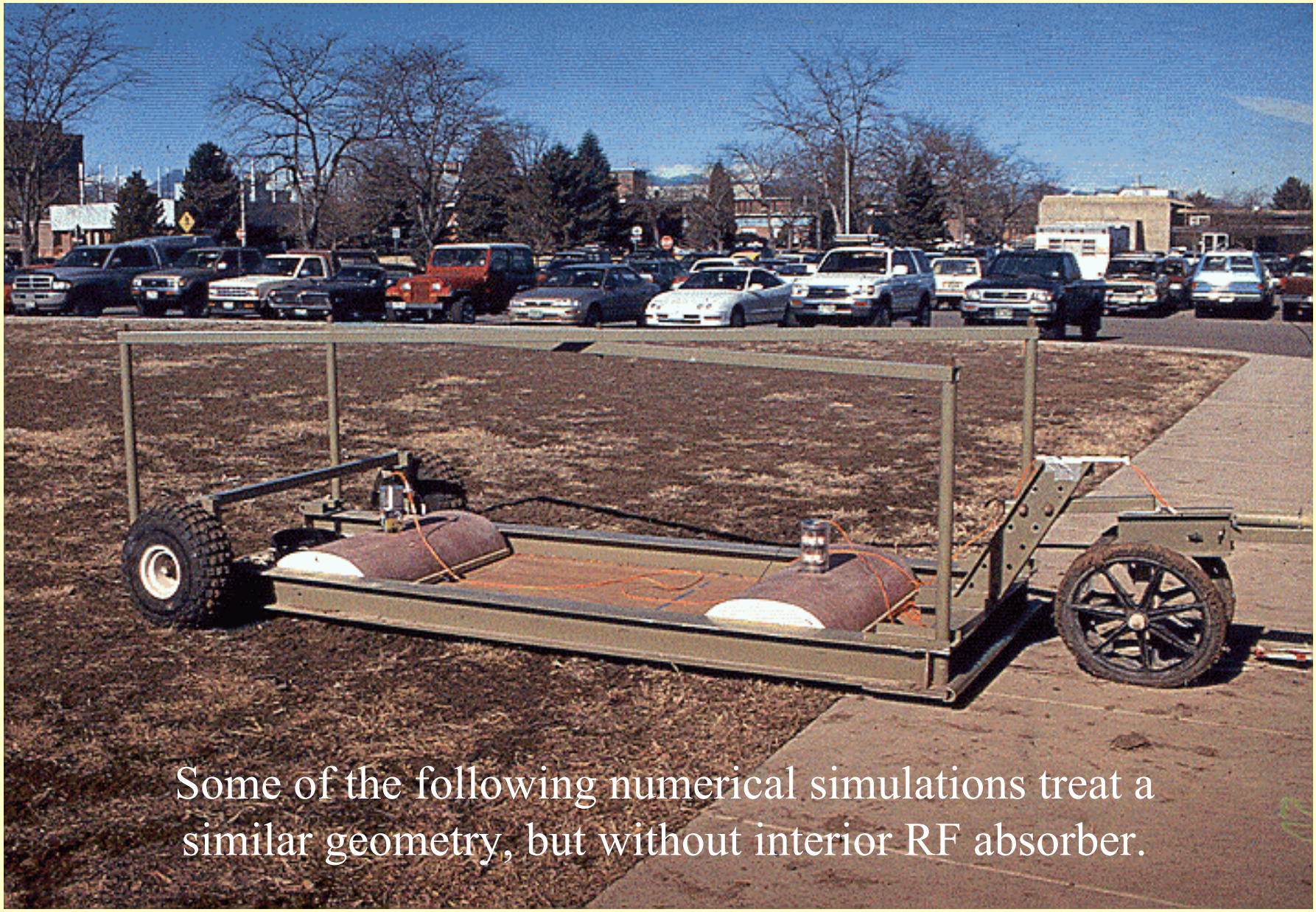
This slide shows the result of passing a train of decreasing amplitude pulses through a non-linear (logarithmic) amplifier at different gains. This is an alternative to active STC. Both approaches require calibration when amplitudes are important to analysis.



Finite Difference Time Domain (FDTD) Numerical Modeling

- FDTD is a numerical time-stepping solution of Maxwell's equations, so almost all physics are automatic, e.g. no near-field or far-field or wave propagation assumptions need be made. There are some limitations and conditions for valid application, however. (See Kunz and Luebbers, Finite Difference Time Domain Method for Electromagnetics, and Taflove, Computational Electrodynamics, for example.)
- Time consuming and lots of memory for large problems, however, so usually used only relatively close to antenna.
- Useful for antenna design.
- Useful to calculate radiated wavelet into the earth.
  - This is very useful as input to models that use far-field approximations.
- Shows attenuation and dispersion as a function of earth properties.

Back-shielded Bowtie Antennas



Some of the following numerical simulations treat a similar geometry, but without interior RF absorber.

FDTD Simulation Parameters

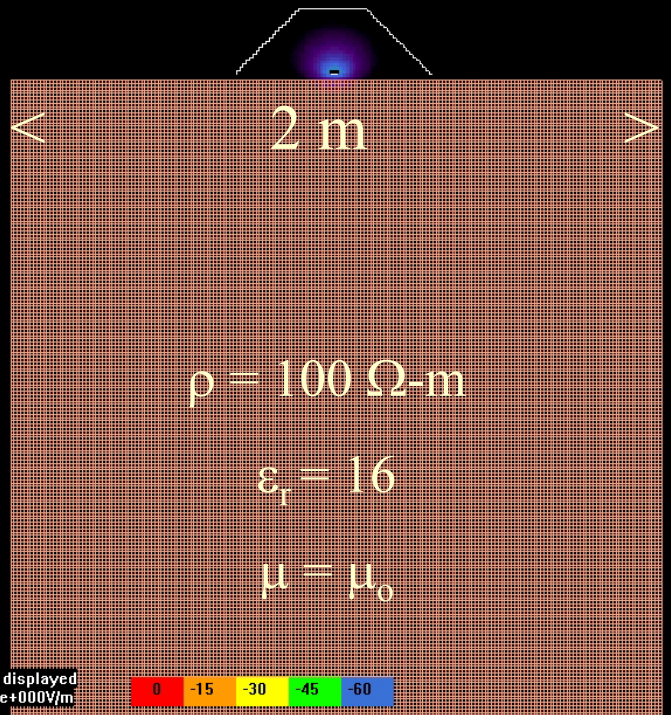
Code: XFDTD from REMCOM. Size: 12 million cells. Time: 21 hours.
Machine: Dell 610 Xeon 550 MHz with dual processors and 1.75 Gb of memory.

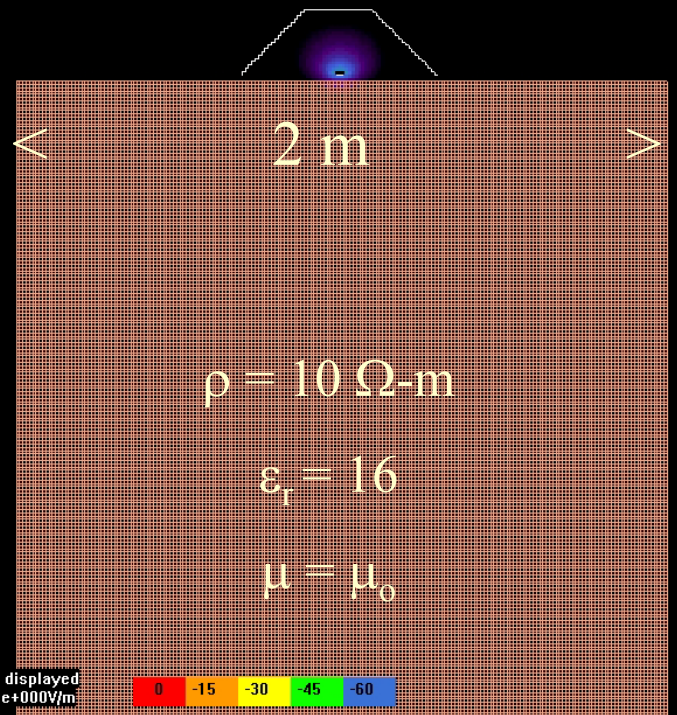
Driving Function: 1 volt peak Gaussian FWHM ~ 4 ns

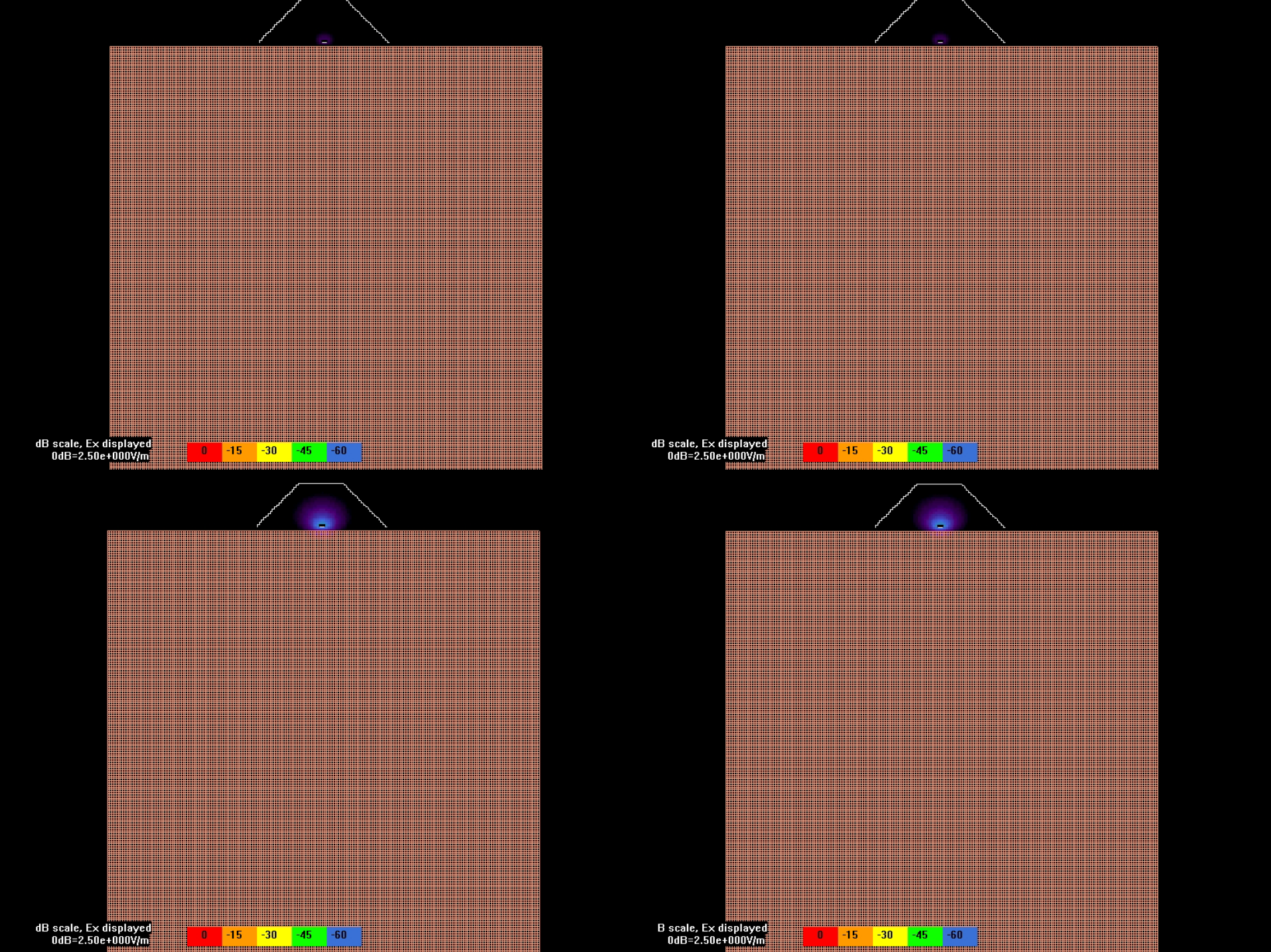
Time Step: 20 ps, Cell size: 1 cm, Duration: 30 ns, Snap shots: Every 1 ns

Field component visualized: E_x (Normal to plane of figure)

Antenna: 112 cm full length, 30° Bow-tie with back shield



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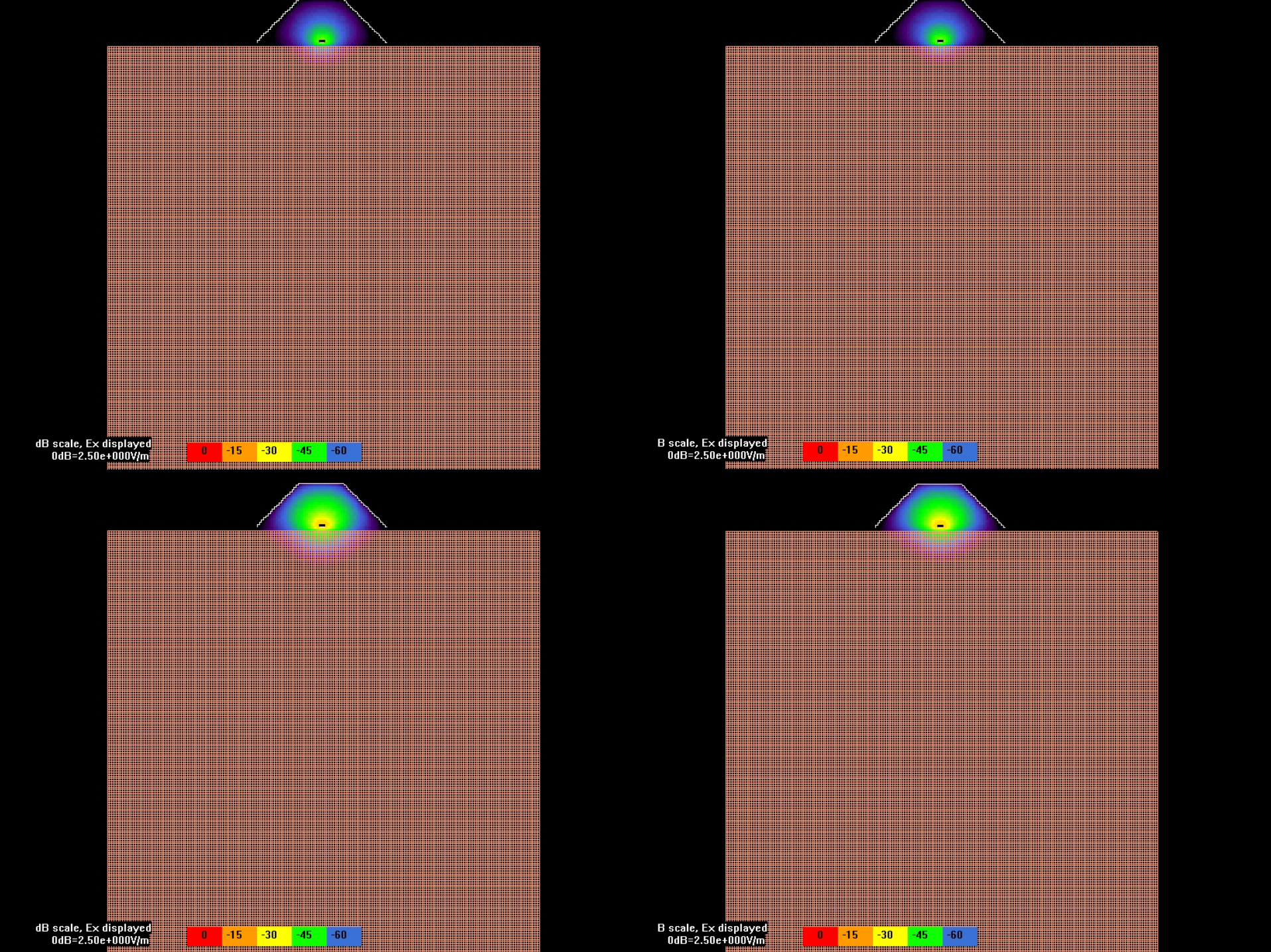
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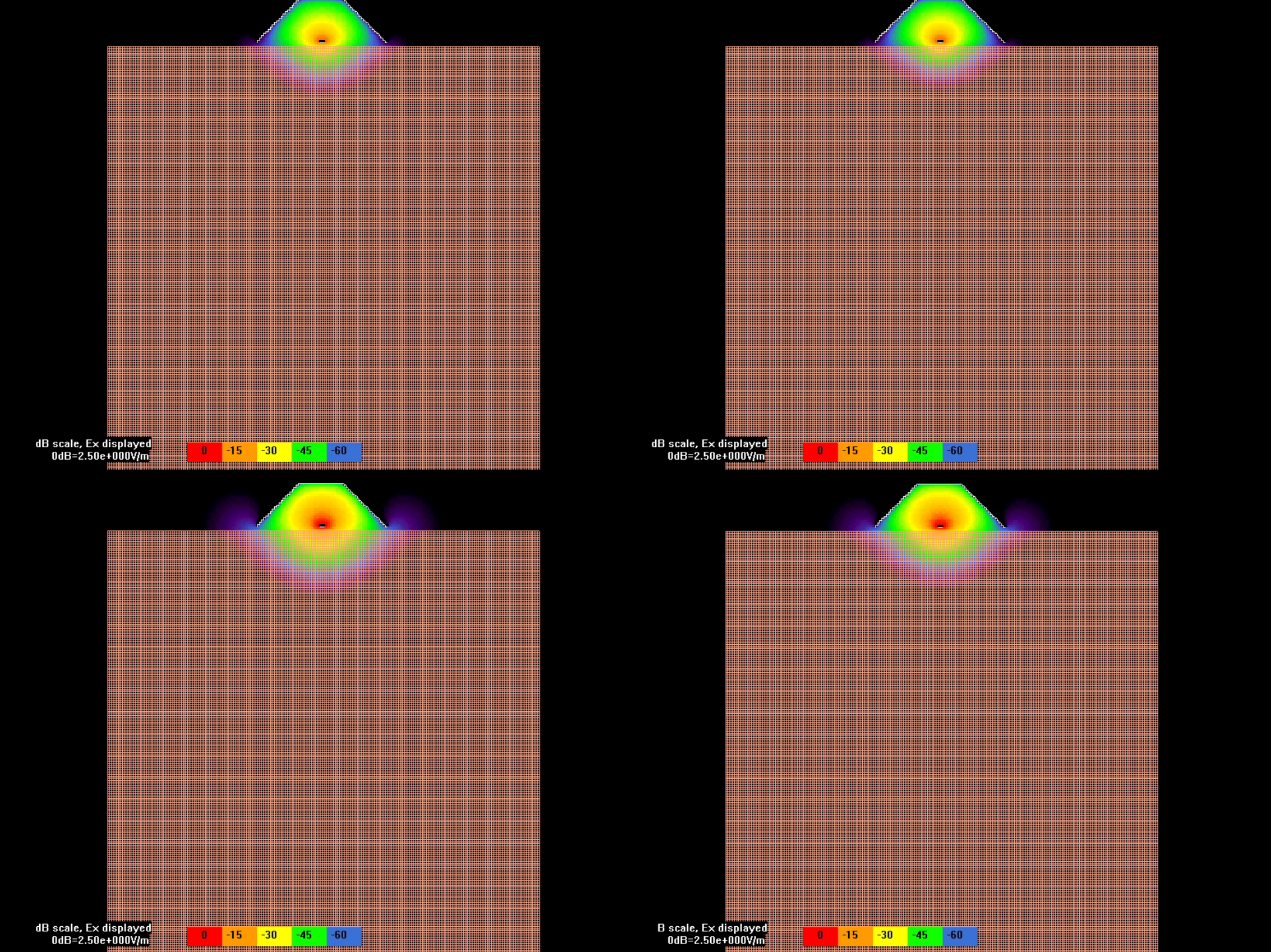
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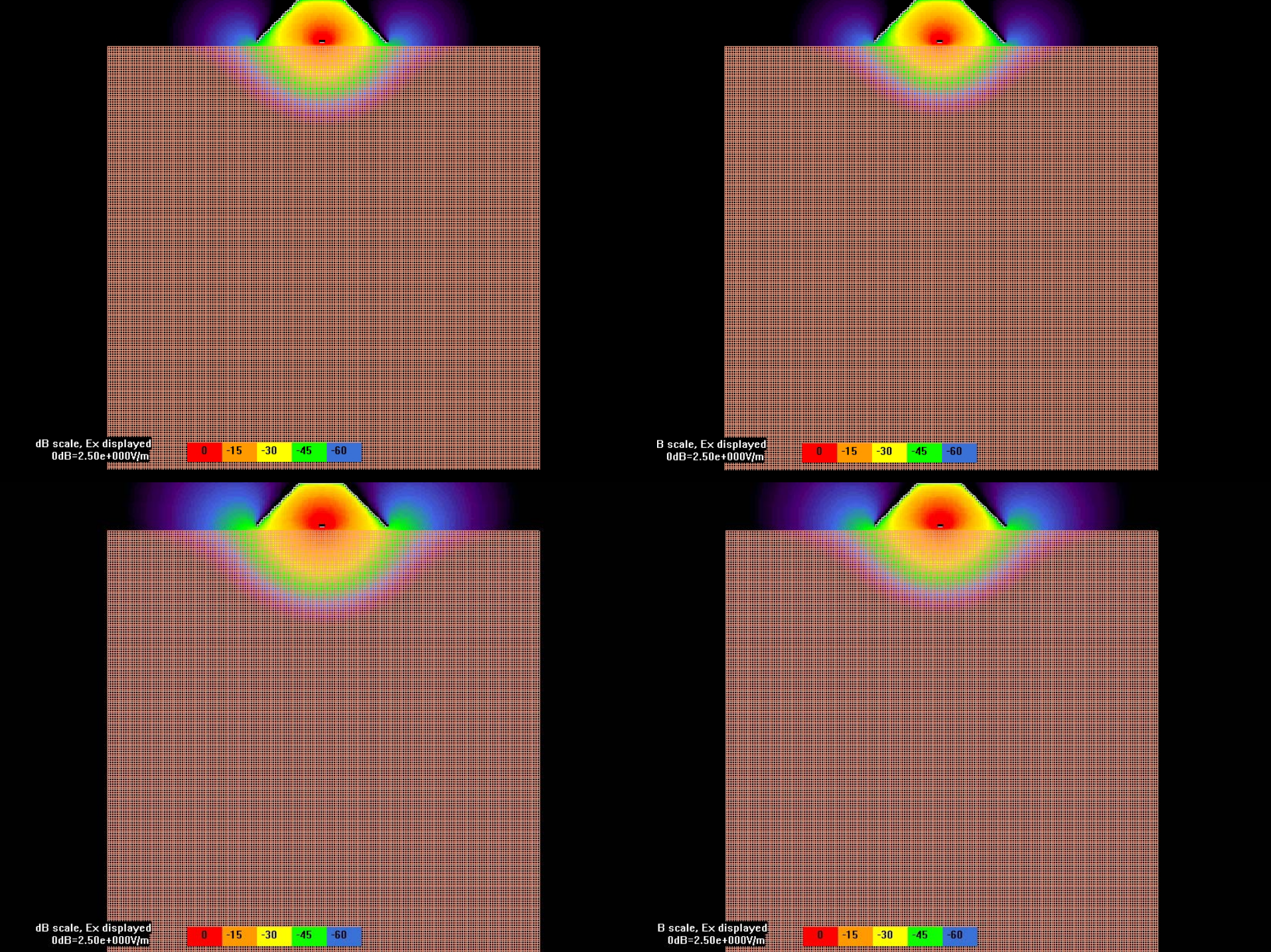
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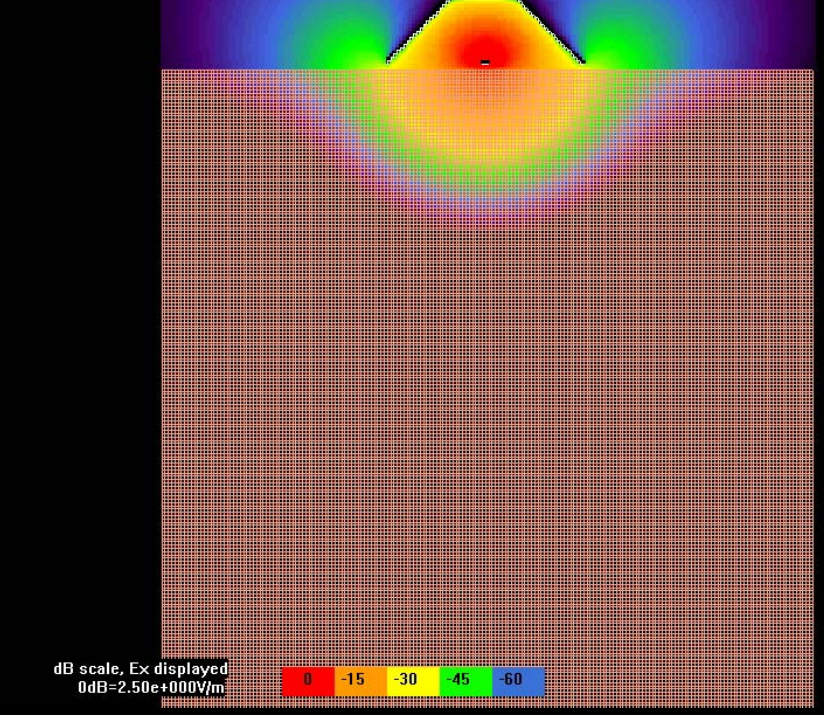
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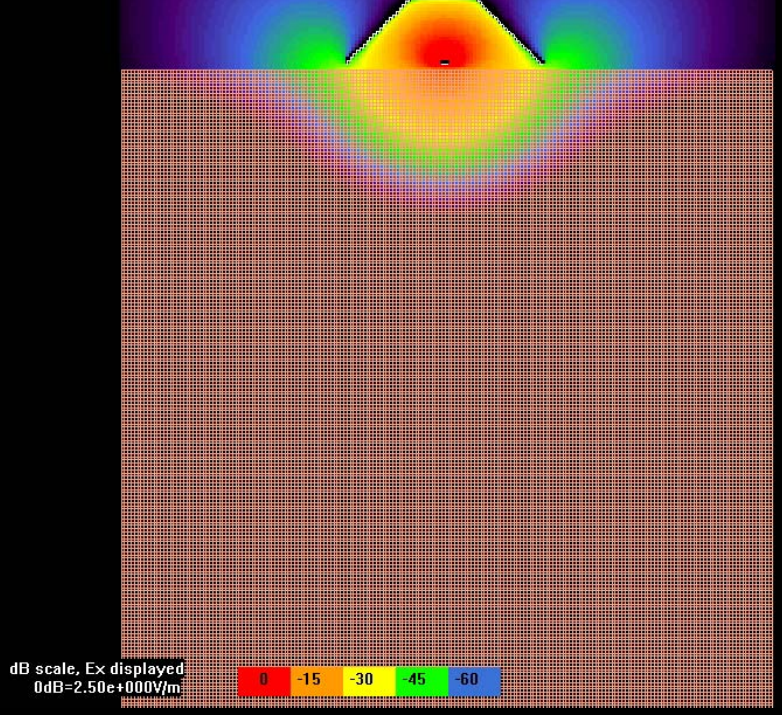
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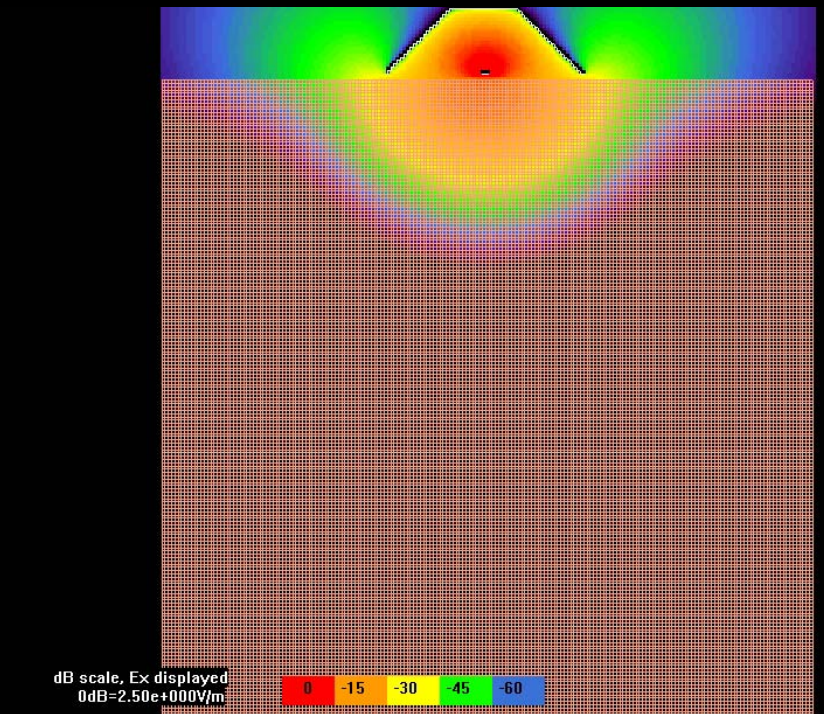
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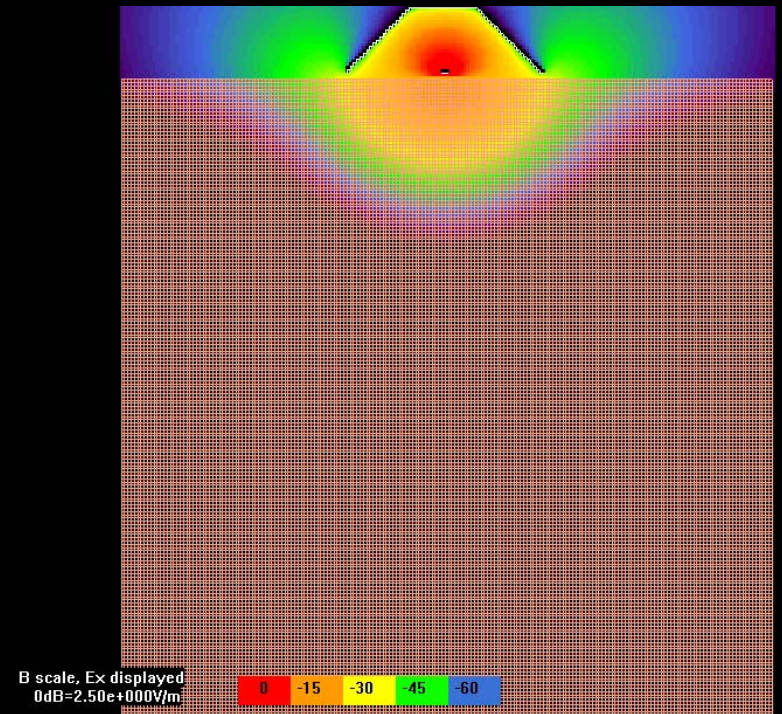
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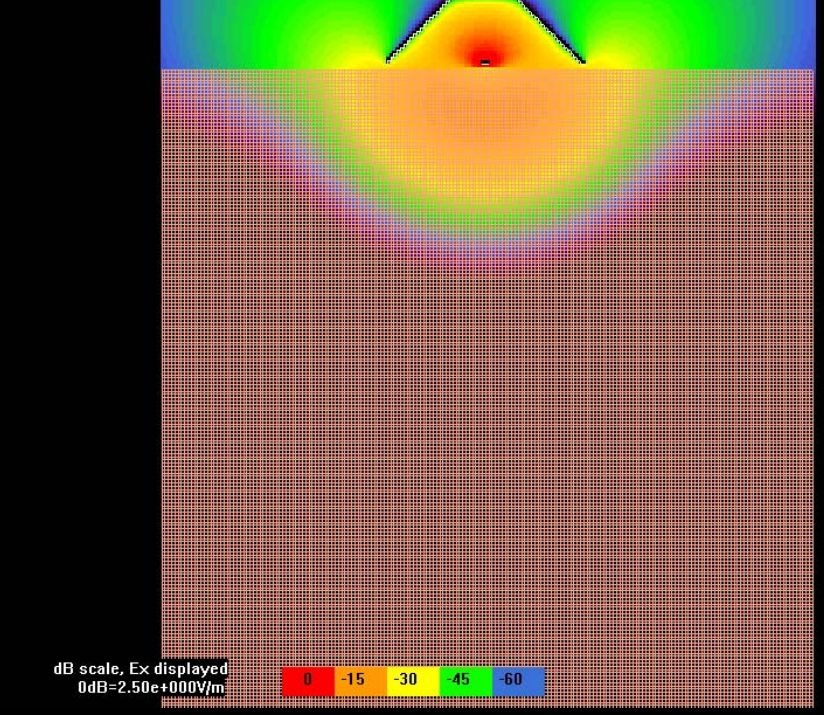
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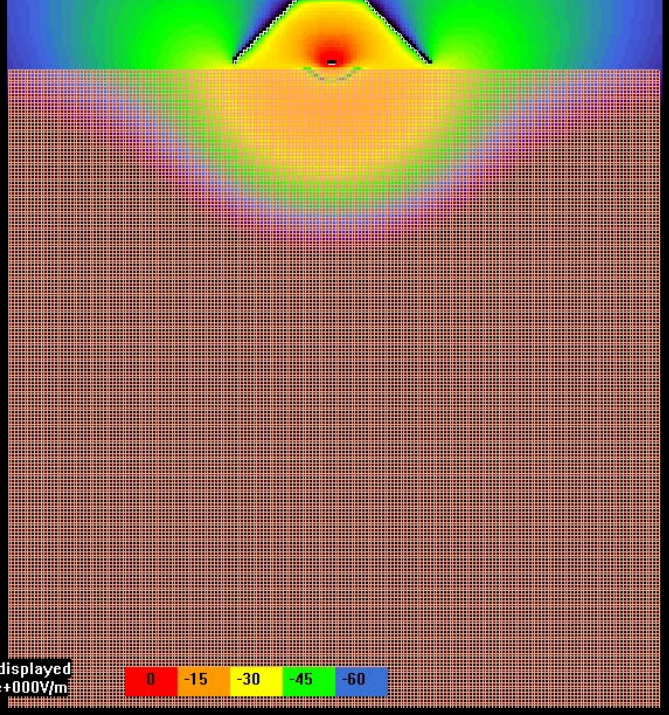
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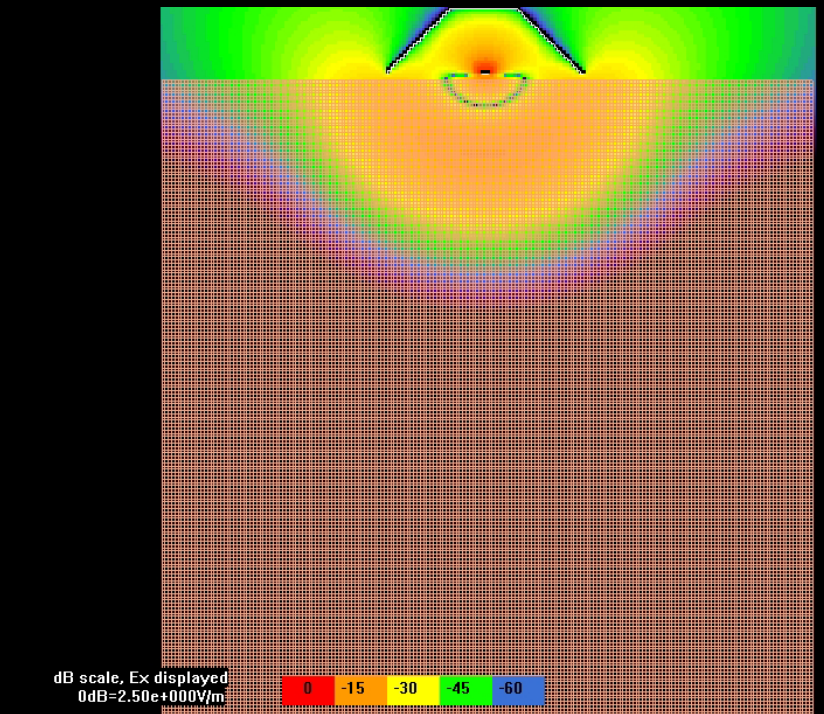
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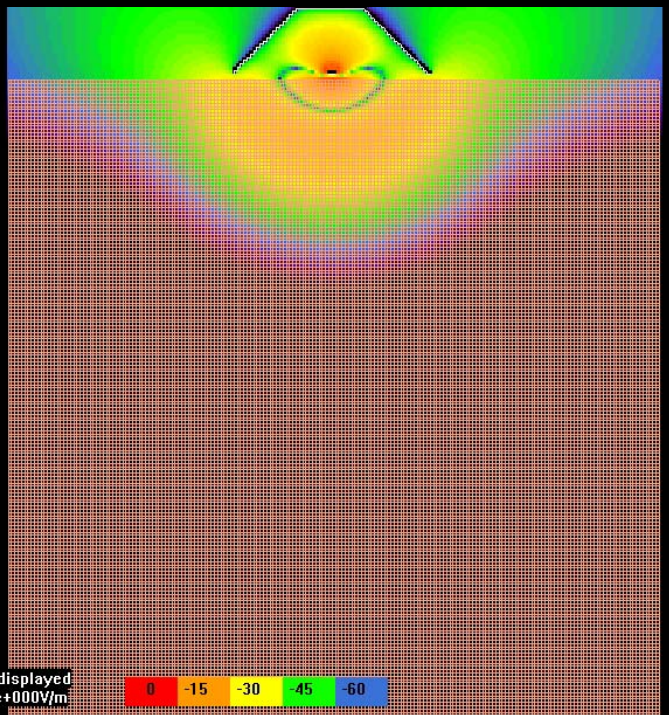
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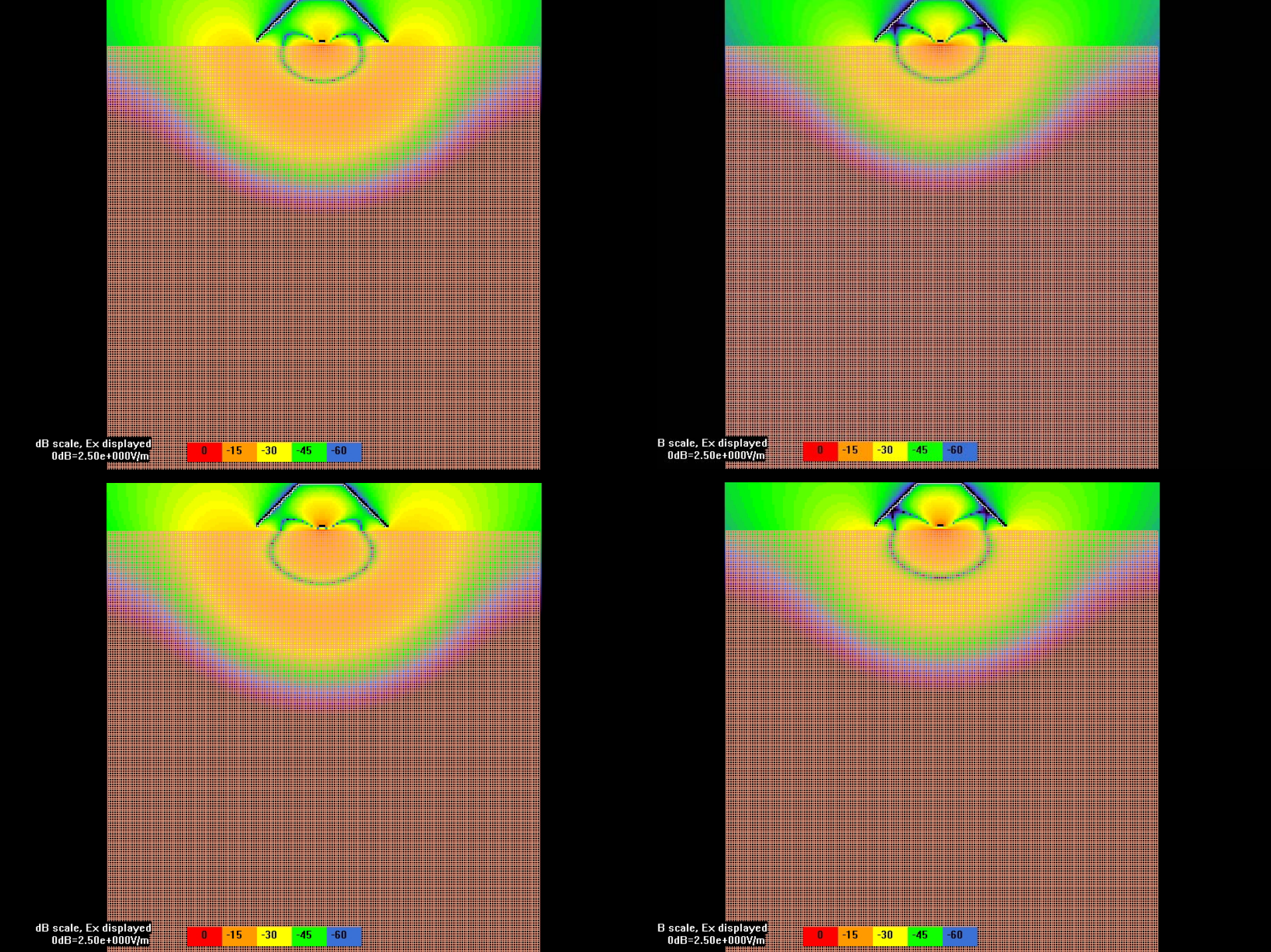
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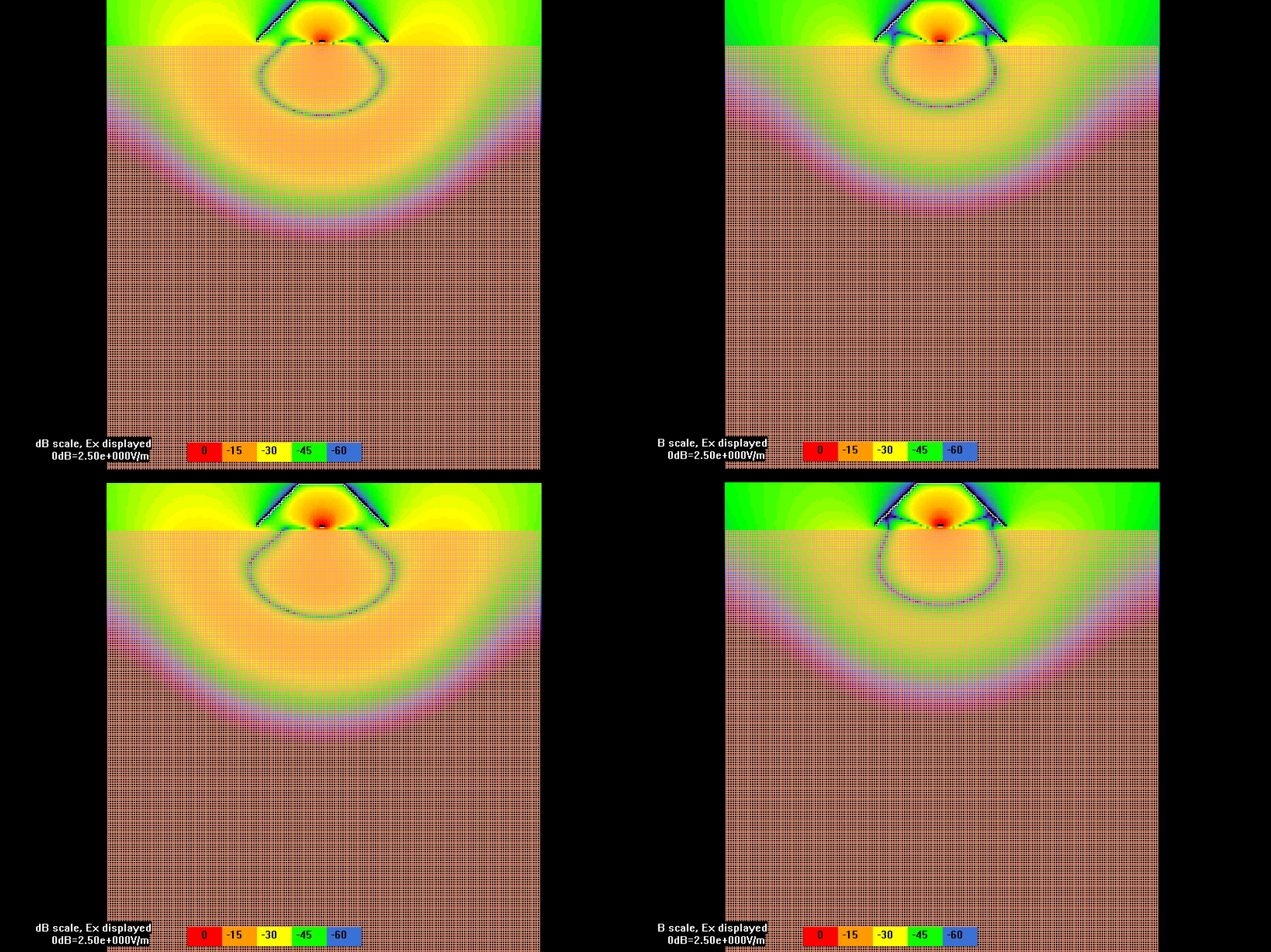
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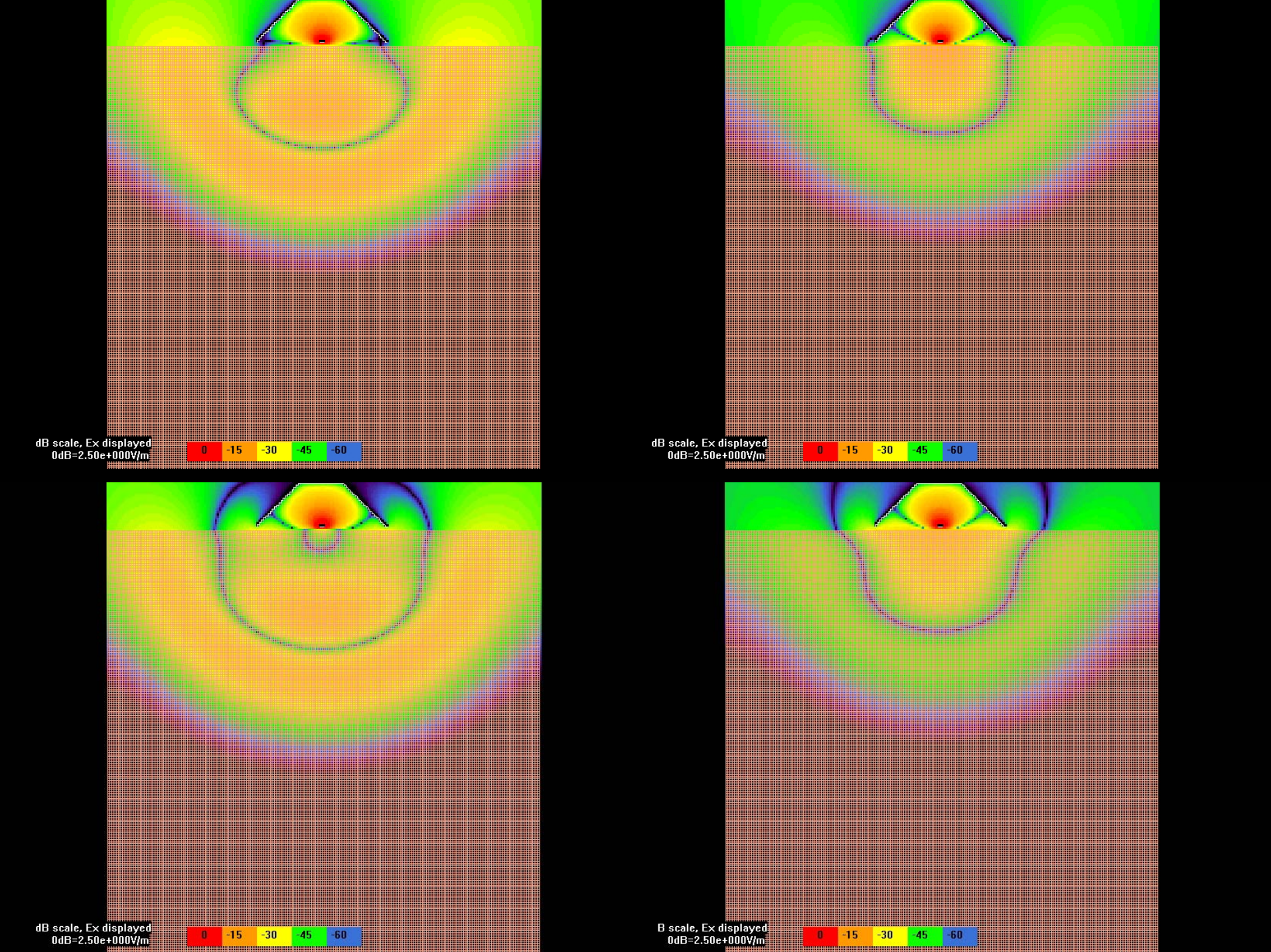
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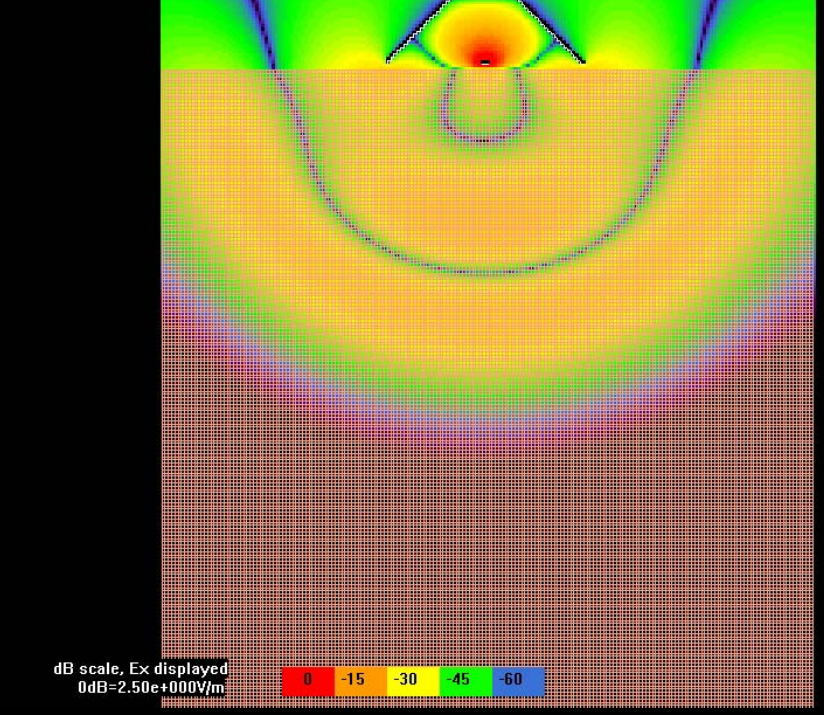
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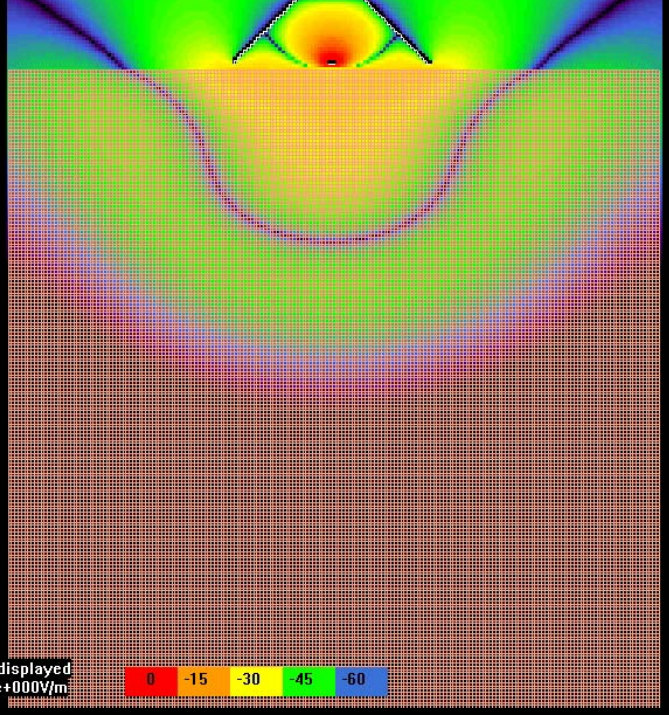
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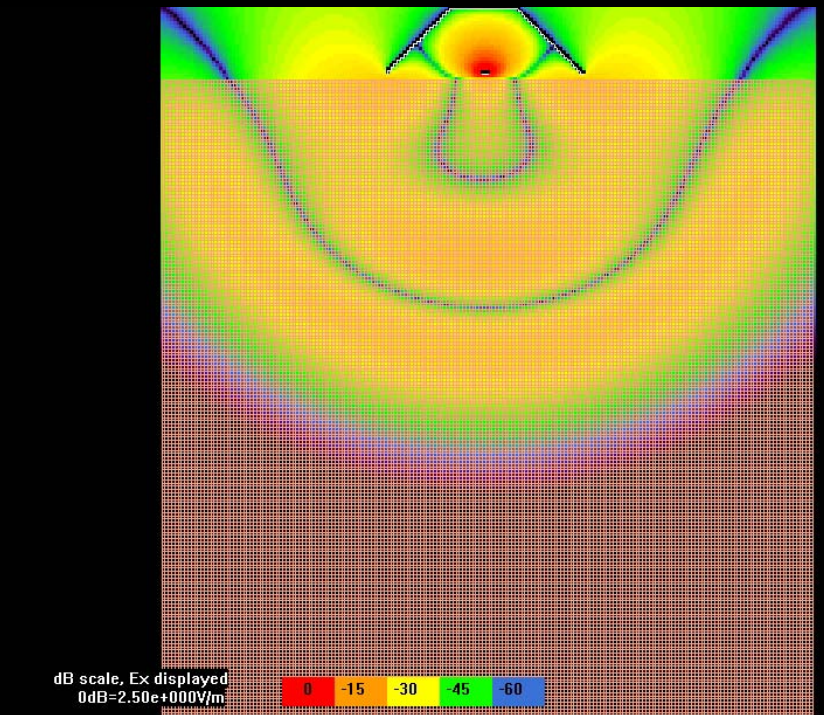
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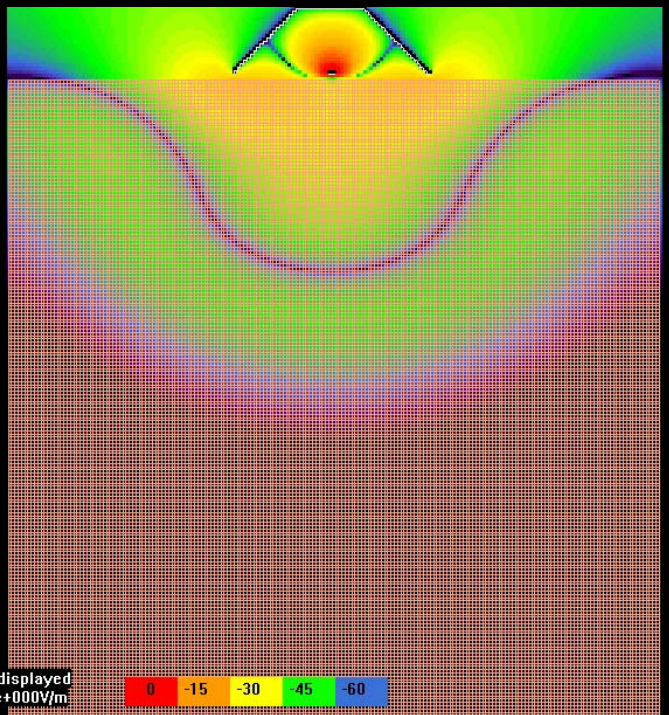
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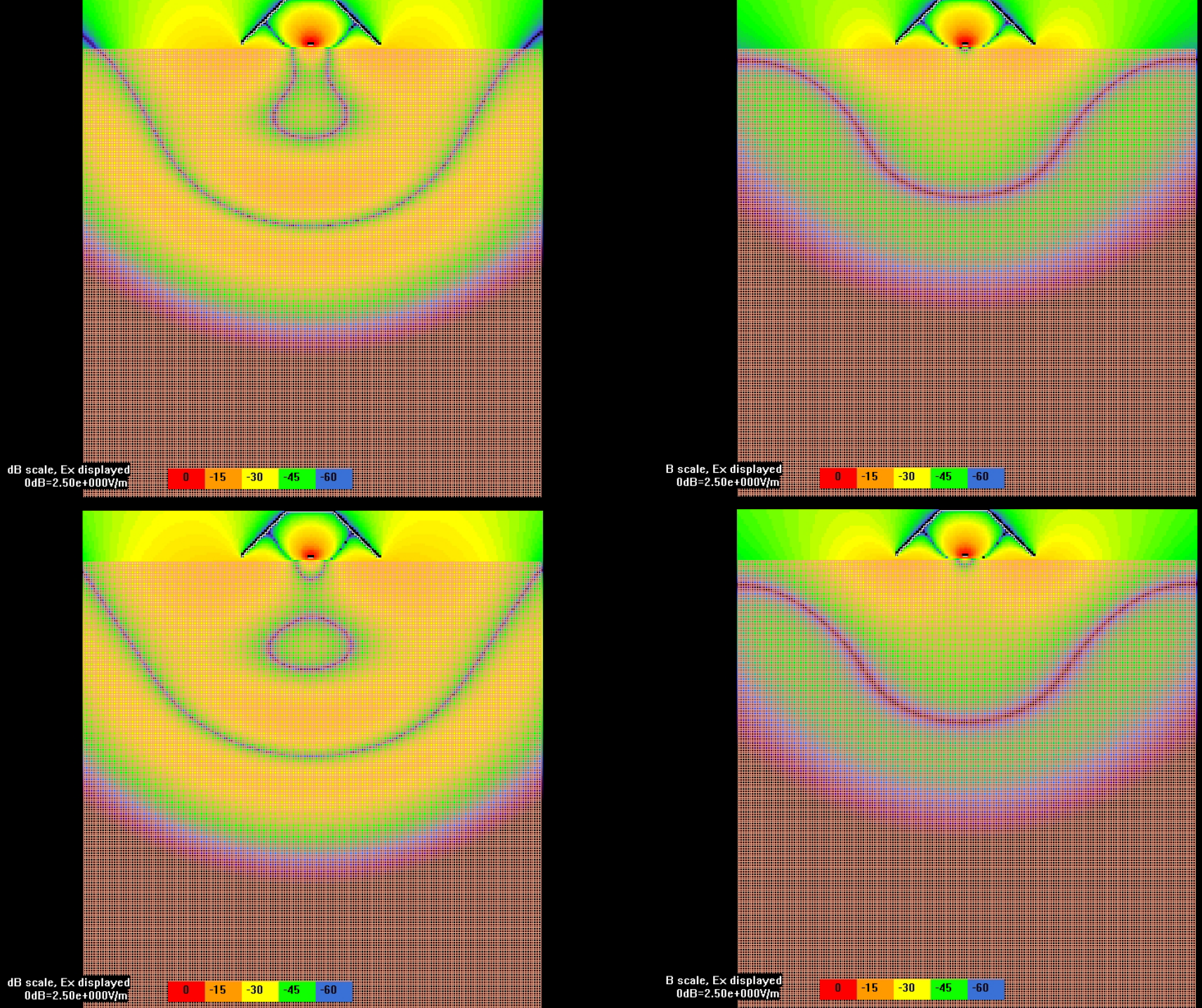
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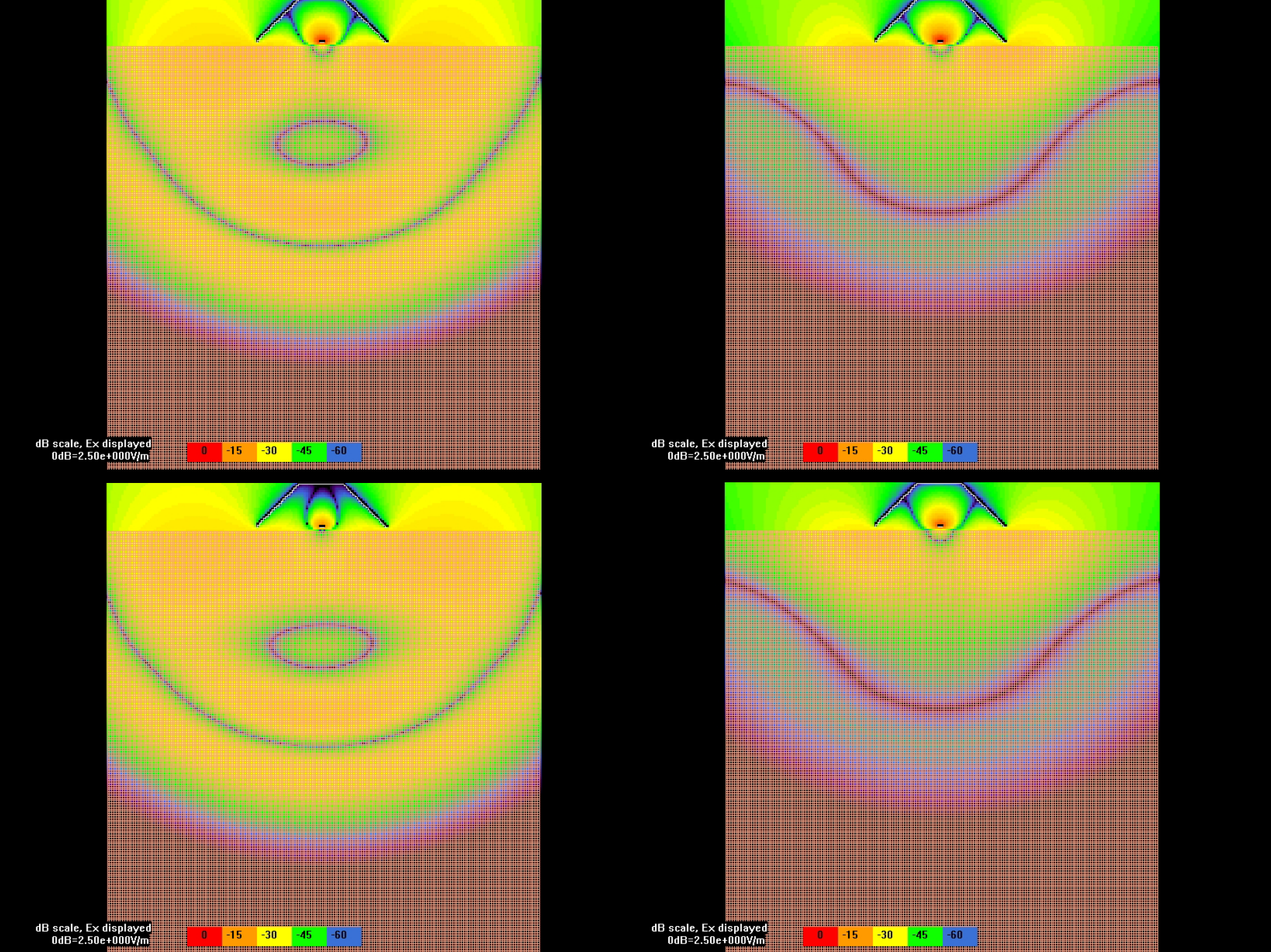
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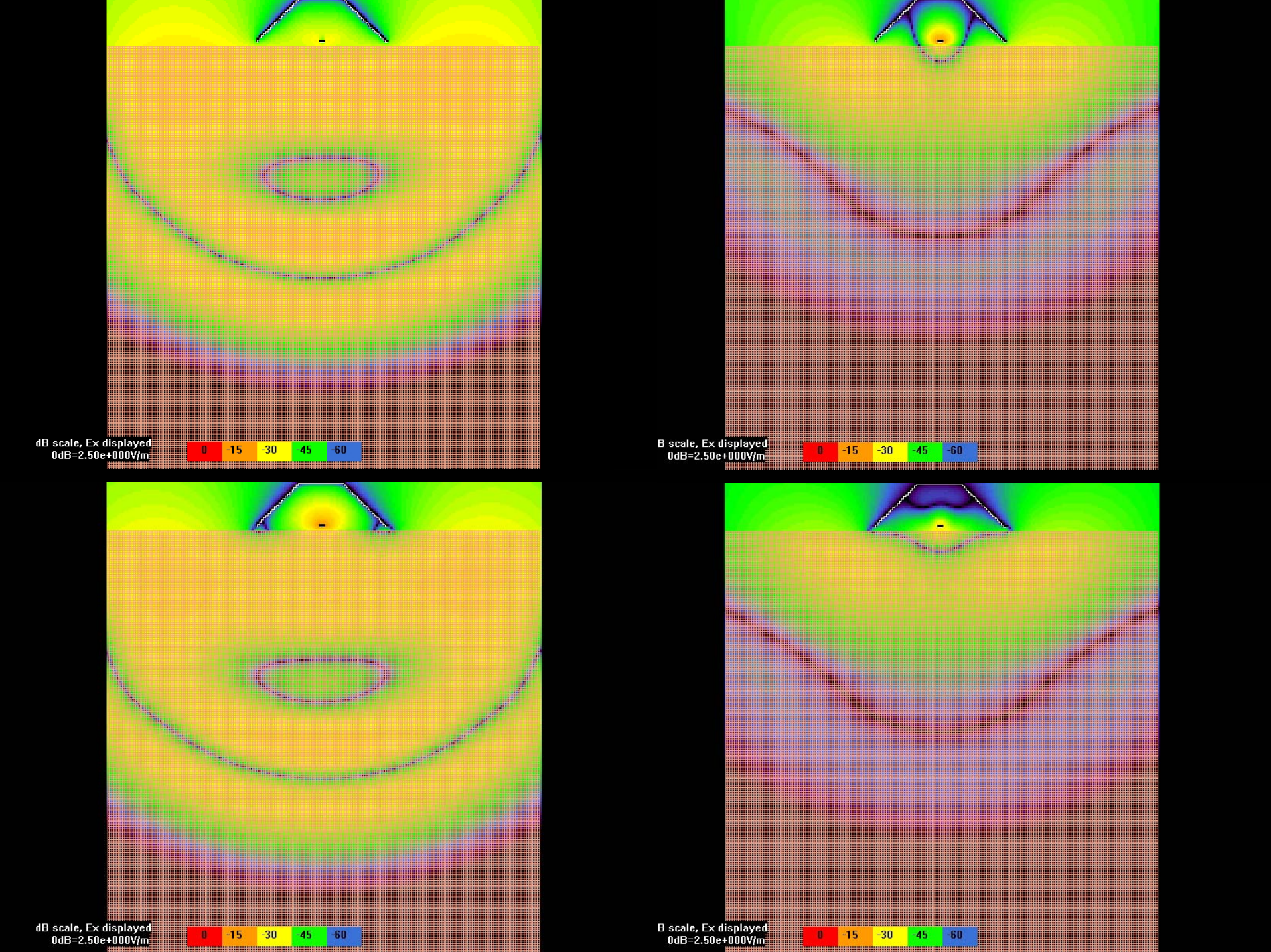
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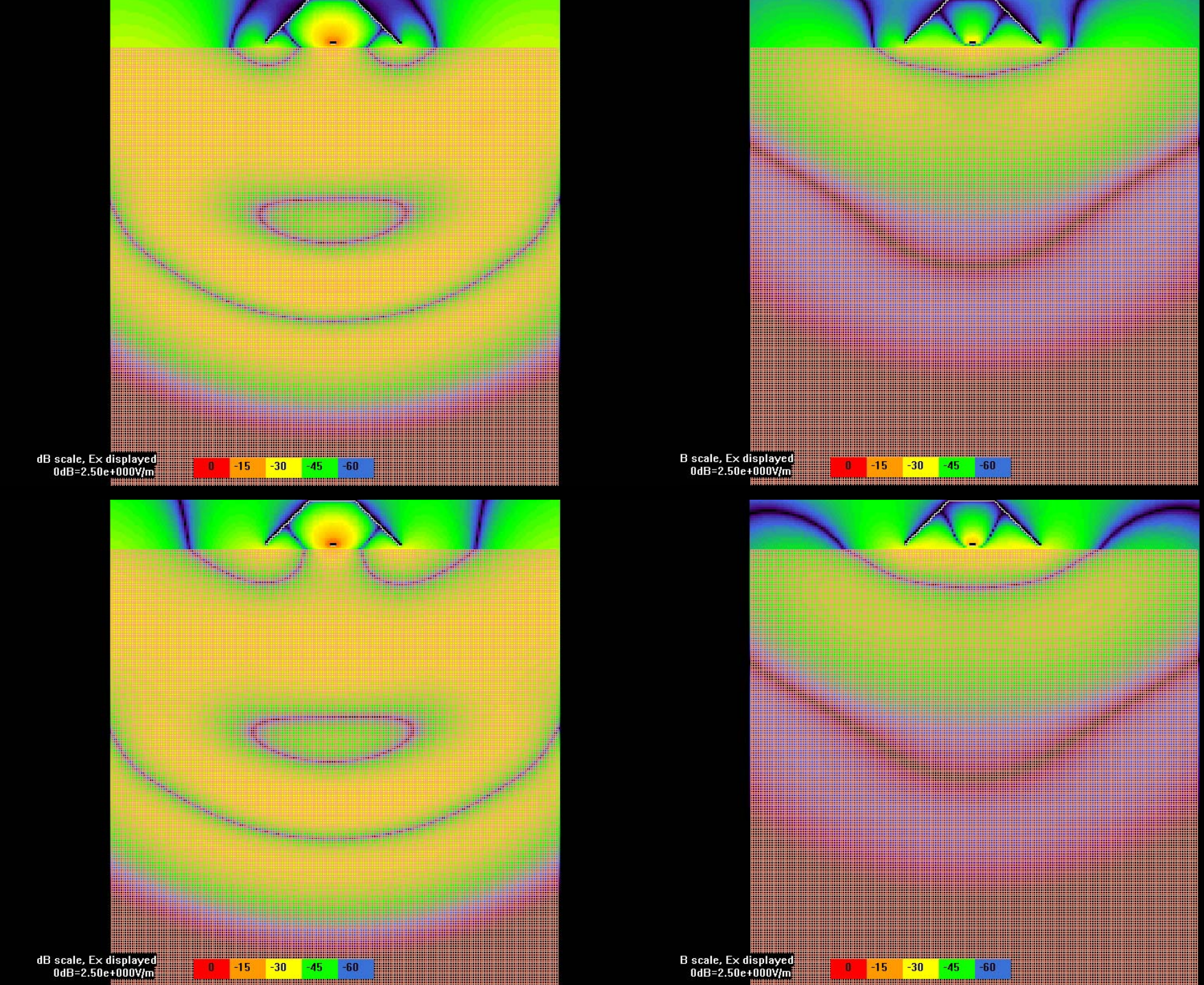
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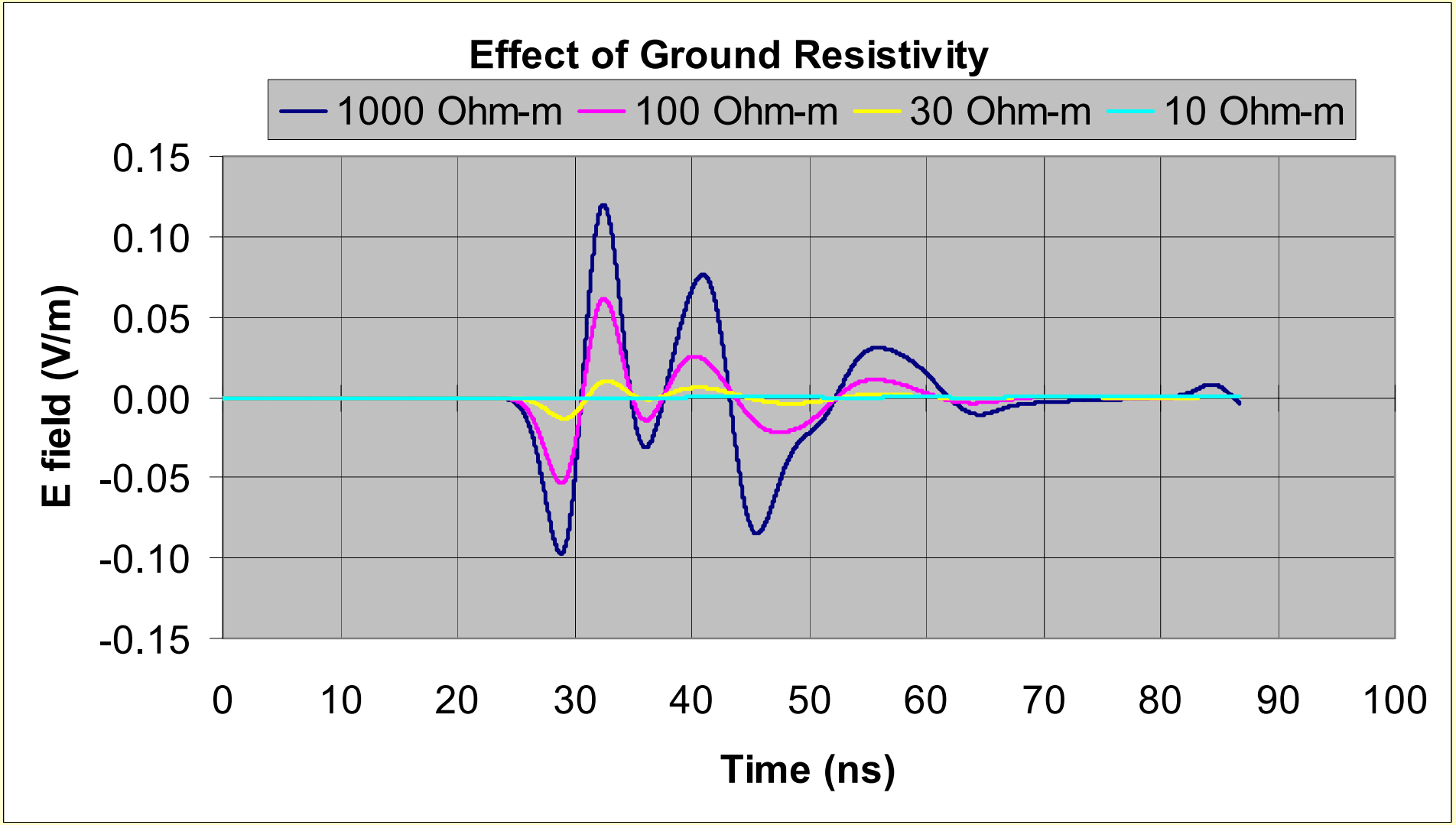
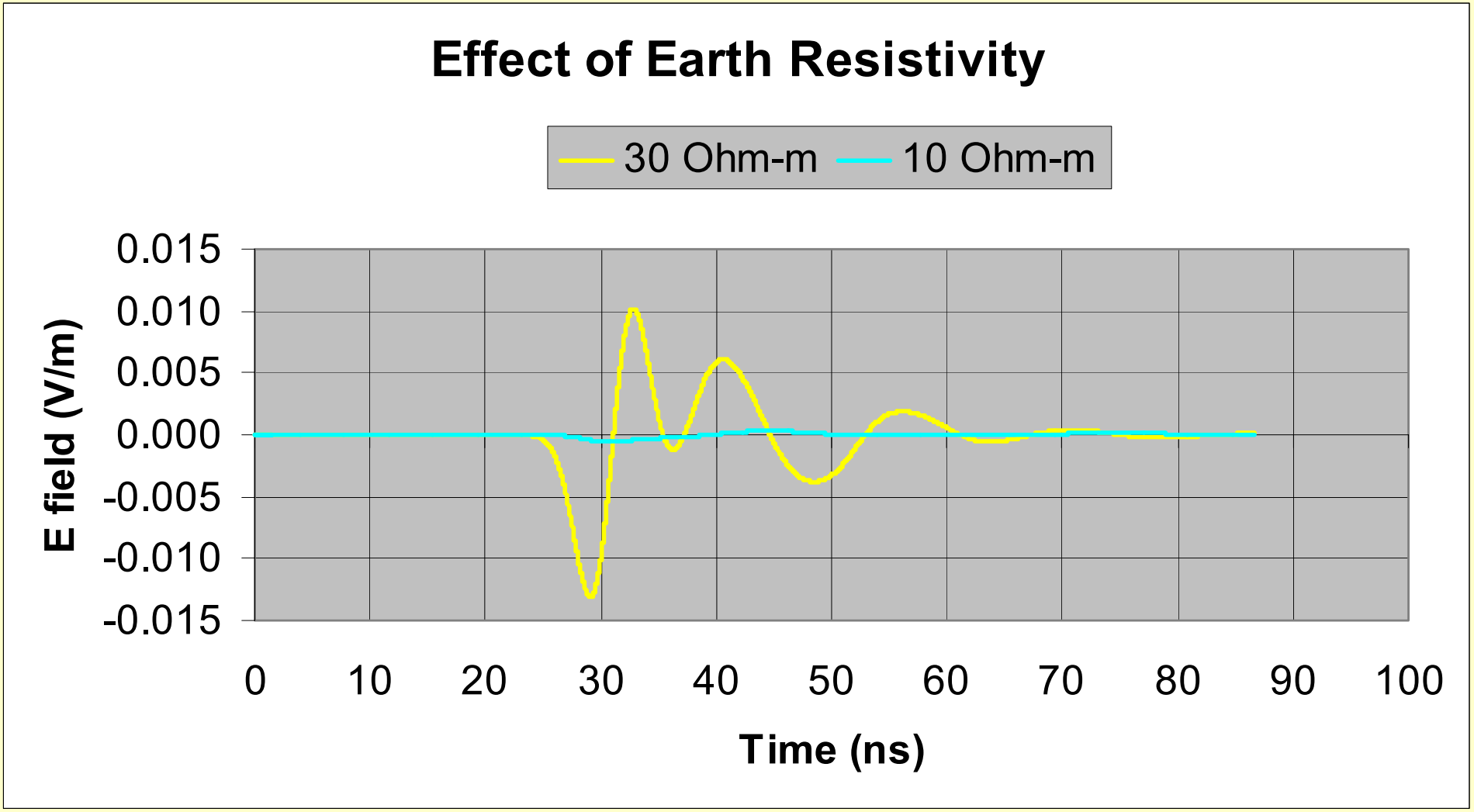
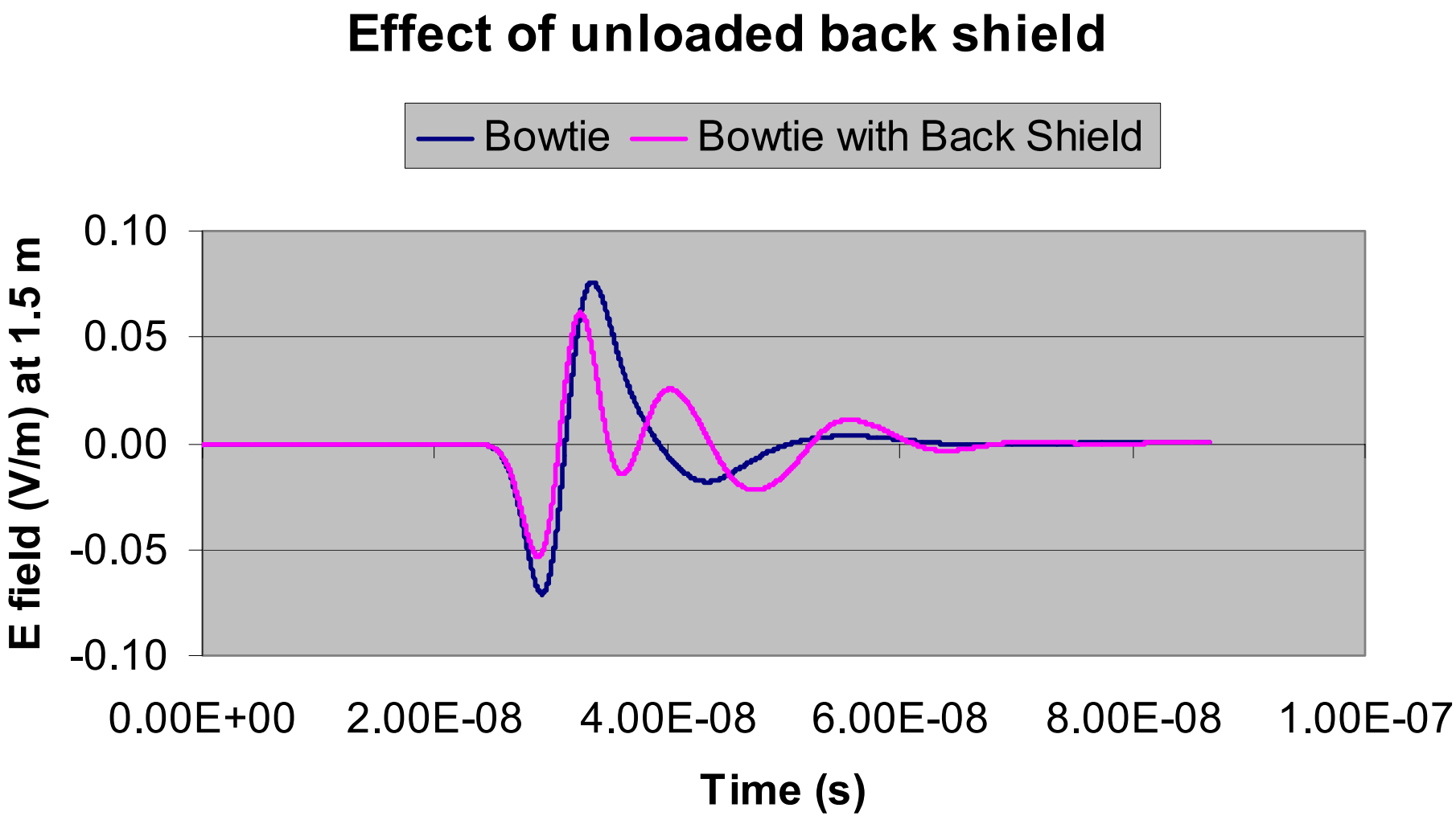
These superimposed waveforms were derived from the same FDTD simulation shown in the previous slides and show the effect of earth resistivity on the transmitted electric field waveform 1.5 m below the ground surface.



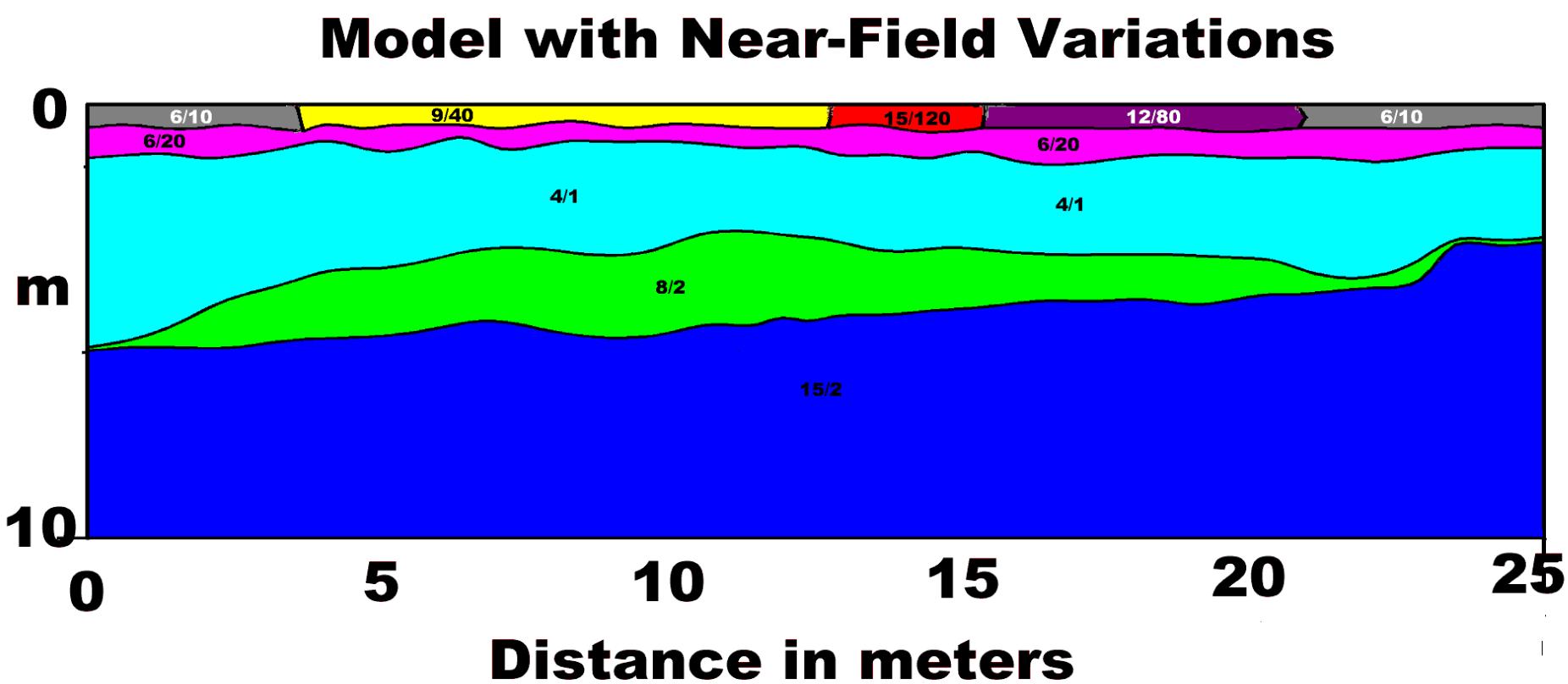
These plots are re-scaled versions of those from the previous slide. Even at 30 Ohm-m the waveform, though attenuated, shows relatively little distortion. At 10 Ohm-m, however, the waveform is not only attenuated, but retarded, and broadened as well, because the high-frequency wave propagation approximation no longer holds.



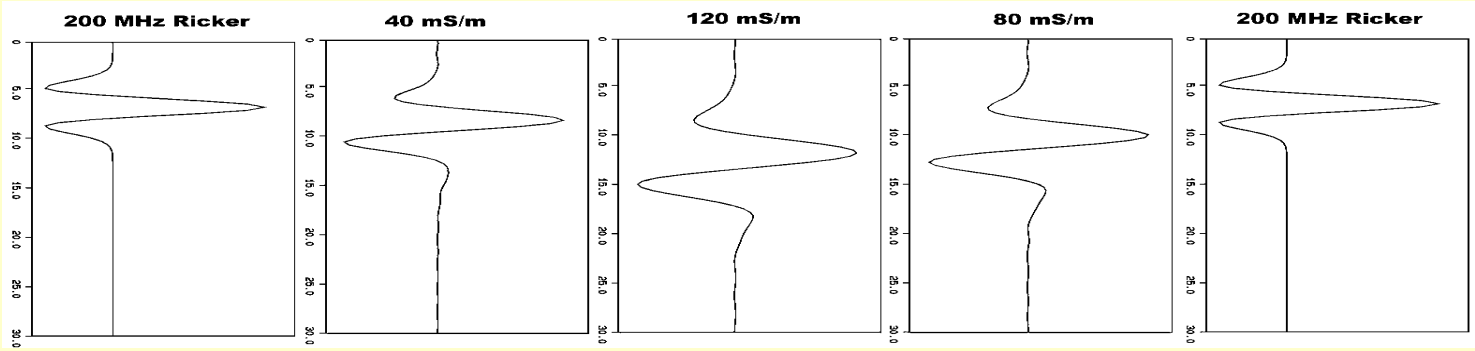
This slide shows an FDTD-calculated transmitted wavelet for the bowtie antenna shown in previous slides, but with and without the back shield. Effects of loading the shield cavity with RF absorbing materials have not yet been added to the model. This calculation assumes an earth resistivity of 100 Ohm-m.

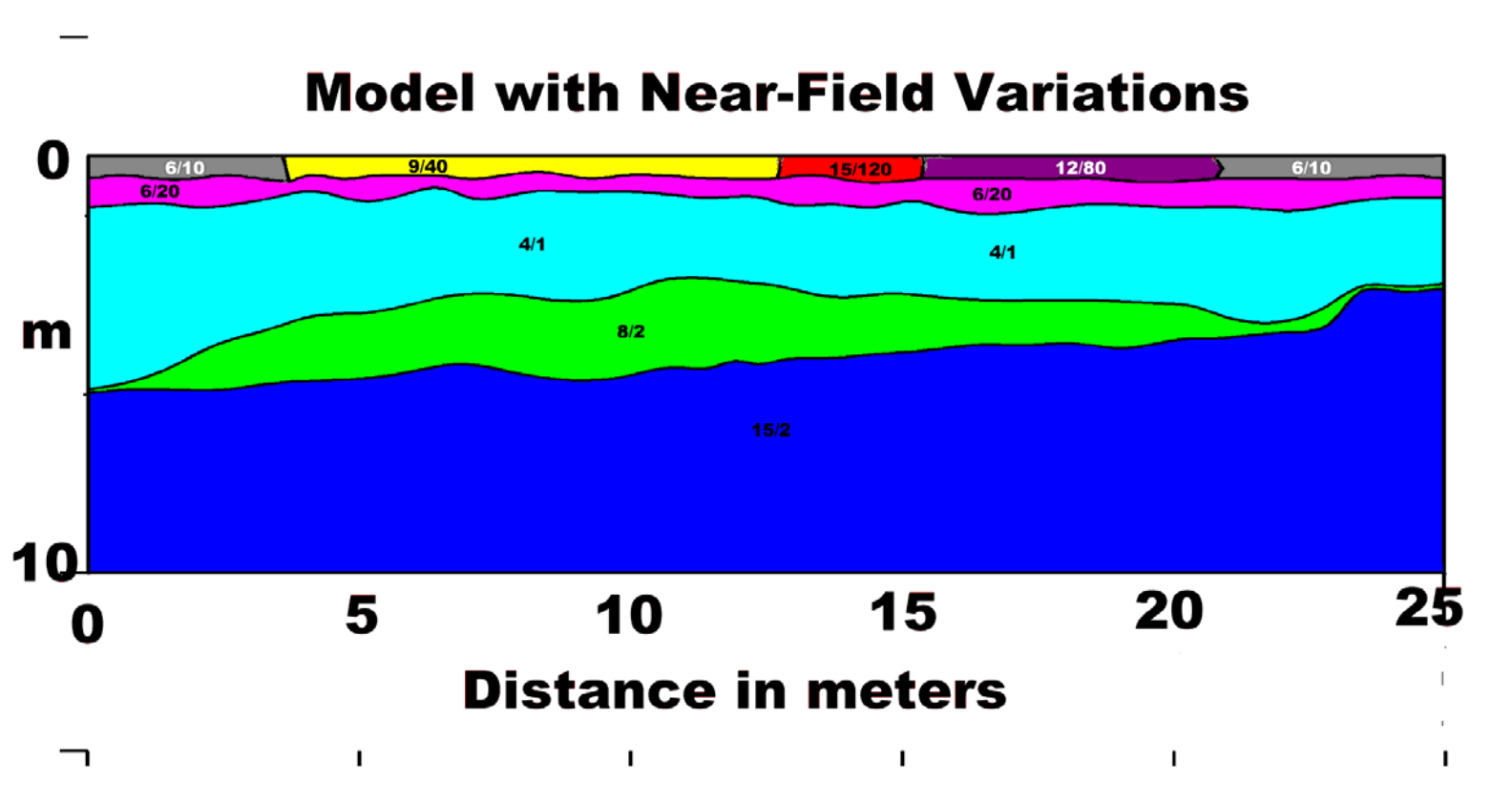


This earth model is used to illustrate effects of changes in relative dielectric permittivity (RDP) and conductivity on GPR signals. The first number in the pairs is RDP, and the second is conductivity in mS/m.

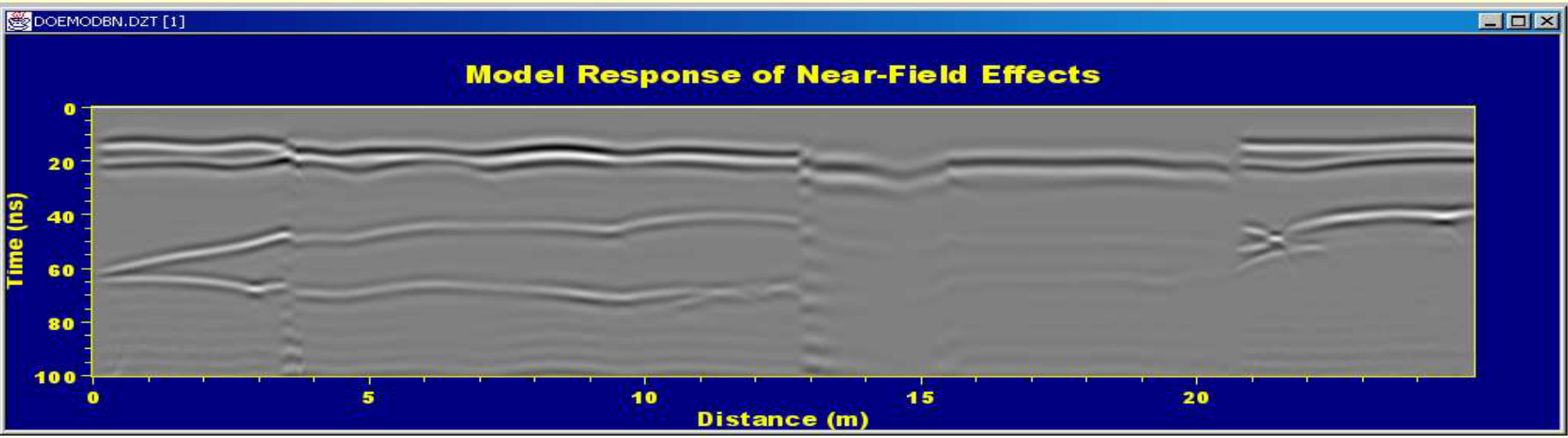


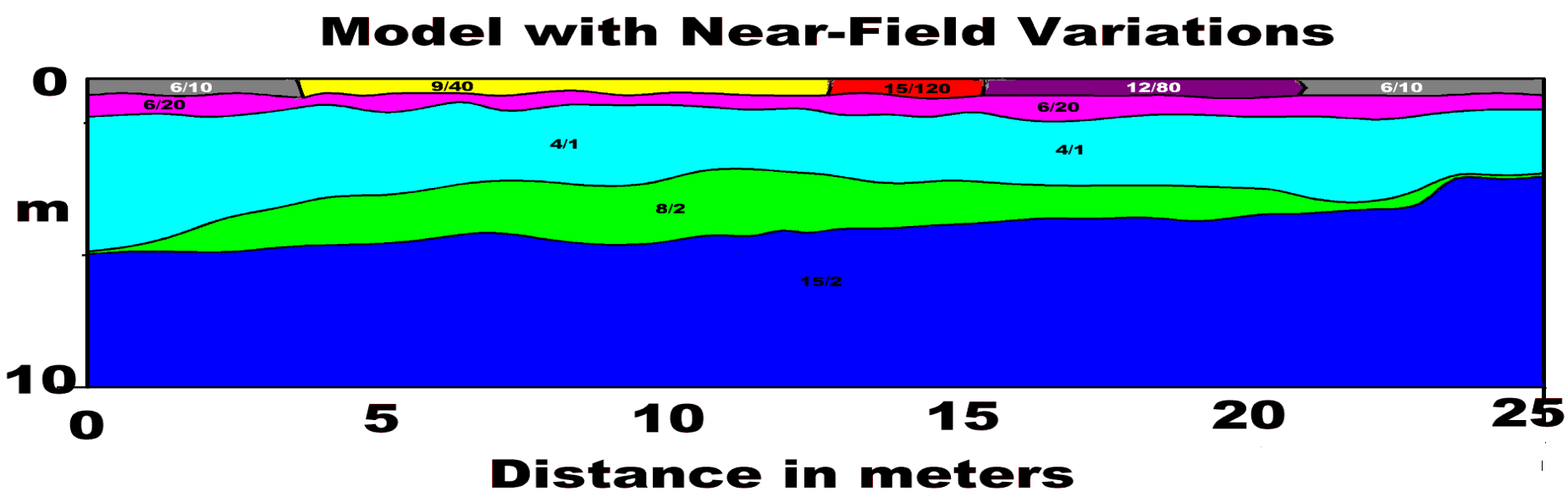
The waveforms below are estimates of the radiated output of a 200 MHz antenna when coupled to the properties of the earth as shown. Amplitudes are normalized, so do not show actual values. FDTD-derived wavelets will improve accuracy.





Model response shows the effects of the changing near field on the far field response, i.e., GPR profiles as commonly acquired. Note that the strong lateral changes shown in this response are due to near-surface property variations.





GPR data processing enhancements

- Determine the laterally changing input wavelet.
  - Must characterize the antennas, driving pulse and coupling as a function of near surface.
- Remove the changing wavelet effect.
  - Standard seismic processing makes assumptions that may not be valid.

Progress and Directions

- Have acquired a fast waveform digitizer/averager (Aqiris AP200) and written data acquisition program in LabView for the AP200.
- Are testing two competing strategies for electronic receiver dynamic range enhancement.
- Are modeling possible antenna geometries with FDTD as an aid to design.
- Are calculating transmitted wavelet as a function of near surface coupling as an enhancement for modeling.
- Our plan is to model several geometries and estimate the effectiveness of embedded current sensors in the transmitting antenna as an aid to accurate determination of the transmitted wavelet.
- We will then build antennas and complete a system.
- Input waveform information will be used to improve processing, such as deconvolution and migration.