RADAR SIMULATION

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OUTLINE

- A Bit of History & Motivation
- Differences between Light and Radar
  - Wave effects
- Radar Transport Equation
- Results
- Conclusion

MOTIVATION

Radar Simulation

MOTIVATION

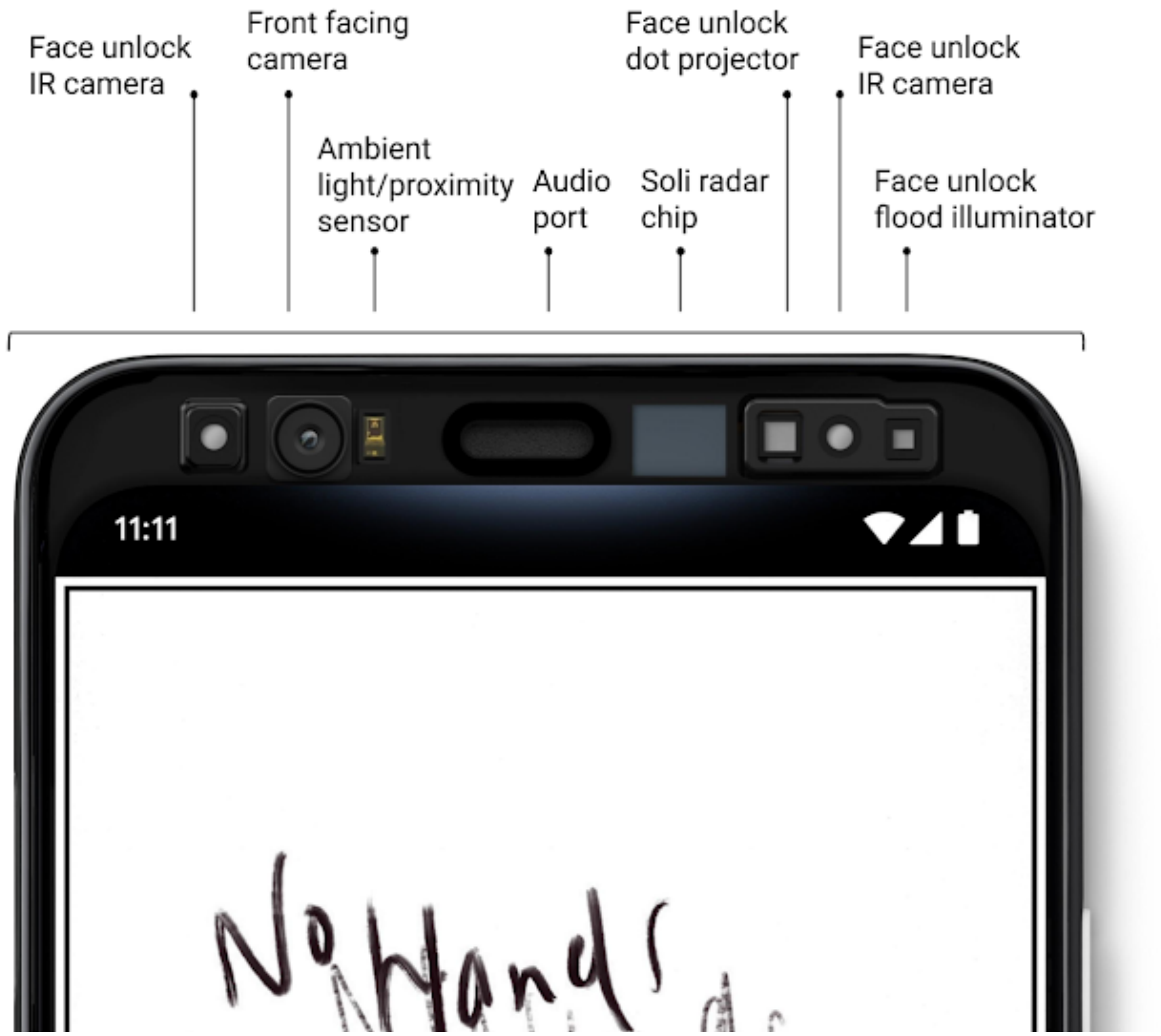
- Radar (*Radio Detection and Ranging*) is a technique to measure the position and velocity of objects
- Based on sending *Radio Waves* (i.e., *Electromagnetic Radiation*) and listening for the echo
- Its origins can be traced back to *Heinrich Hertz* in the late 1880s
- Initial research was conducted by militaries of multiple countries in the 1930s
- Many other uses for Radar have since been found, for instance…

MOTIVATION

Marcelo via Pixnio, Radar Air Traffic Control

- Radar has become an indispensable tool for airborne surveillance since the 1950s

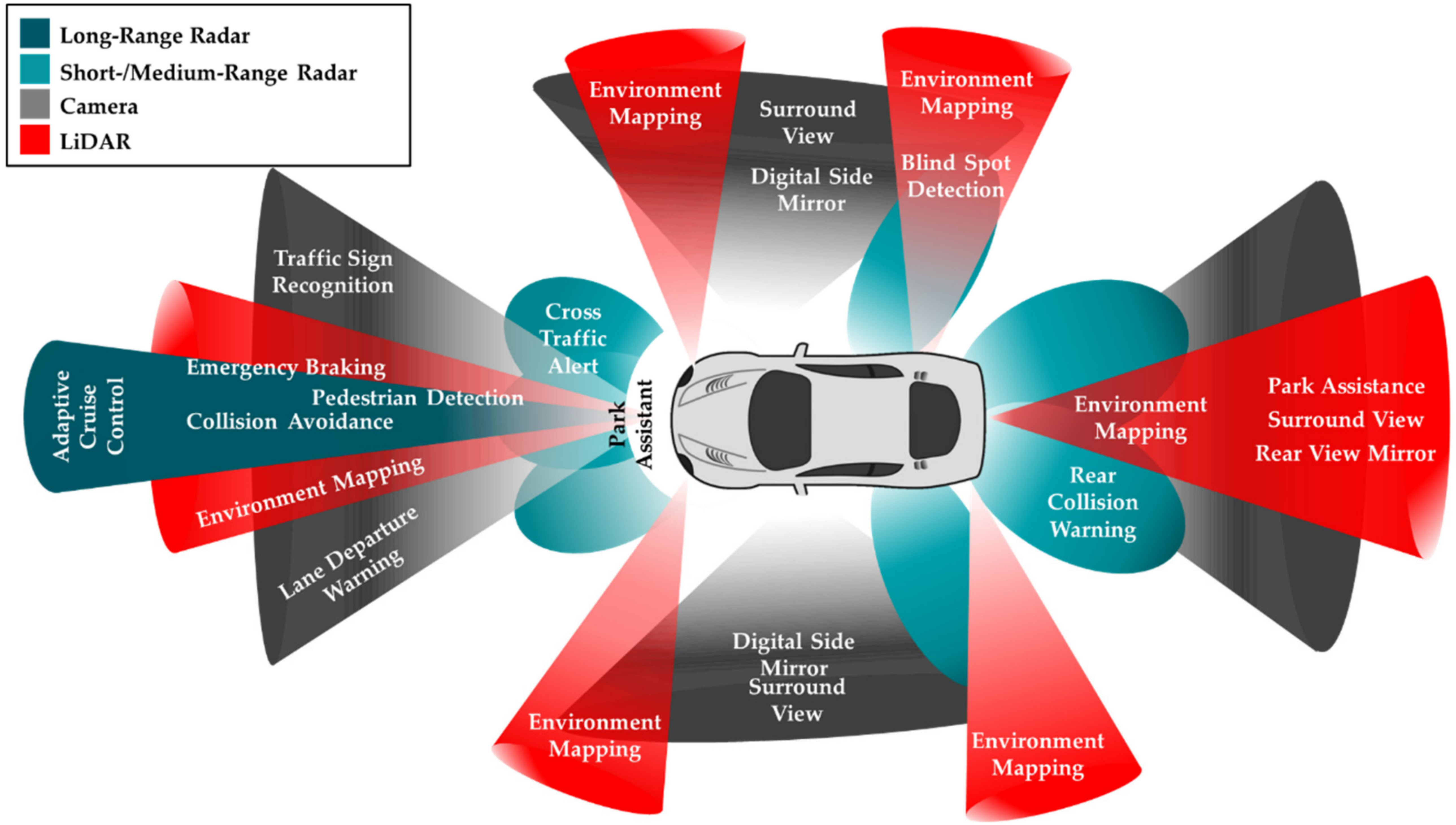
MOTIVATION



Lien et al., 2020, Soli Radar-Based Perception and Interaction in Pixel 4

- But Radar technology can also be found in every-day devices like smartphones

MOTIVATION



Wendt et al., Vehicle Awareness in the Self-Driving Age, 2019

- Most interesting for us, however, is the use of Radar in autonomous driving vehicles

MOTIVATION

- But why simulate Radar?
  - Autonomous Driving algorithms need **a lot** of data for training, validation, etc.
  - We cannot (and in many cases do not want to) capture all this data
- Here the idea of *Virtual Reality* comes to the rescue
  - Already well established for LIDAR and cameras
  - Not so well established for Radar

➡ <u>Can we solve this with techniques from Light Transport Simulation?</u>

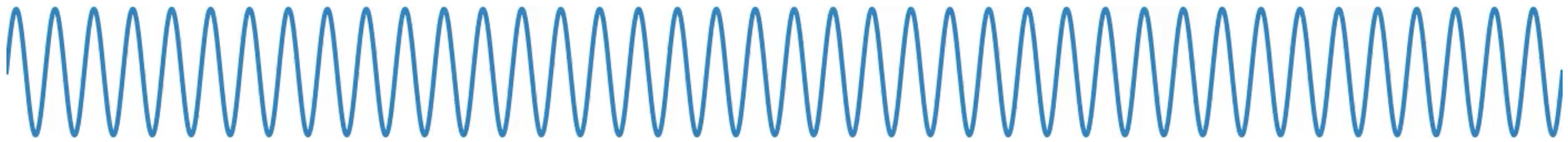
DIFFERENCES BETWEEN LIGHT AND RADAR

Radar Simulation

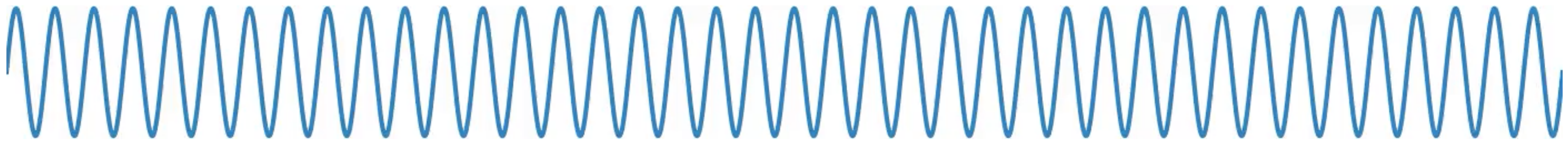
DIFFERENCES BETWEEN LIGHT AND RADAR

- Light and Radar are both *electromagnetic radiation*

Light



Radar



however…

- The wavelength of Radar is $\sim 10^4$ as long (→ *Diffraction, Doppler*)
- Radar is emitted coherently (→ *Interference*)
- Radar is strongly polarized (→ *Polarization*)

WAVE EFFECTS

Differences between Light and Radar

INTERFERENCE

- Arguably the most important wave effect of all
- Happens when waves overlay each other (waves can also self-interfere when they can take paths of different lengths)

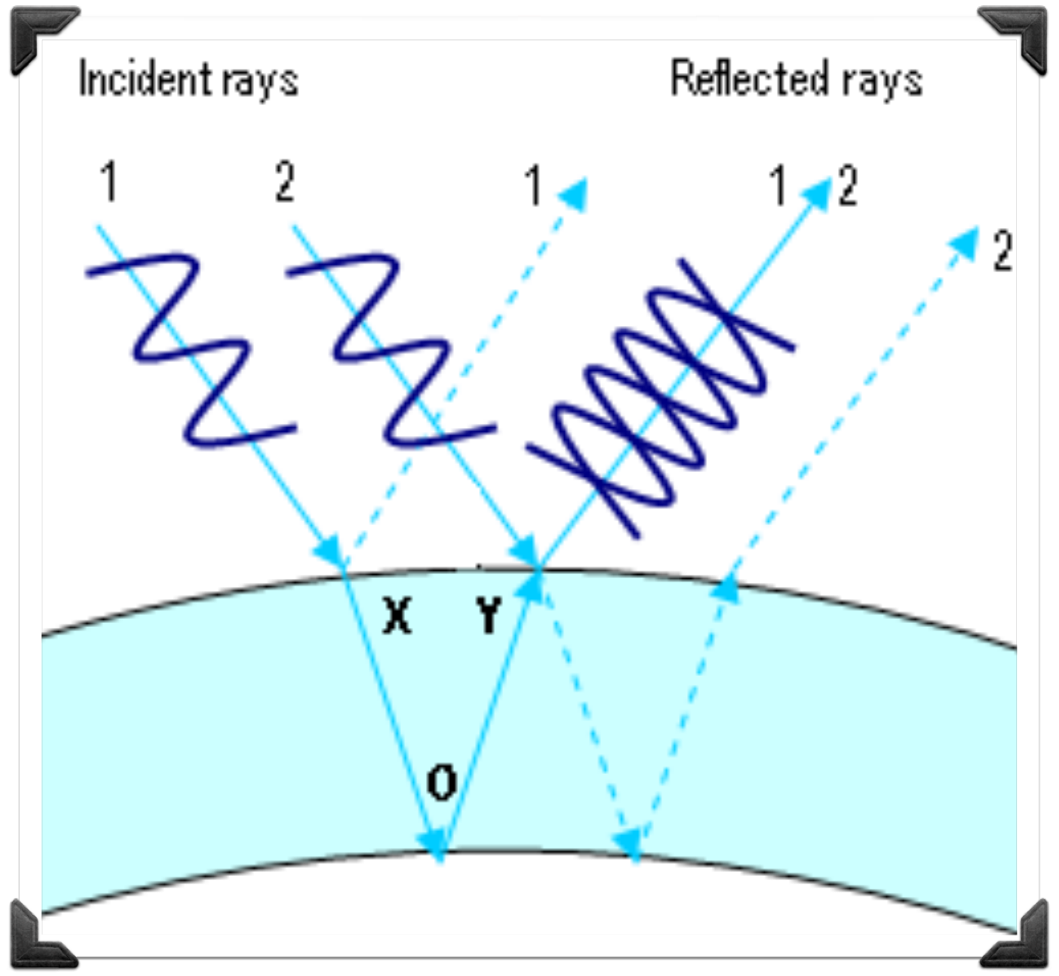
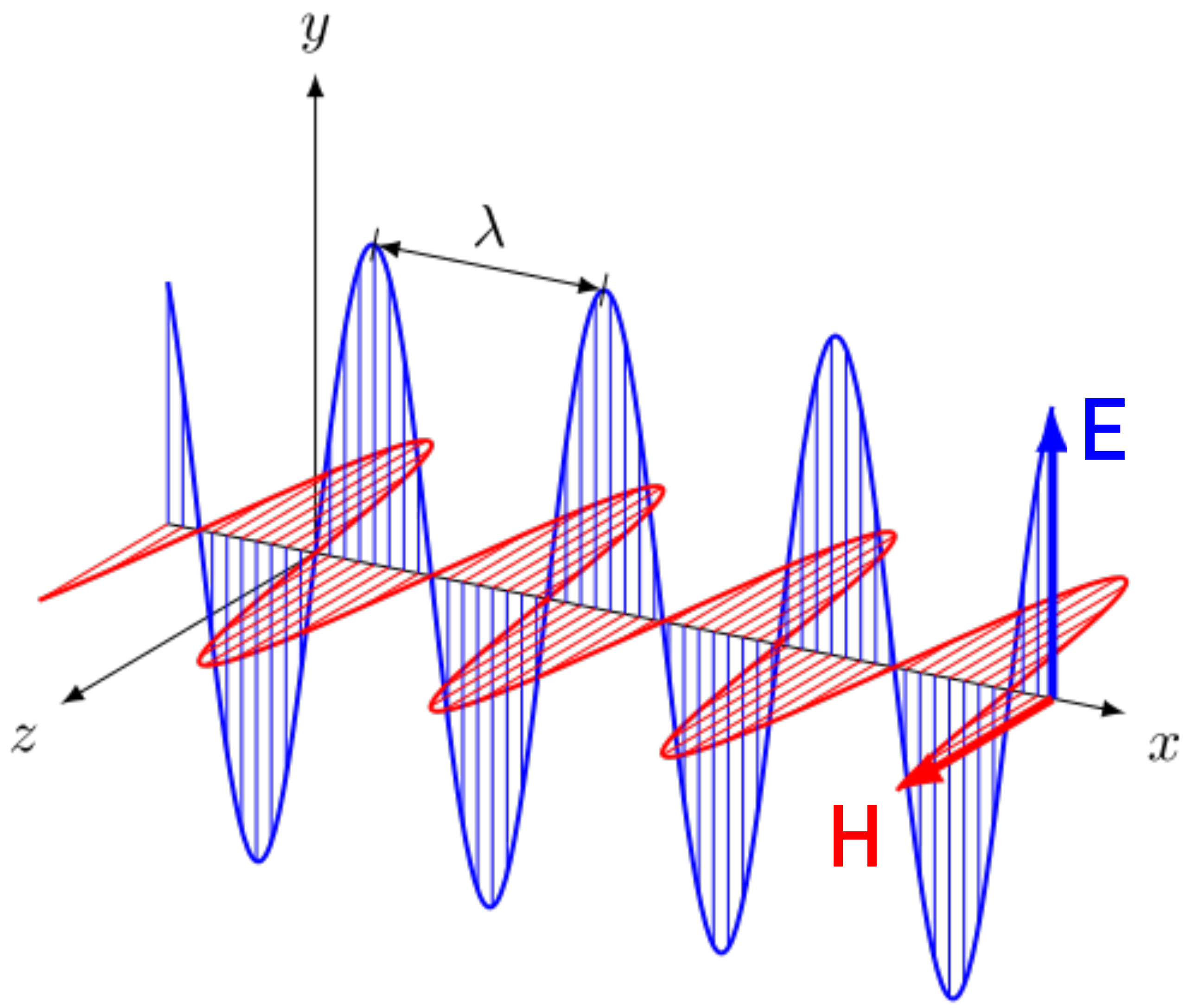


Image courtesy of Saperaud~commonswiki

- Typically not important for light transport, since the phase relation between the wave and its time shifted version is random

POLARIZATION

- Very important for accurate simulation of interference
- EM waves have an orientation in space



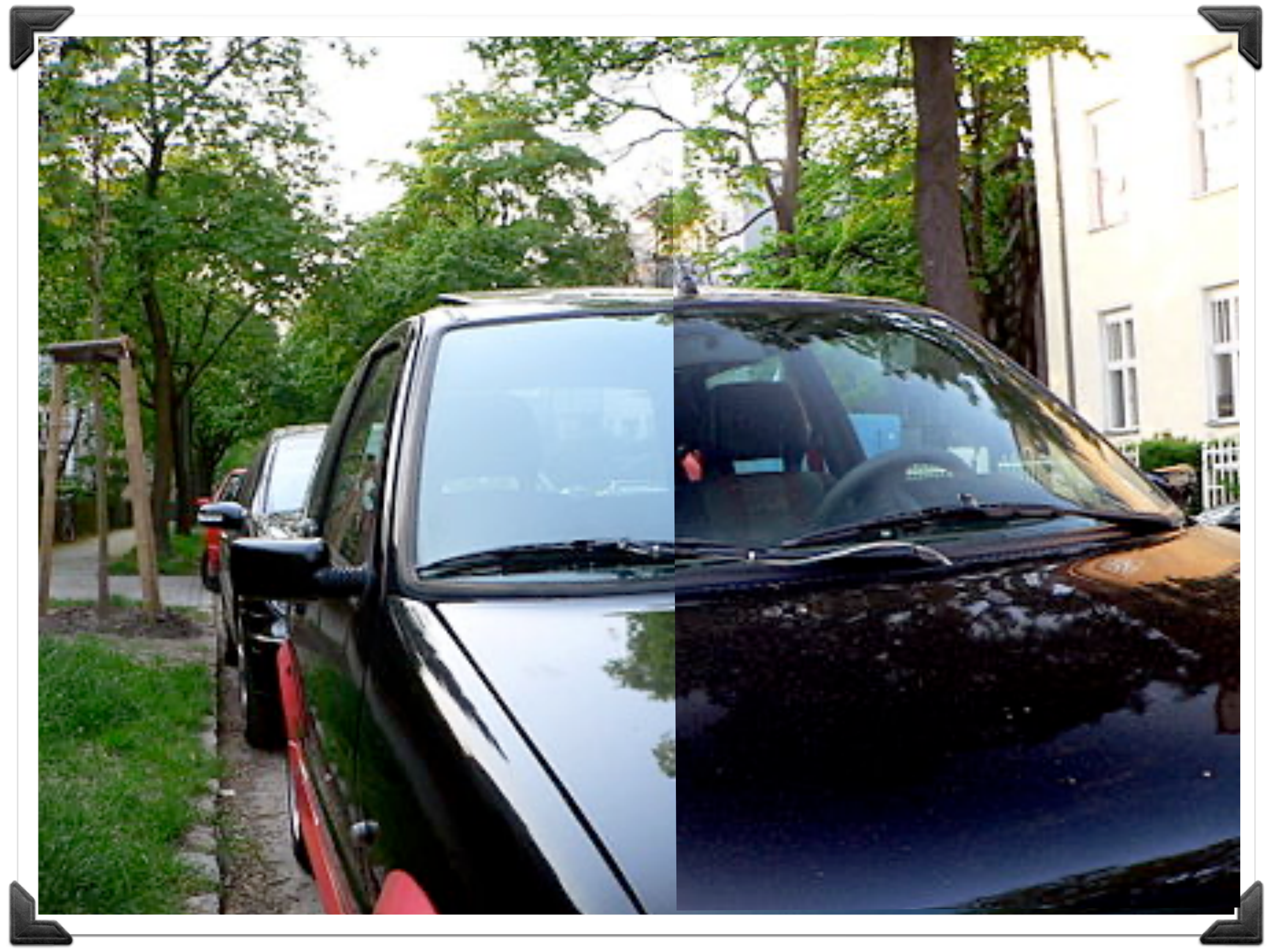


Image courtesy of Florian Lindner (Wikimedia Commons)

- *Electric field* **E**, *magnetic field* **H**, and propagation direction are orthogonal
- Most light sources emit "unpolarized light" (i.e. the orientation keeps changing randomly, similar to how the phase changes randomly)

DOPPLER EFFECT

- Happens when there is a relative movement between sender and receiver or when a reflection object moves

- Typically unnoticeable for visible light (you would need to travel at very high speeds)
- Relevant for some kinds of Radar sensors though

DIFFRACTION

- Typically the hardest effect to simulate, but very important
- Occurs because of discontinuities in reflections
  (i.e., every edge and corner causes diffraction)


Image courtesy of u/Kafshak

- Important when objects are small relative to the wavelength

RADAR TRANSPORT EQUATION

Radar Simulation

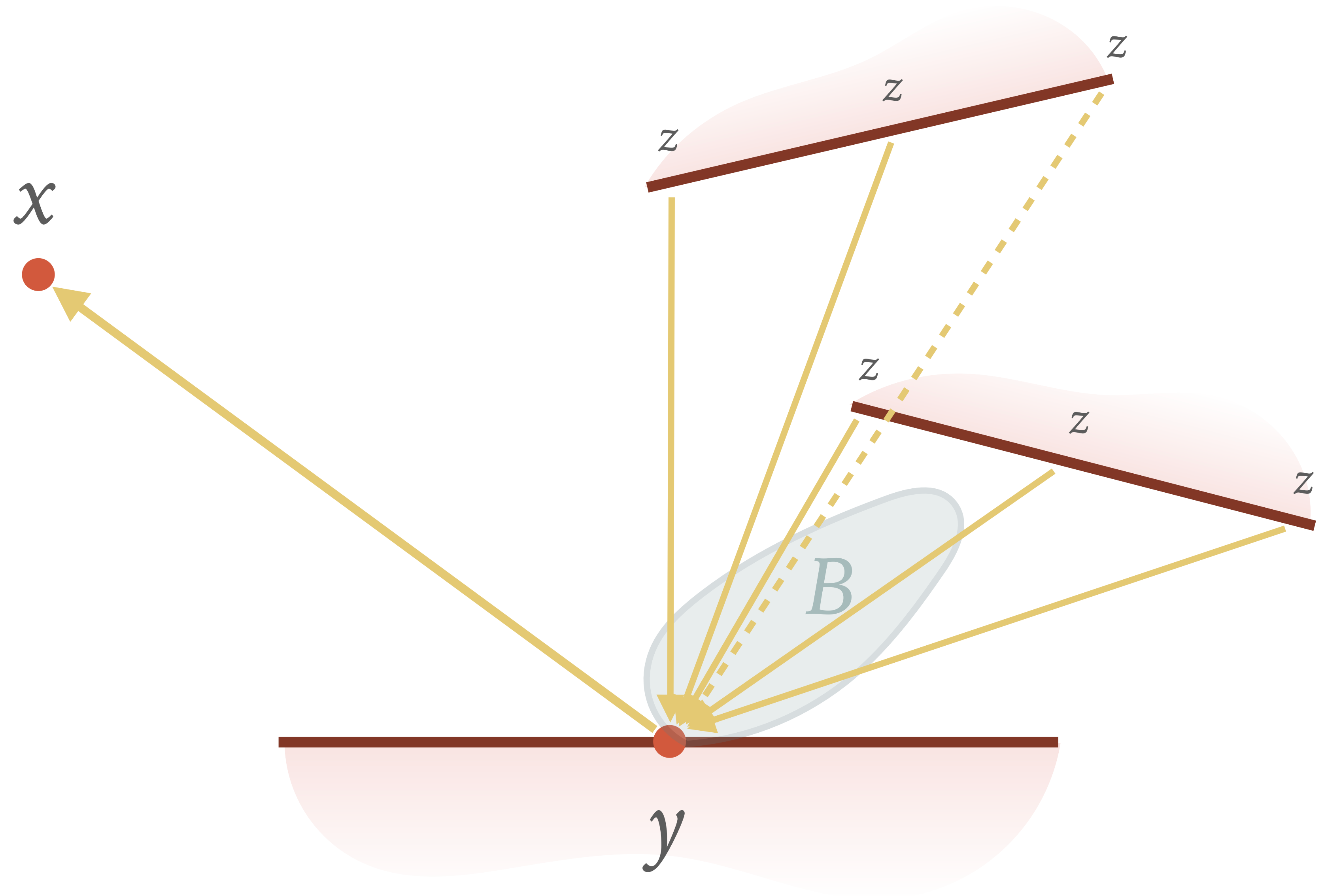
RADAR TRANSPORT EQUATION

- Some assumptions that the Light Transport Equation makes are unfortunately violated in the Radar context
- In the following, we will replace those with different assumptions that are more general and simulate wave effects
- Keep in mind that all physical models are always a tradeoff between accuracy and convenience/performance
  - You could for example use the equations we will derive for Light Transport, but it would be terribly slow

RADAR TRANSPORT EQUATION

- Let us see how the familiar *Light Transport Equation* (LTE) can be adapted to Radar

$$L_o(y \to x) = L_e(y \to x) + \int_A B(z \to y \to x) \cdot L_o(z \to y) \cdot G(y \leftrightarrow z) \cdot V(y \leftrightarrow z)\, \mathrm{d}z$$



RADAR TRANSPORT EQUATION

- The LTE assumes that radiance behaves linearly, i.e.

$$L_{total} = \sum_i L_i$$

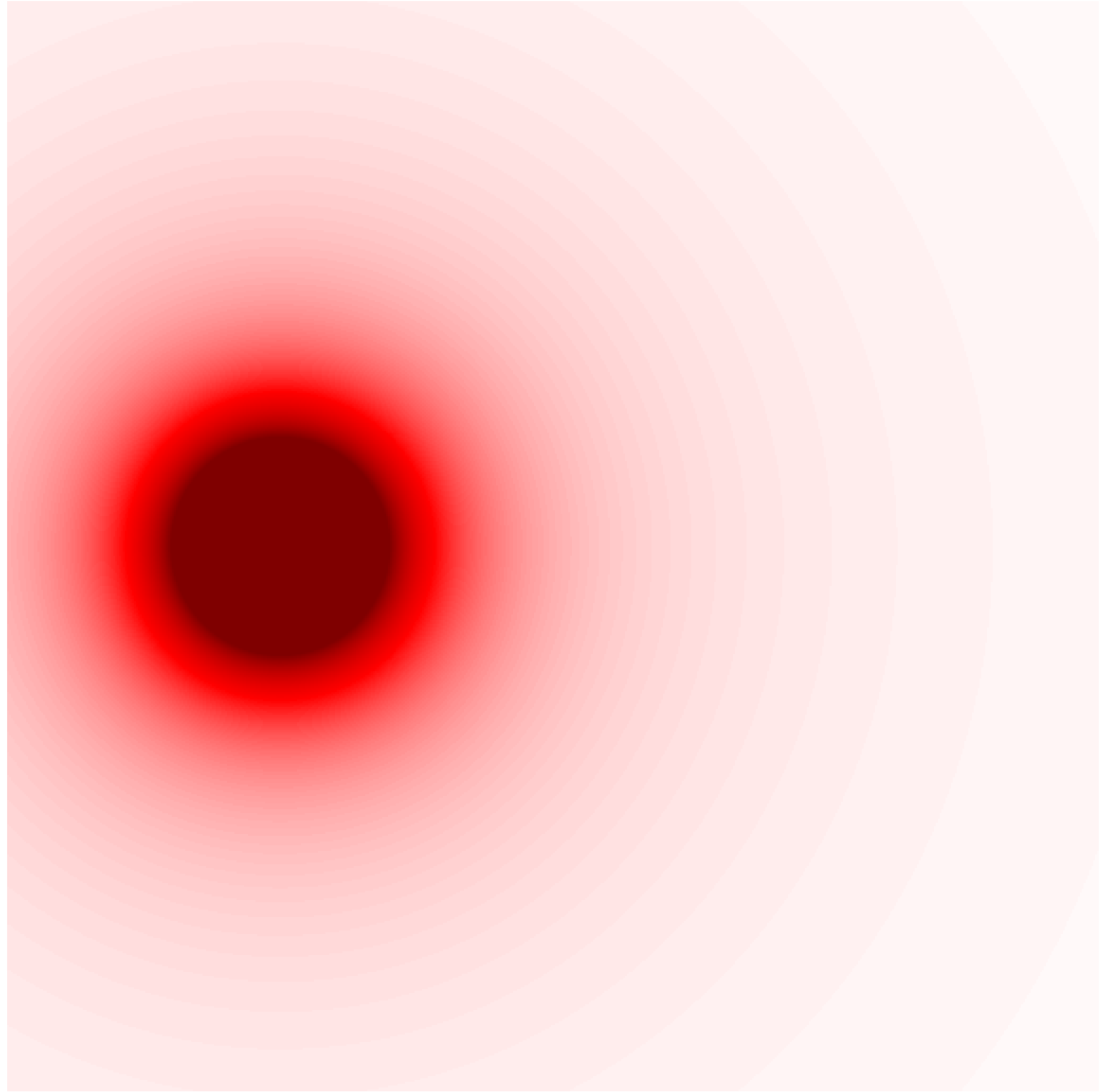
- Since radiance is proportional to the electric field squared:

$$\left|E_{total}\right|^2 = \sum_i \left|E_i\right|^2$$

- This works as long as the electric fields are uncorrelated, but to allow for interference we will need a more accurate model:

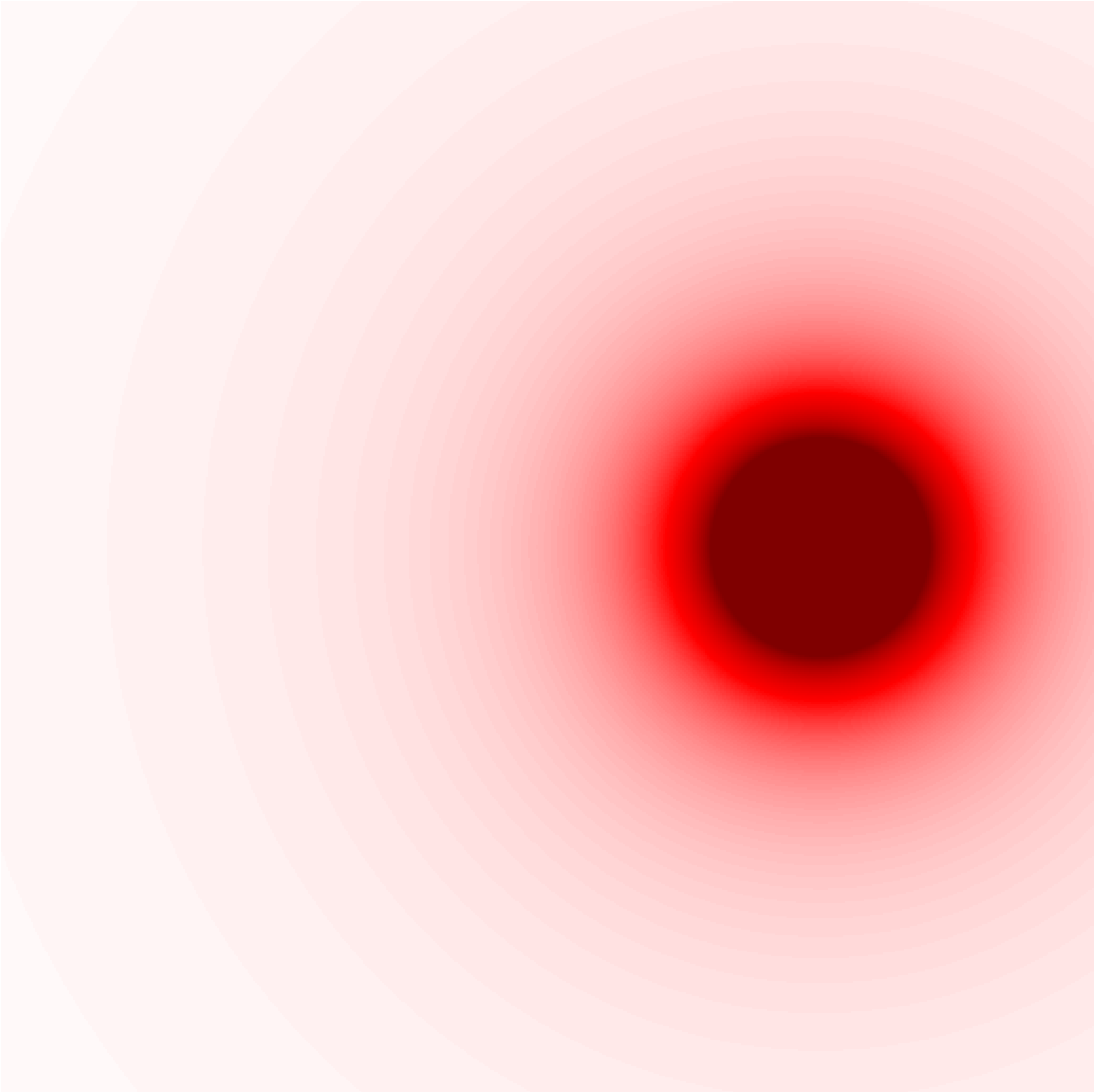
$$E_{total} = \sum_i E_i$$

INTERFERENCE



Left light source

INTERFERENCE

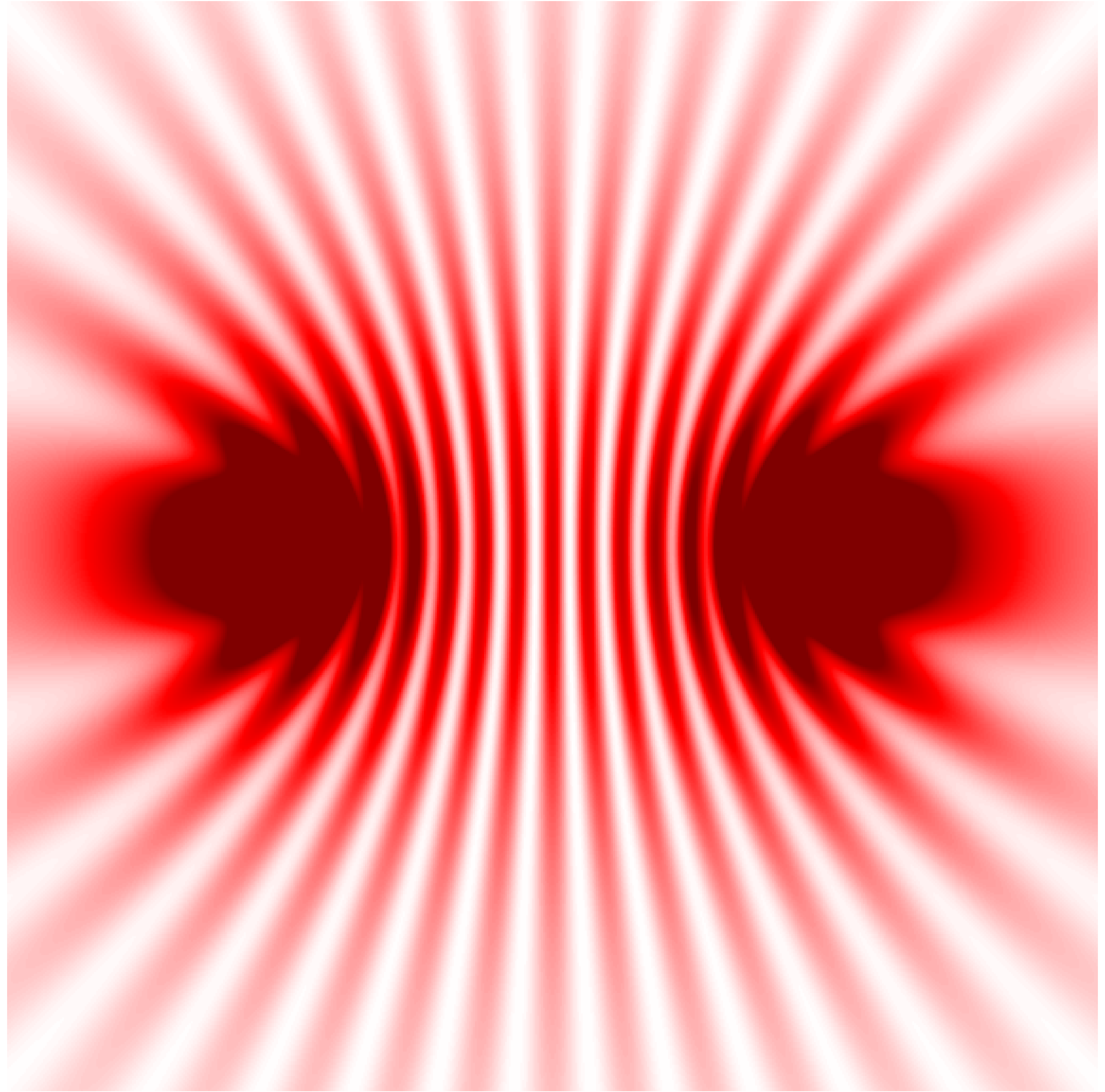


Right light source

INTERFERENCE

Incoherent addition

INTERFERENCE



Coherent addition

INTERFERENCE

RADAR TRANSPORT EQUATION

- Replacing *radiance* with *electric fields* gives us:

$$E_o(y \to x) = E_e(y \to x) + \int_A B(z \to y \to x) \cdot E_o(z \to y) \cdot G(y \leftrightarrow z) \cdot V(y \leftrightarrow z) \, \mathrm{d}z$$

- Note that this means we are not working with non-negative reals $\mathbb{R}^+$ anymore, but rather with complex numbers $\mathbb{C}$
- Why complex numbers?
  - They allow us to neatly keep track of the information that constitutes a wave: *amplitude* and *phase*
  - Other representations are possible, but are usually less convenient for calculations

THE GEOMETRY TERM FOR RADAR

- Remember that the geometry term in the LTE is defined as:

$$G(y \leftrightarrow z) = \frac{\cos(\angle(y, n_y)) \cdot \cos(\angle(z, n_z))}{\left| y - z \right|^2}$$

- When working with fields, however, this becomes:

$$G(y \leftrightarrow z) = \frac{1}{4\pi \left| y - z \right|} \cdot e^{-jk\left| y - z \right|}$$

- There are some interesting differences here:
  - No *inverse square law* (since radiance was field squared)
  - No *cosines* (we simulate *interference* and *polarization* properly)
  - The exponential function advances the phase of the wave

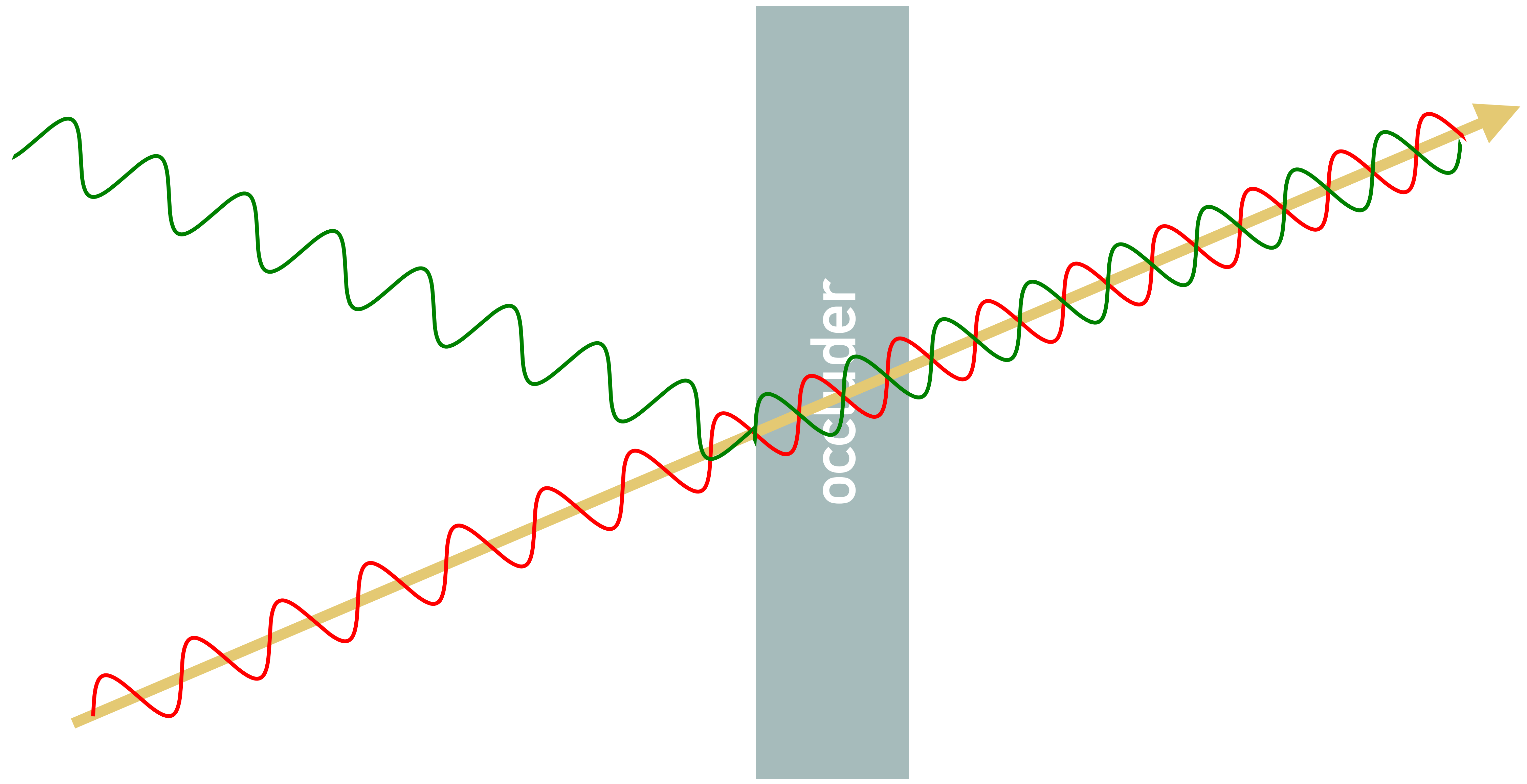
RADAR TRANSPORT EQUATION

- Last but not least, we will also need to get rid of V:

$$E_o(y \to x) = E_e(y \to x) + \int_A B(z \to y \to x) \cdot E_o(z \to y) \cdot G(y \leftrightarrow z)\, \mathrm{d}z$$

- This seems to suggest that waves can just travel through obstacles without ever being stopped!
- Luckily, that is not the case: shadows are a side effect of interference, and since we are simulating interference, we are also getting shadows for free!
- Let me give you an example why this works…

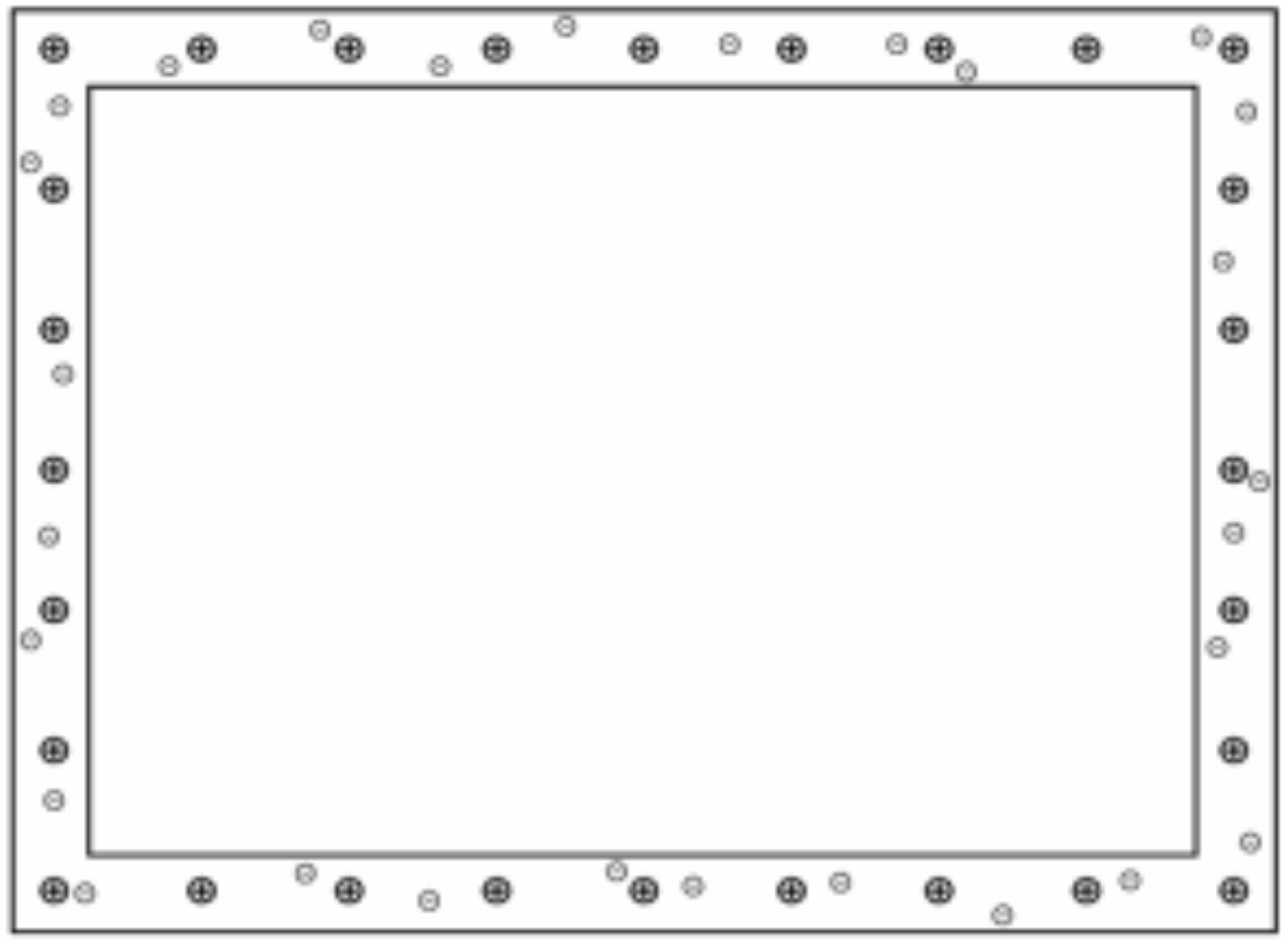
SHADOW AS A SIDE EFFECT OF INTERFERENCE



- For perfect conductors, the original and backscattered field are 180° out of phase and cancel completely
- Interesting things happen when they do not perfectly cancel:
  - Exponential decay in media, Refraction, Dispersion, …

SHADOW AS A SIDE EFFECT OF INTERFERENCE

- By the way, this is the *electrodynamic* pedant to how an *electrostatic* Faraday cage works:



Animation courtesy of Stanisław Skowron (Wikimedia Commons)

POLARIZATION FOR RADAR

- Now that *interference* is included, let us work on *polarization*
- For this, we only need to upgrade our electric fields from scalars ($\mathbb{C}$) to vectors ($\mathbb{C}^3$)

$$\overrightarrow{E}_o(y \to x) = \overrightarrow{E}_e(y \to x) + \int_A B(z \to y \to x) \cdot \overrightarrow{E}_o(z \to y) \cdot G(y \leftrightarrow z)\, \mathrm{d}z$$

- This is a lot simpler than how polarization is usually simulated in Light Transport (using *Stokes vectors*), because we do not need to model unpolarized light
- We need to address the *BSDF* though...

BSDFS FOR RADAR

- We are going to keep things simple for now by sticking to the assumption that materials behave linearly (even though *non-linear optics* is definitely an exciting research field!)
- To add support for polarization, we will need to upgrade our BSDF from $\mathbb{R}^+$ to a full matrix $\mathbb{C}^{3\times3}$

$$\vec{E}_o(y \to x) = \vec{E}_e(y \to x) + \int_A \mathbf{B}(z \to y \to x) \cdot \vec{E}_o(z \to y) \cdot G(y \leftrightarrow z) \, \mathrm{d}z$$

- Note that material models for BSDFs are also quite different (micro-scale geometry tends to matter less, typically no frequency dependent absorptions, ...)

SENSORS

- Another area where Radar and Light differ is *sensors*
- Cameras capture light intensity for a lot of pixels (typically millions) times a few color channels (typically RGB)
- Radar sensors usually only have very few "pixels" (typically around 4 receiving antennas), but they capture a lot more than just intensity:
    - Each antenna captures an entire spectrum to measure distance (usually 256 channels)
    - Each spectrum is captured multiple times to measure velocity (usually 128 samples)

RESULTS

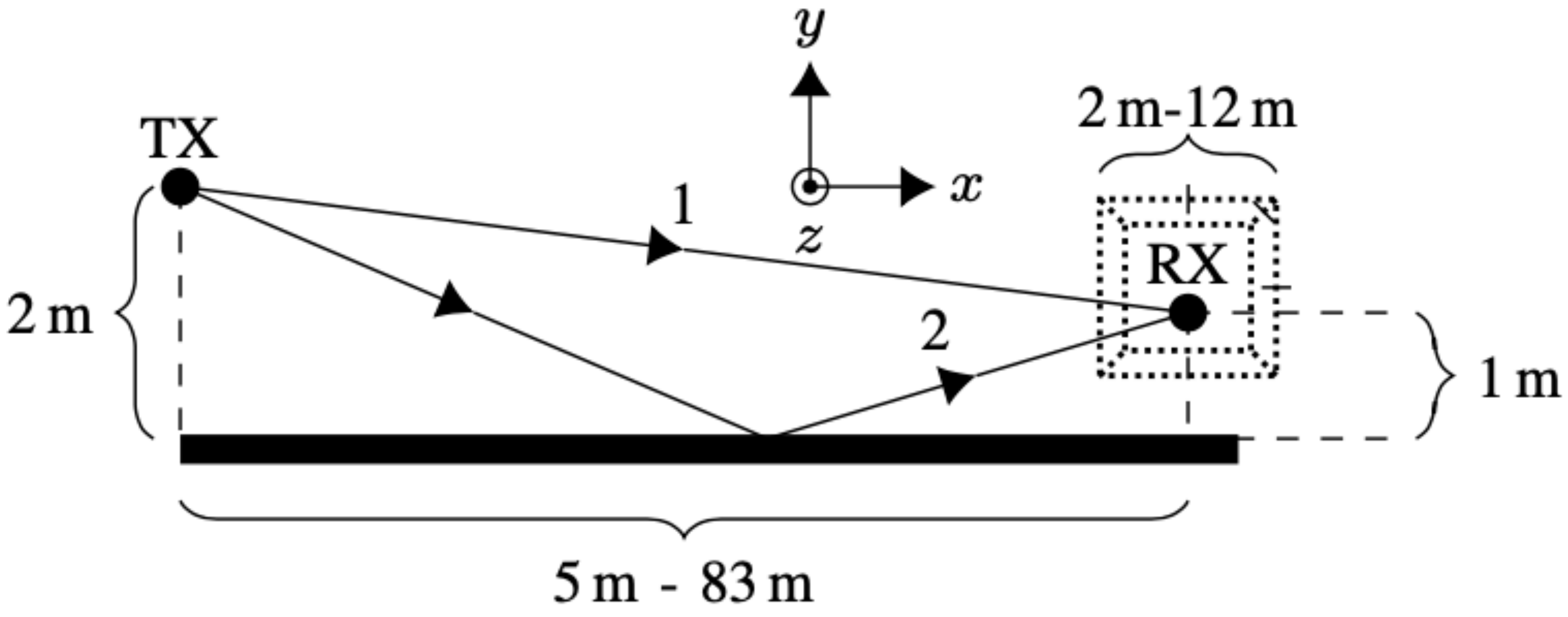
Radar Simulation

RESULTS

- We have used this *Radar Transport Equation* as basis to transfer some popular methods from Light Transport:
  - Path Tracing
  - Texture Filtering
  - Guiding
  - Low Discrepancy Sampling
- In the following, we will show a simple test scene that demonstrates that the improvements from these methods carry over nicely to Radar

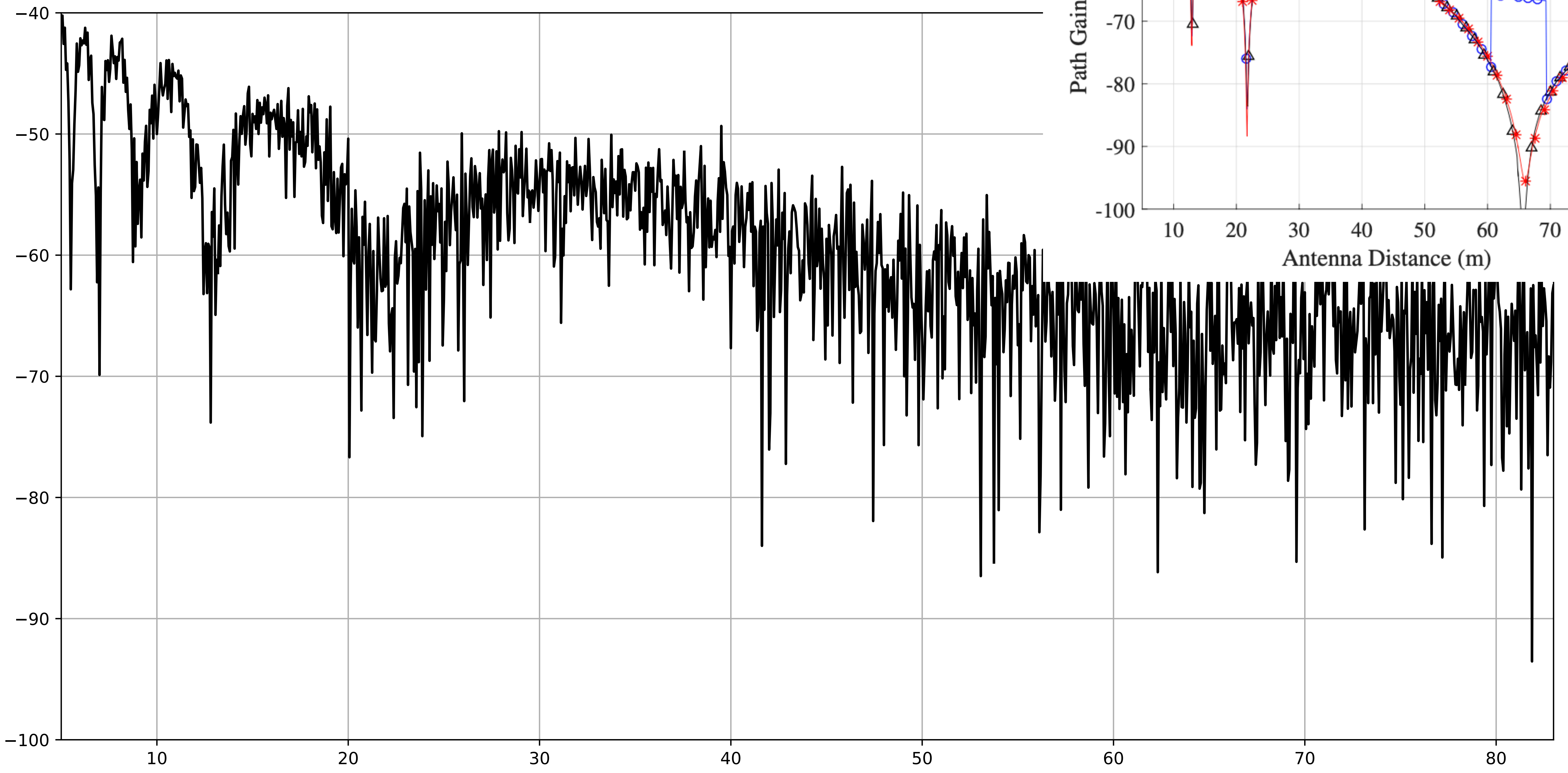
TWO-WAY GROUND REFLECTION

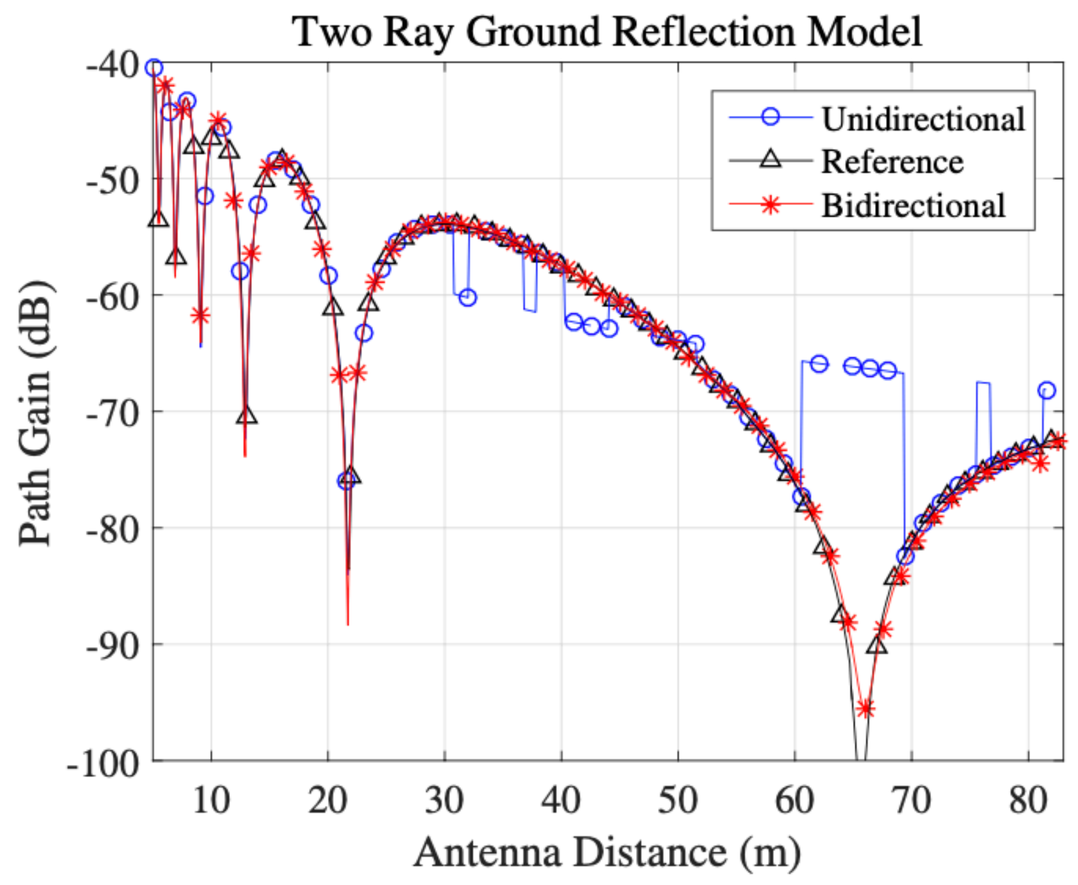
- Let us take a look at a simple Radar test scene:
  a *transmitting antenna* (TX) and a *receiving antenna* (RX) are placed over a *perfect electric conductor* ground plane
- We now vary their distance (from 5m to 83m) and measure how much signal we get at the receiving antenna



Taygur et al. 2018

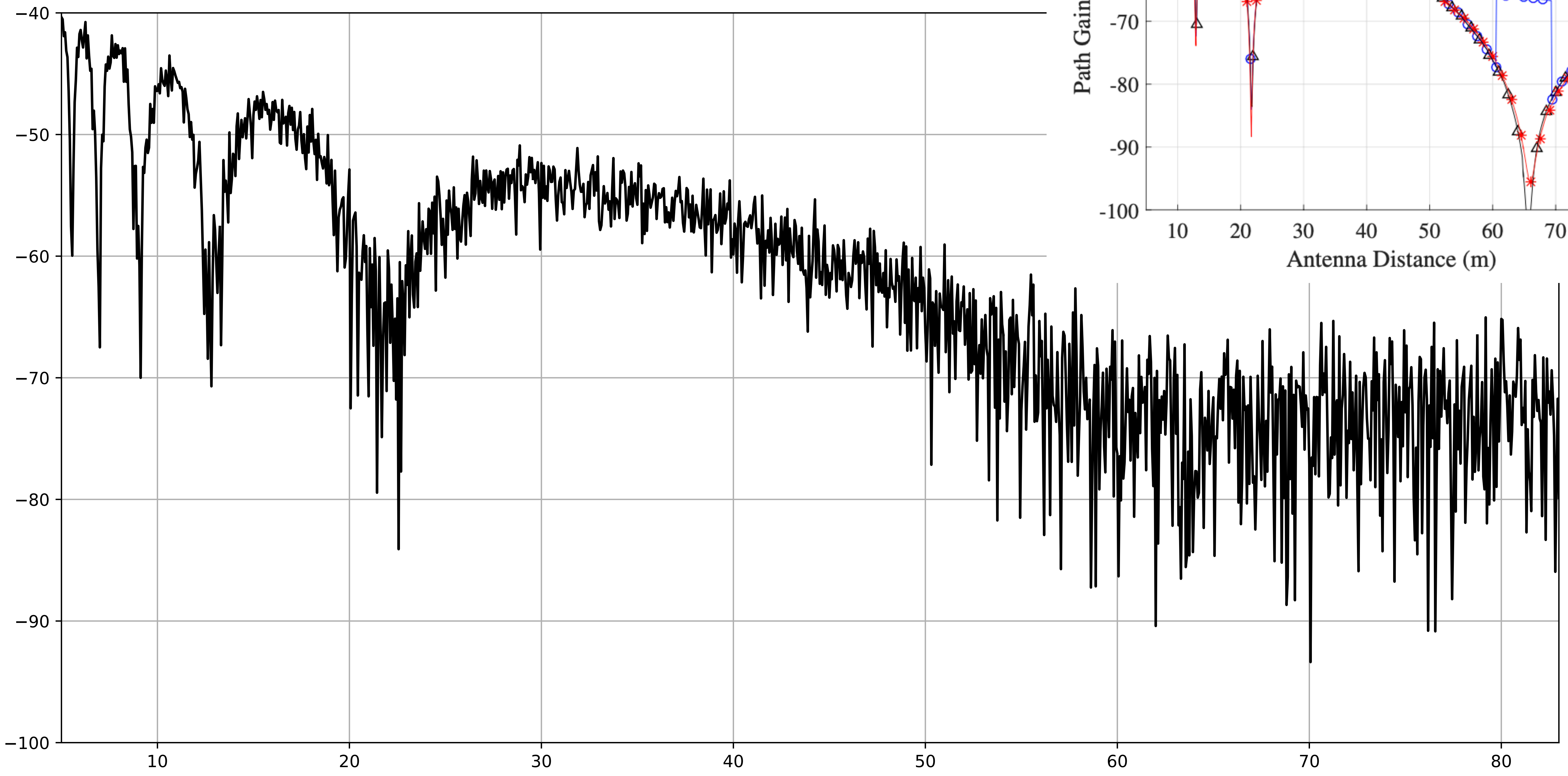
TWO-WAY GROUND REFLECTION

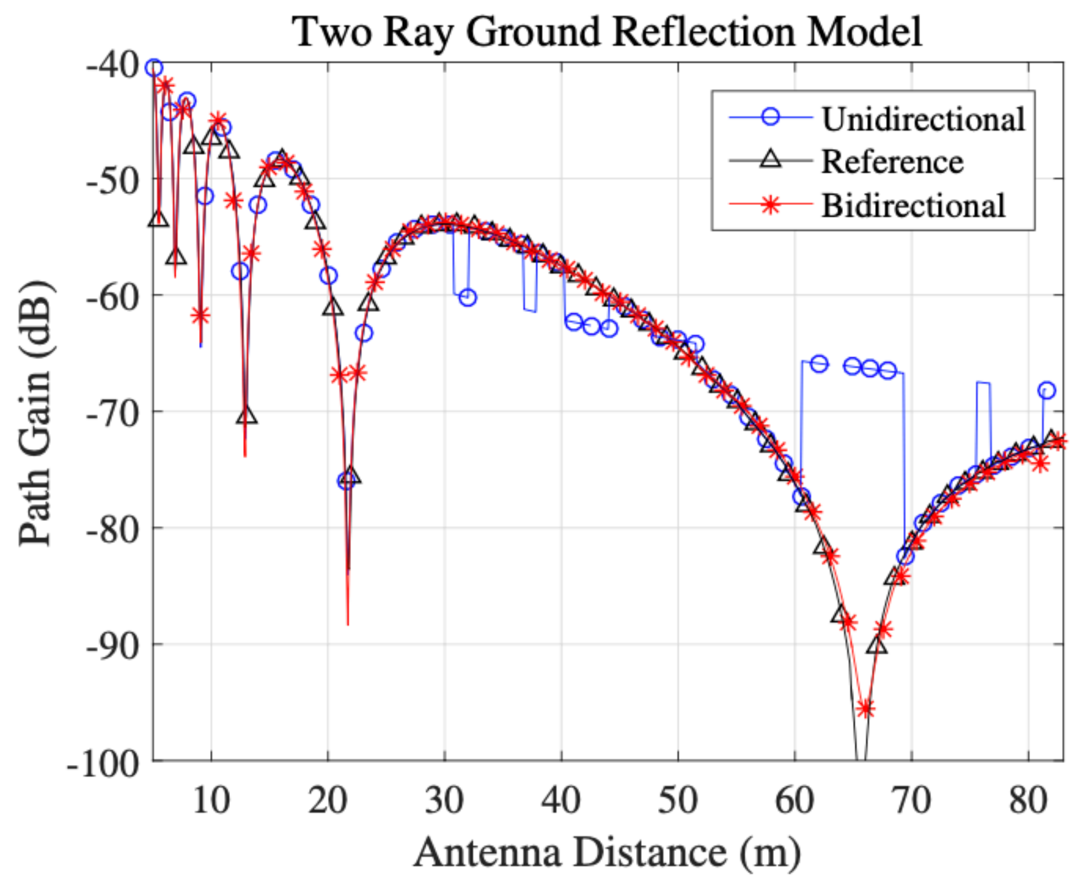




Path Tracing

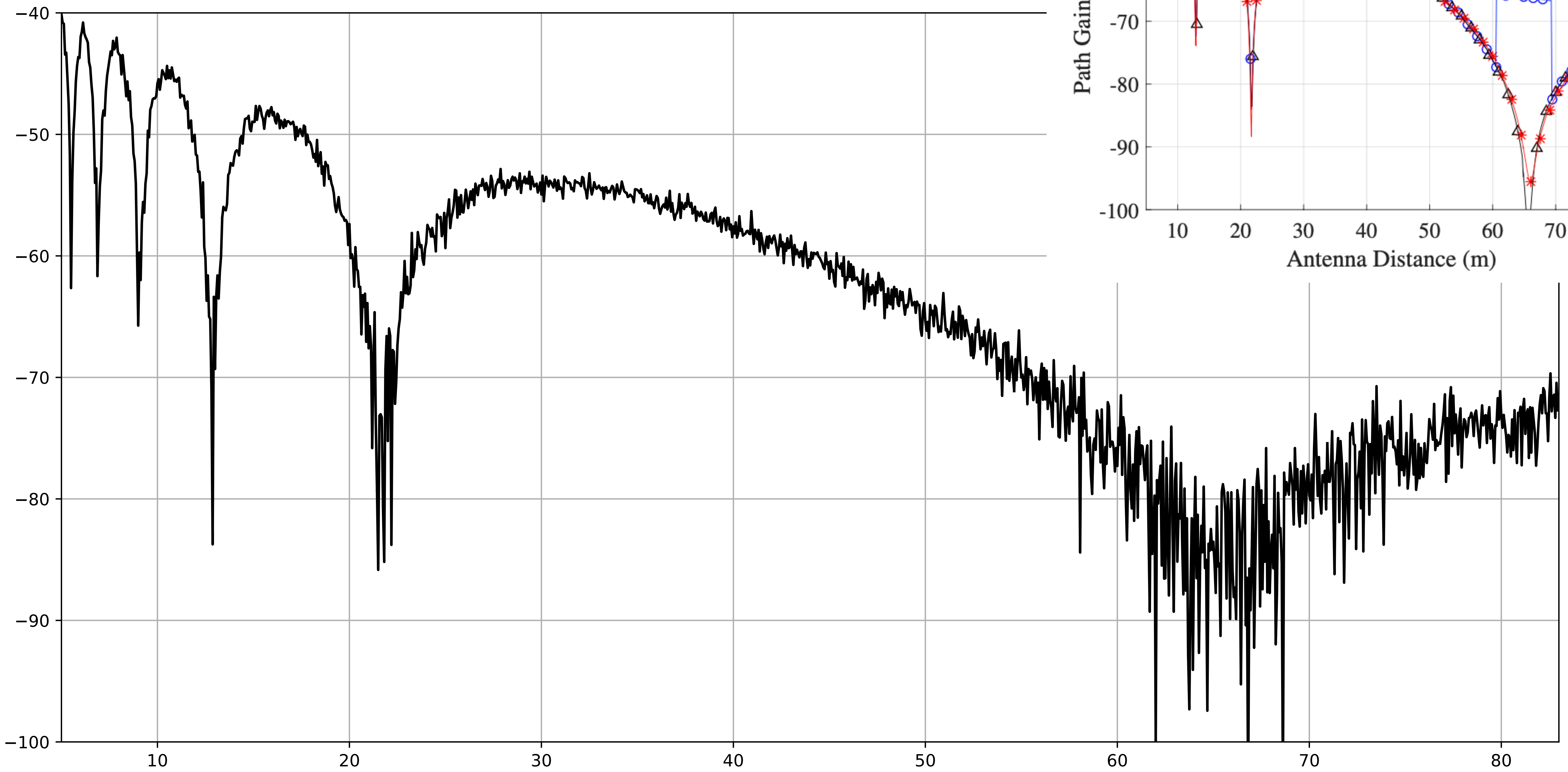
TWO-WAY GROUND REFLECTION

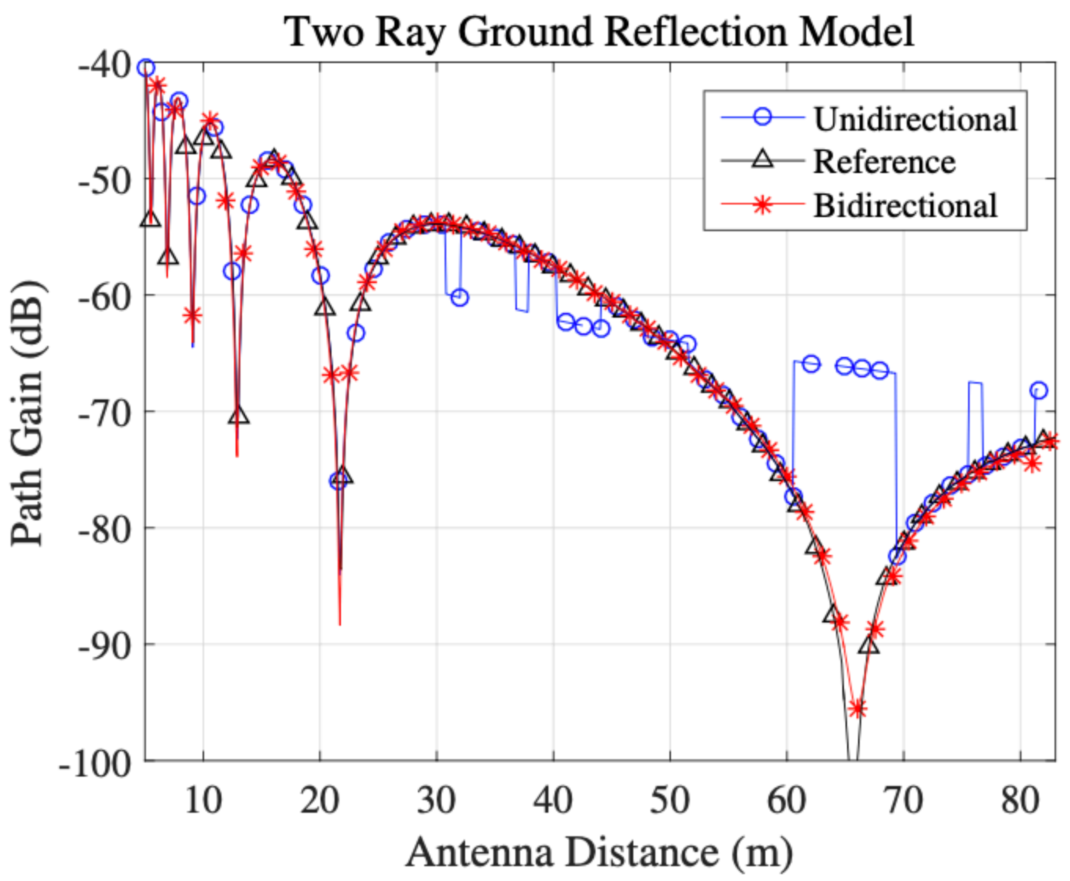




Path Tracing + "Texture Filtering"

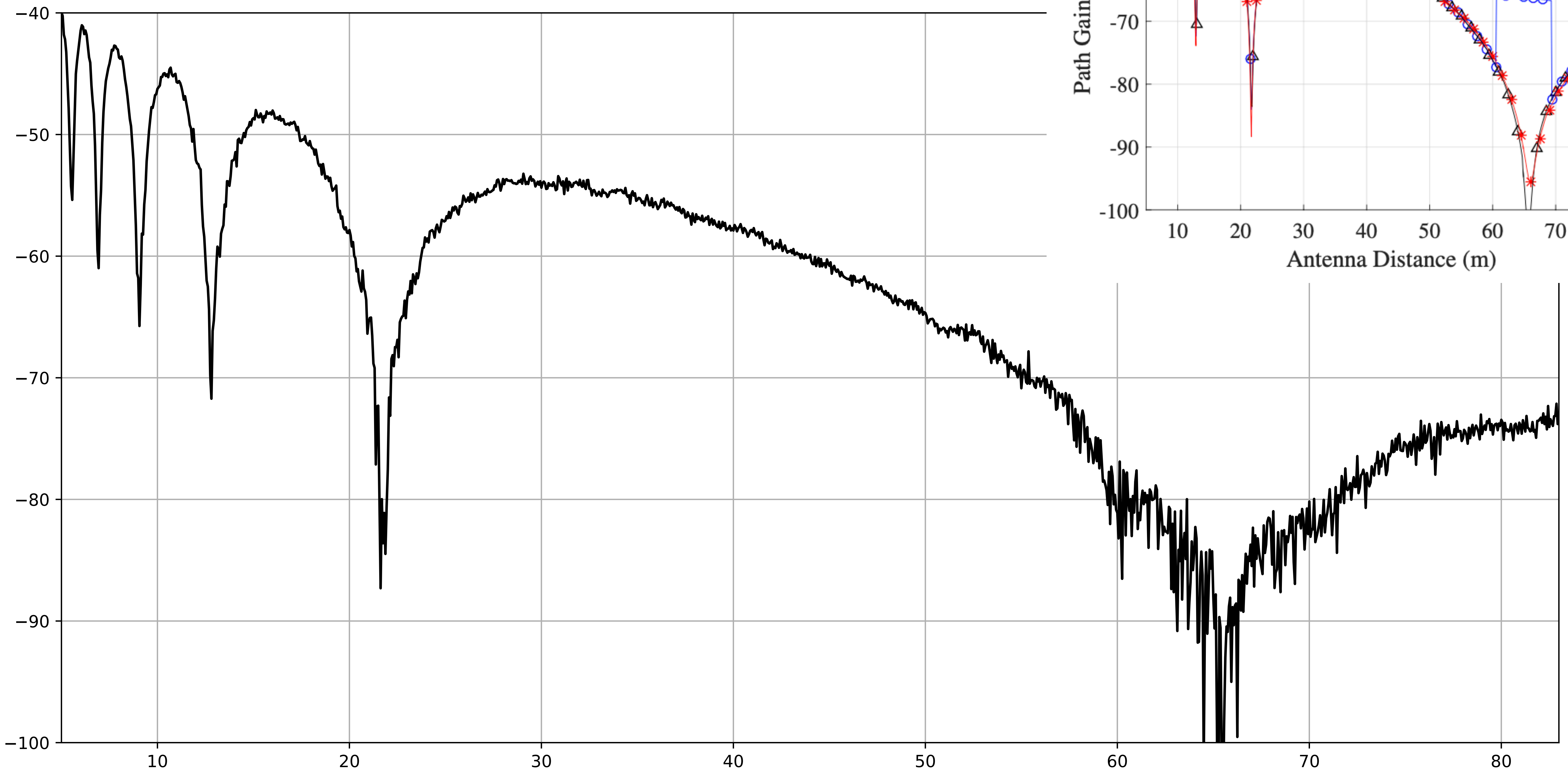
TWO-WAY GROUND REFLECTION

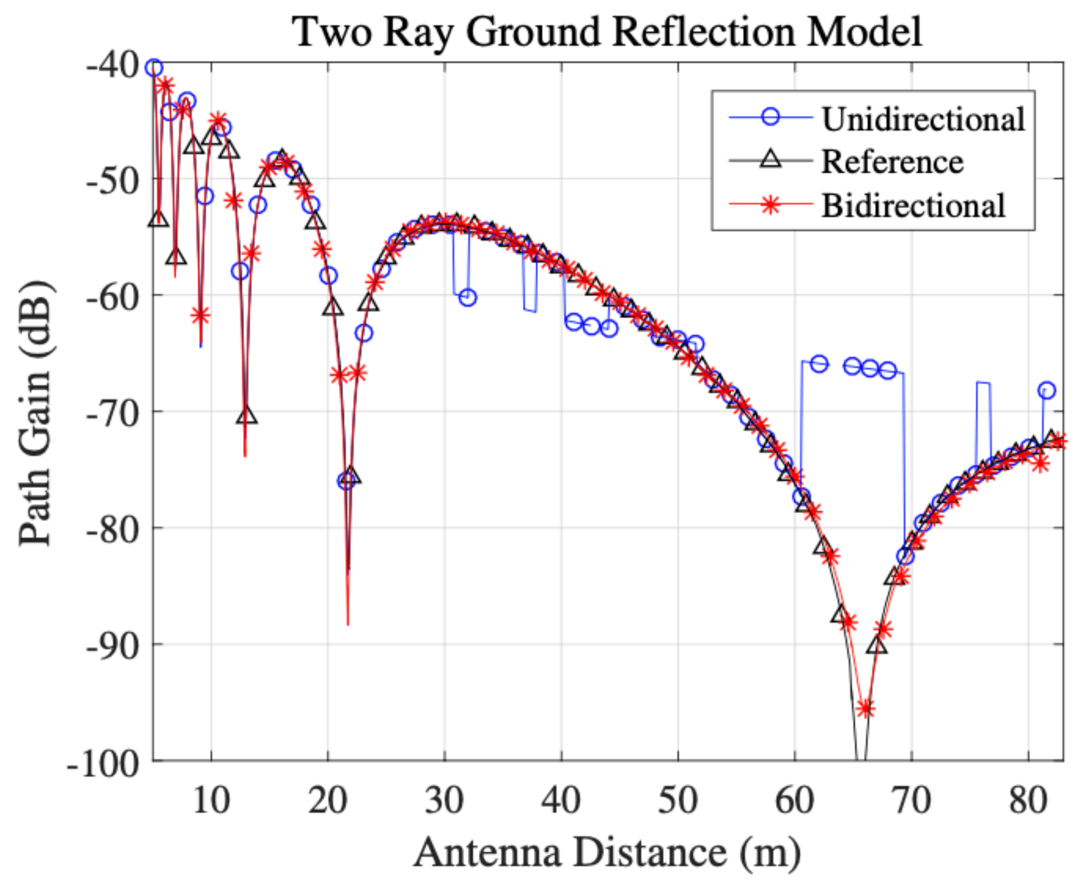




Path Tracing + "Texture Filtering" + Guiding

TWO-WAY GROUND REFLECTION

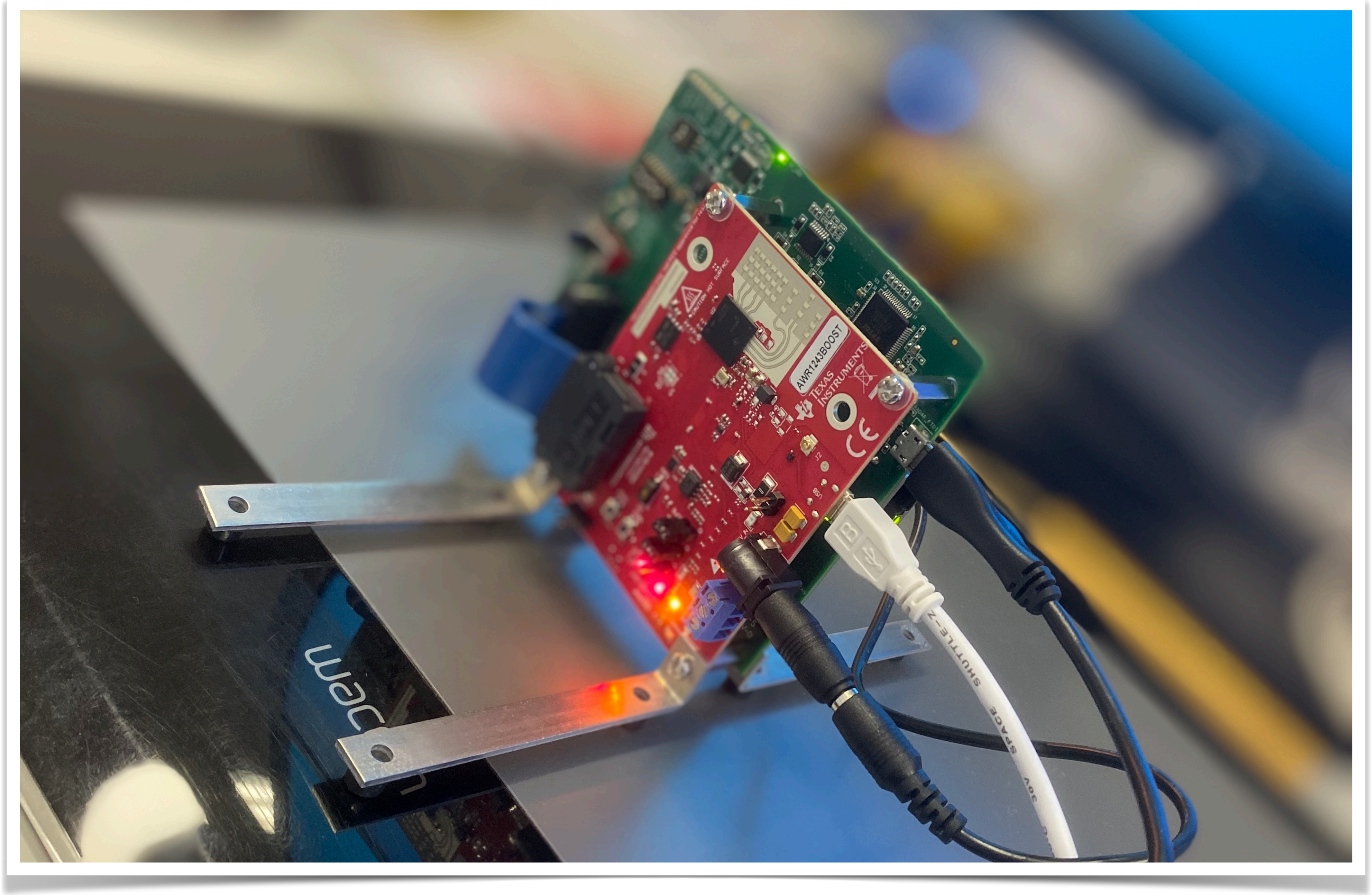




Path Tracing + "Texture Filtering" + Guiding + Low Discrepancy Sampling

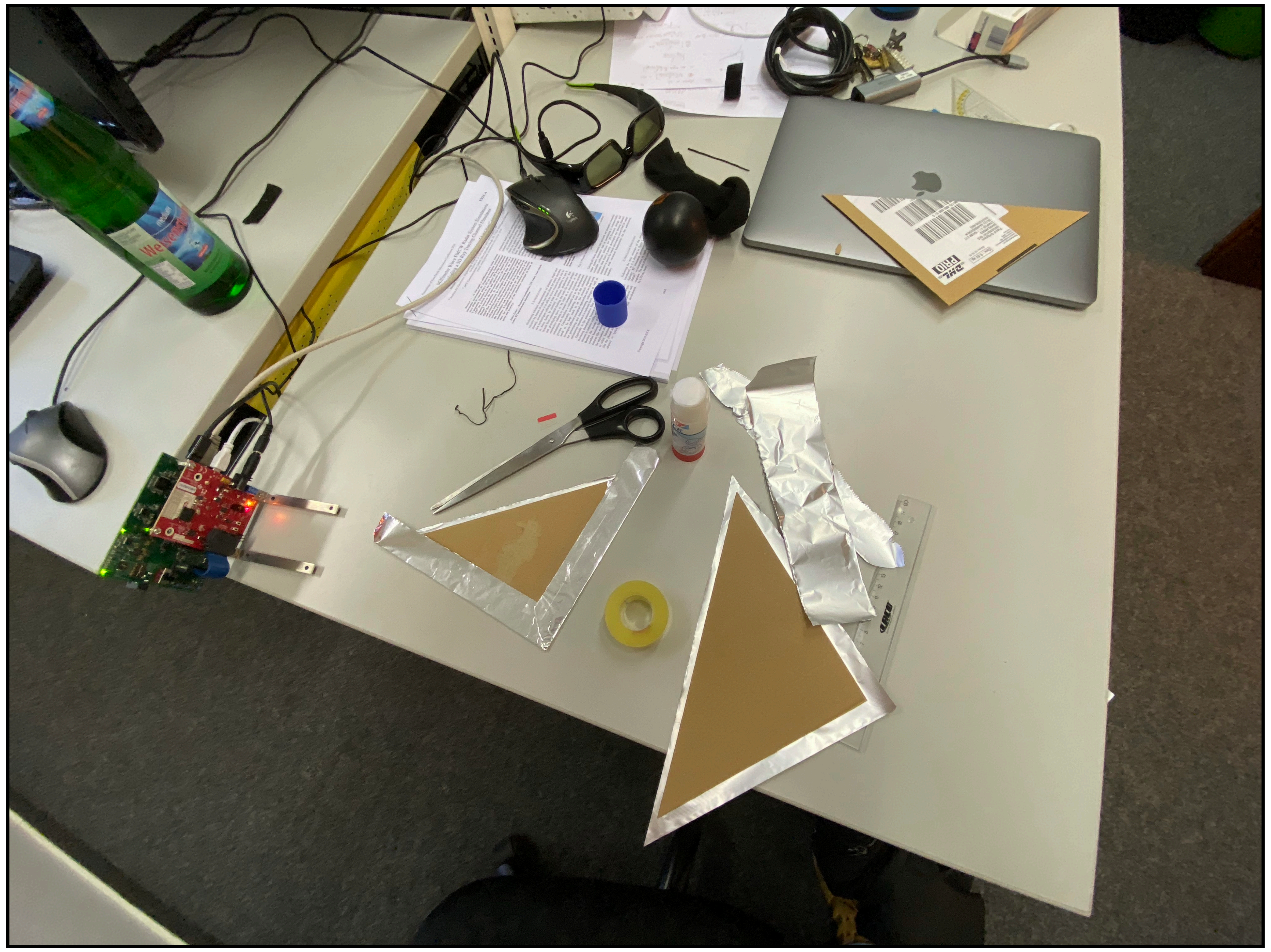
RESULTS

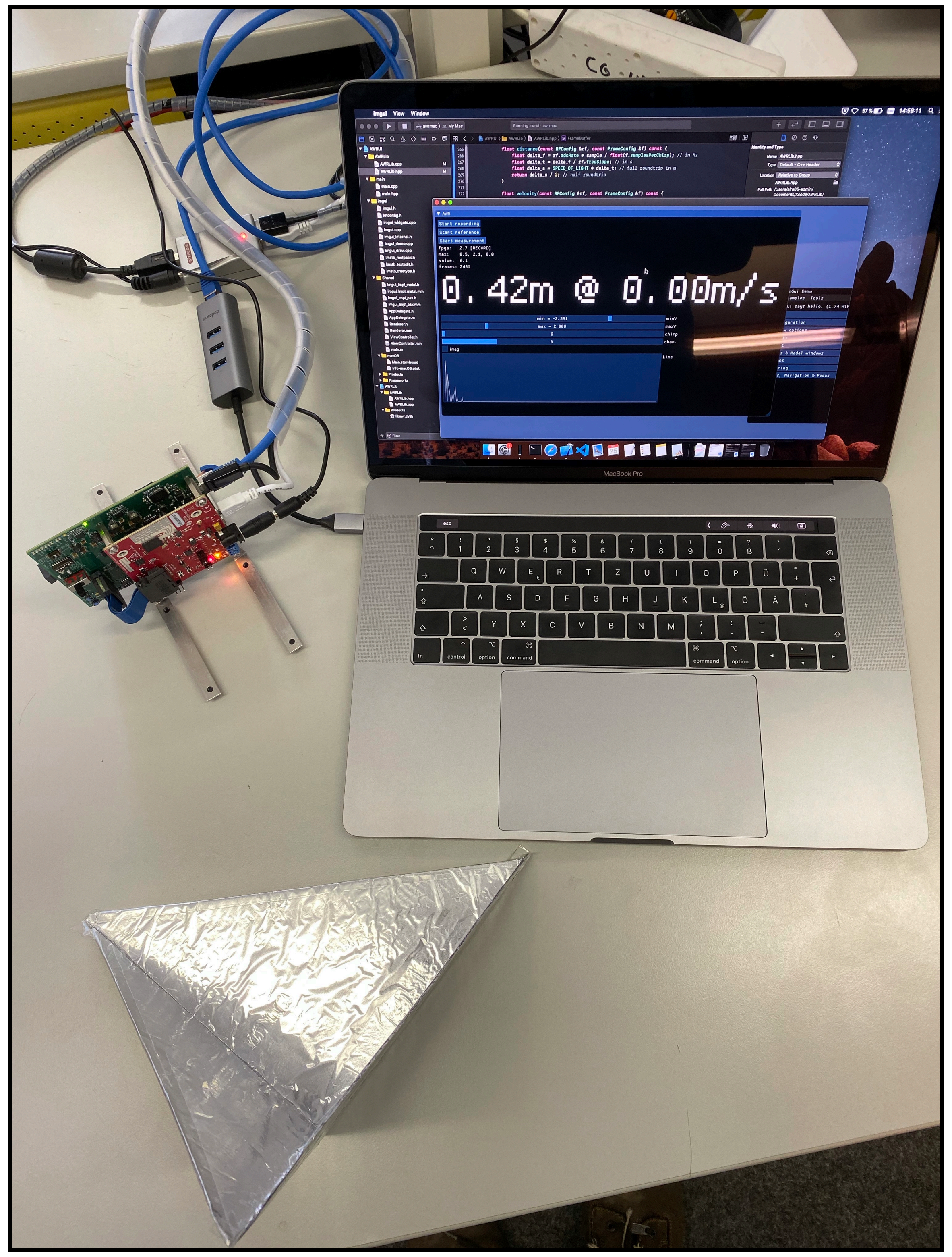
- How do we know this works for more sophisticated scenes?
- Simple: we just buy a Radar sensor and see for ourselves!
  (note that there is next to no publicly available data, so capturing it yourself is the only viable option)



RESULTS

- Our first experiments were rather ad-hoc…

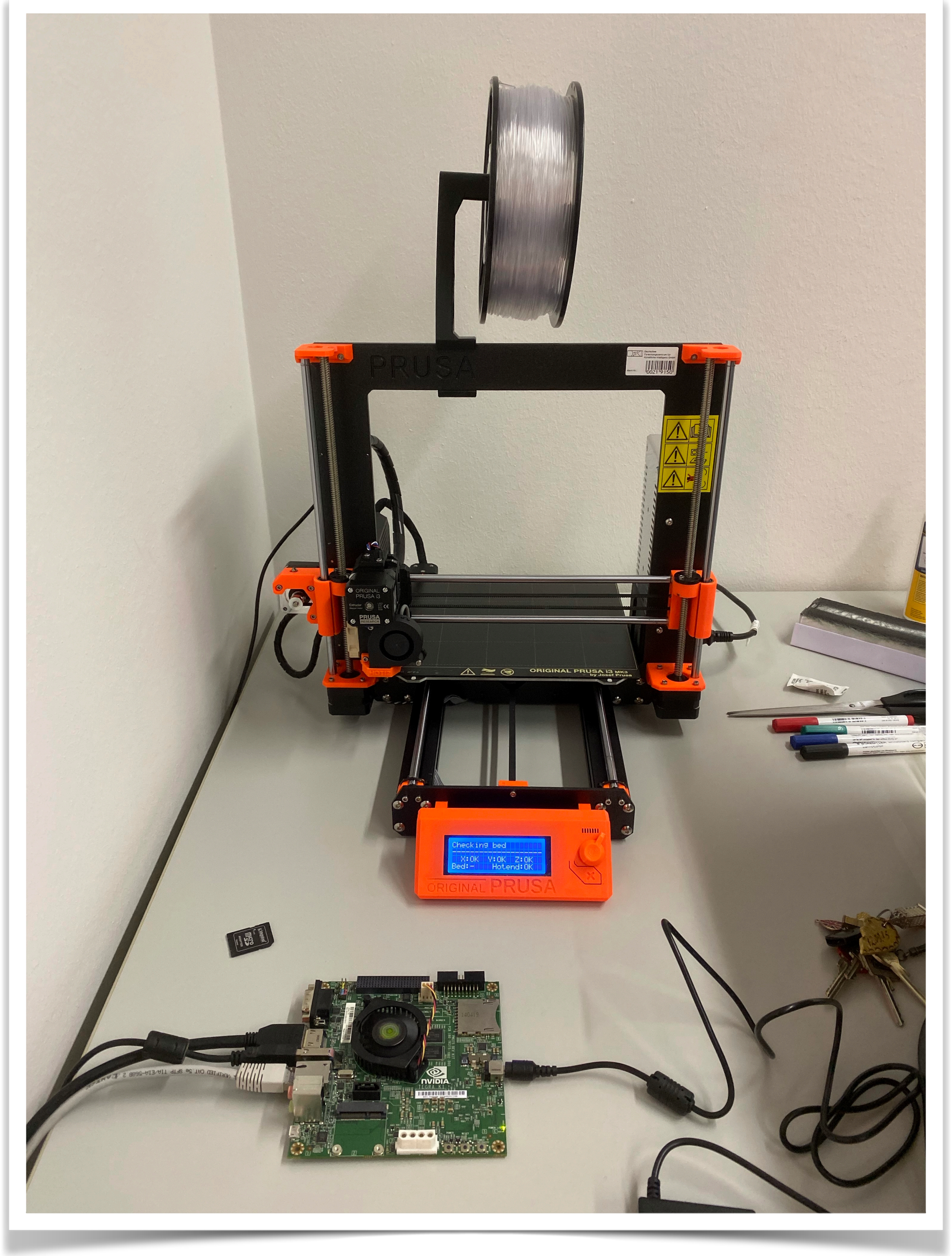




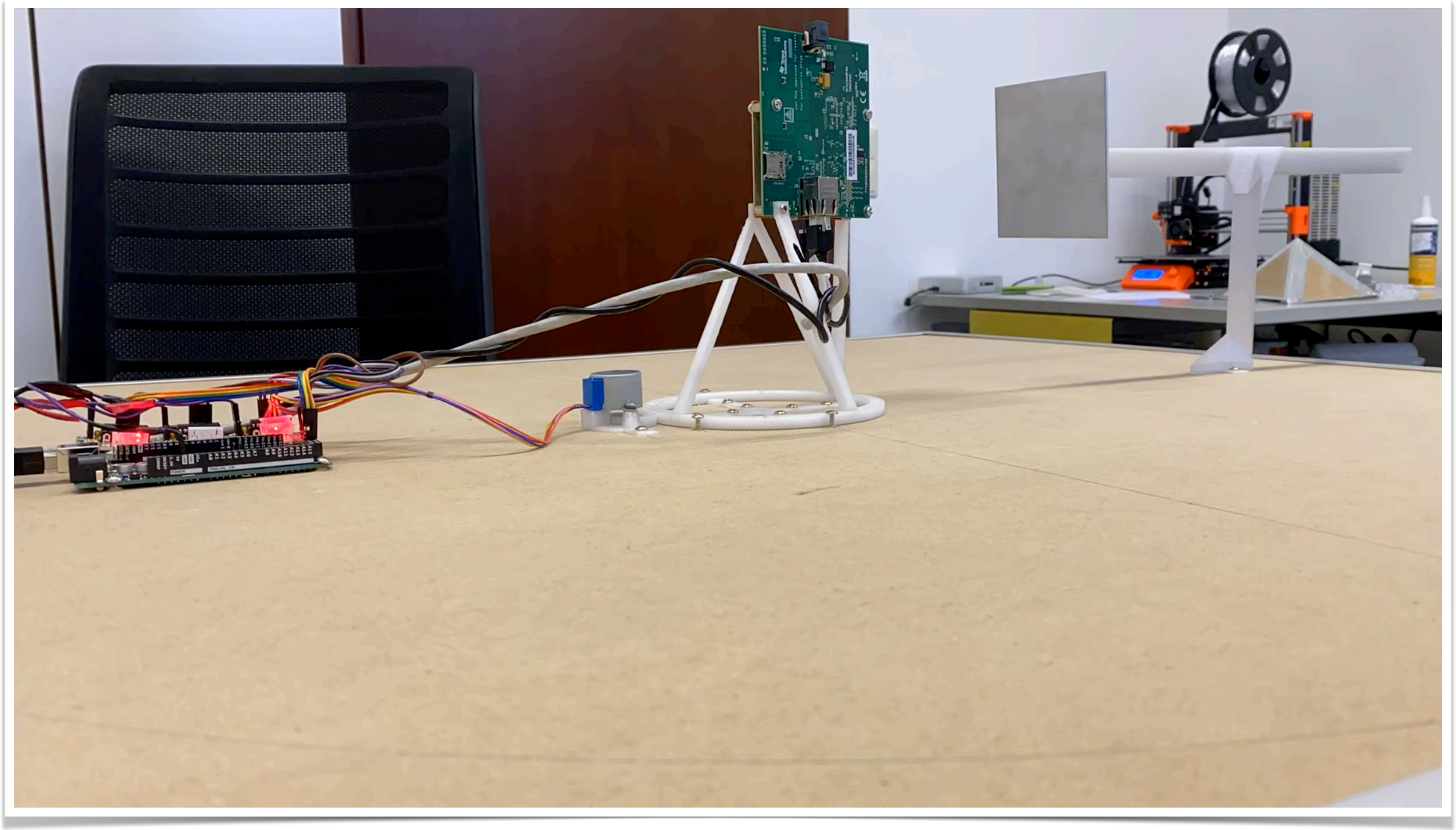
- …but still yielded valuable insights!

RESULTS

- Armed with the right tools, a 3D printer and an Arduino, we were able to take our measurements to the next level

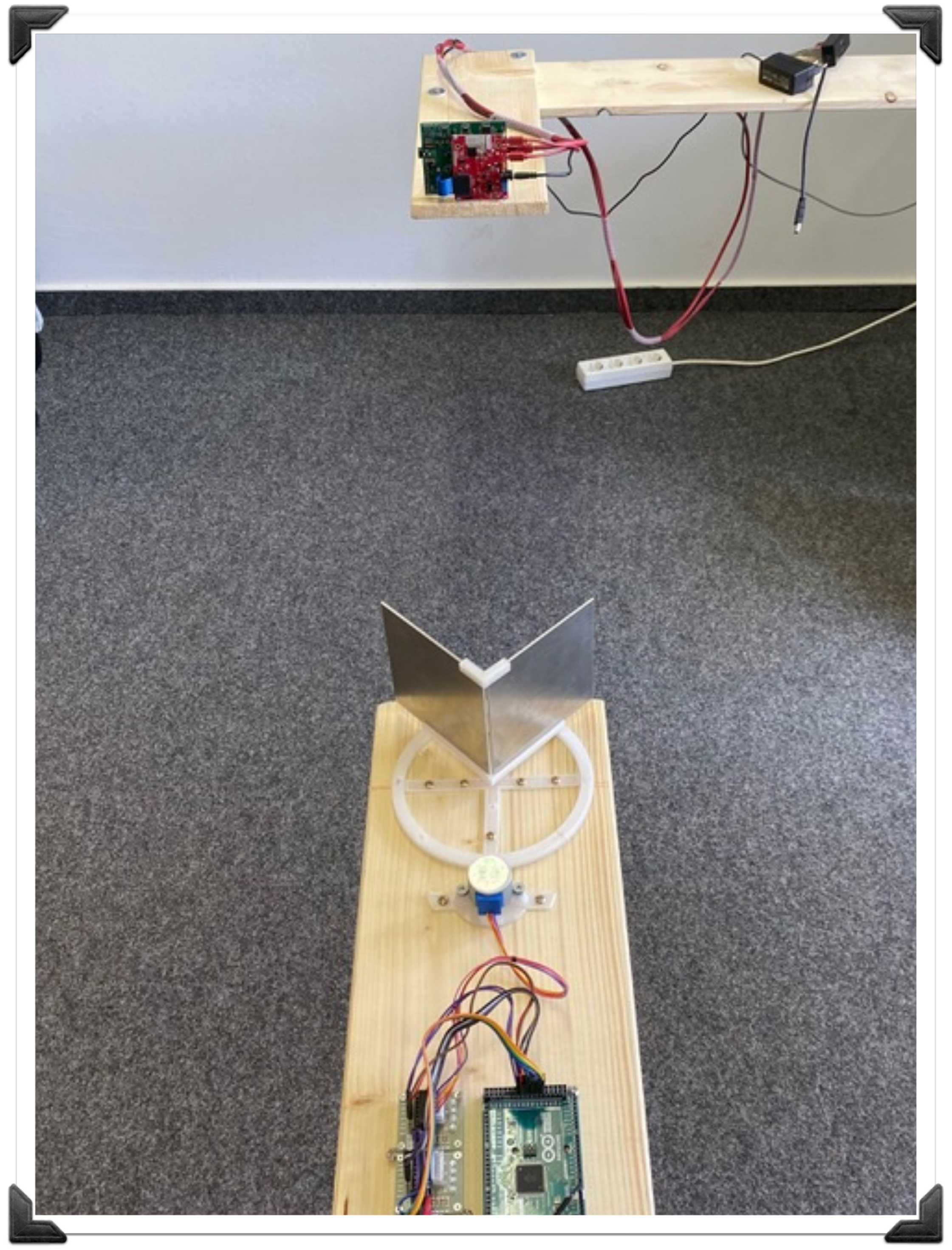


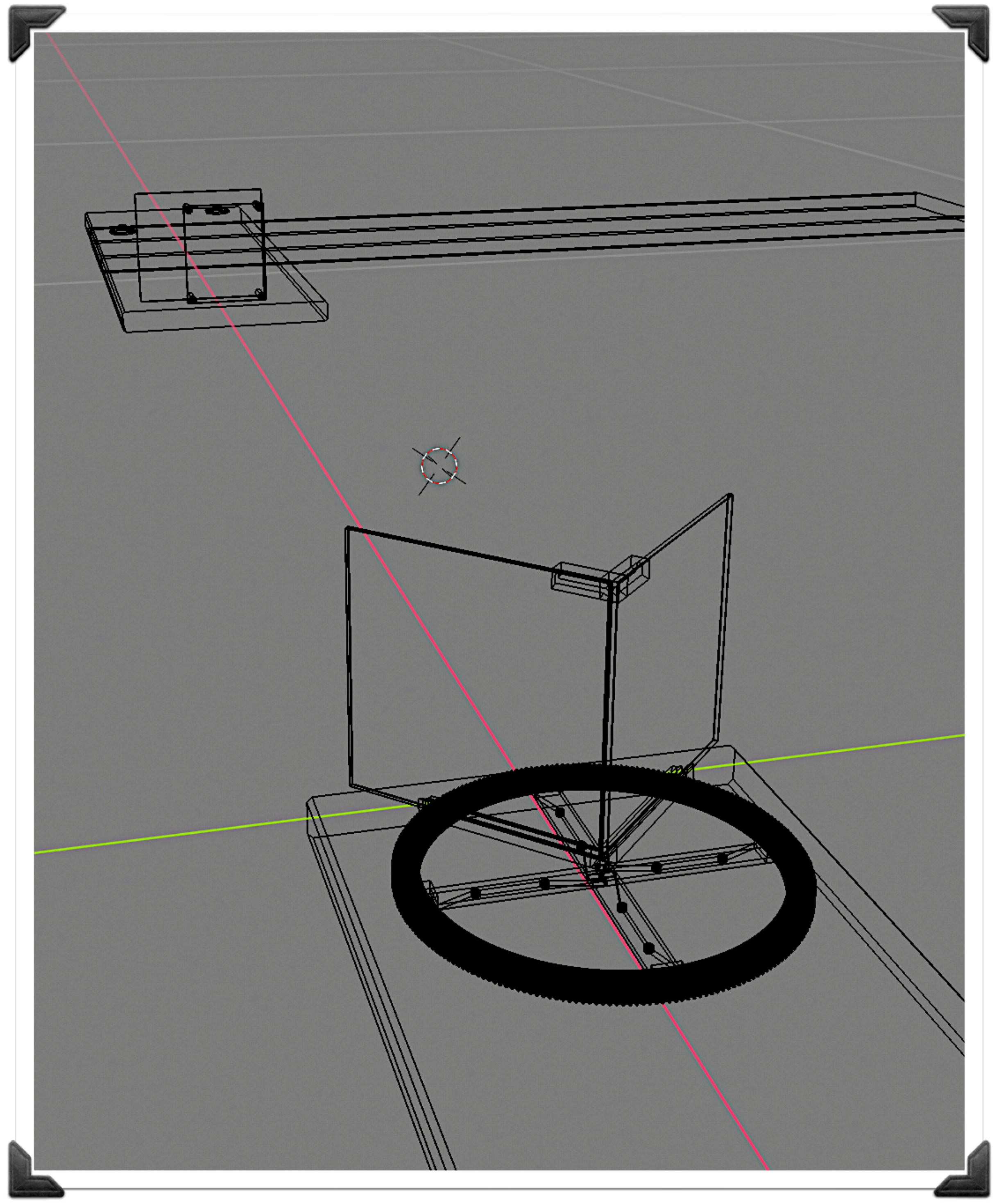
RESULTS



RESULTS

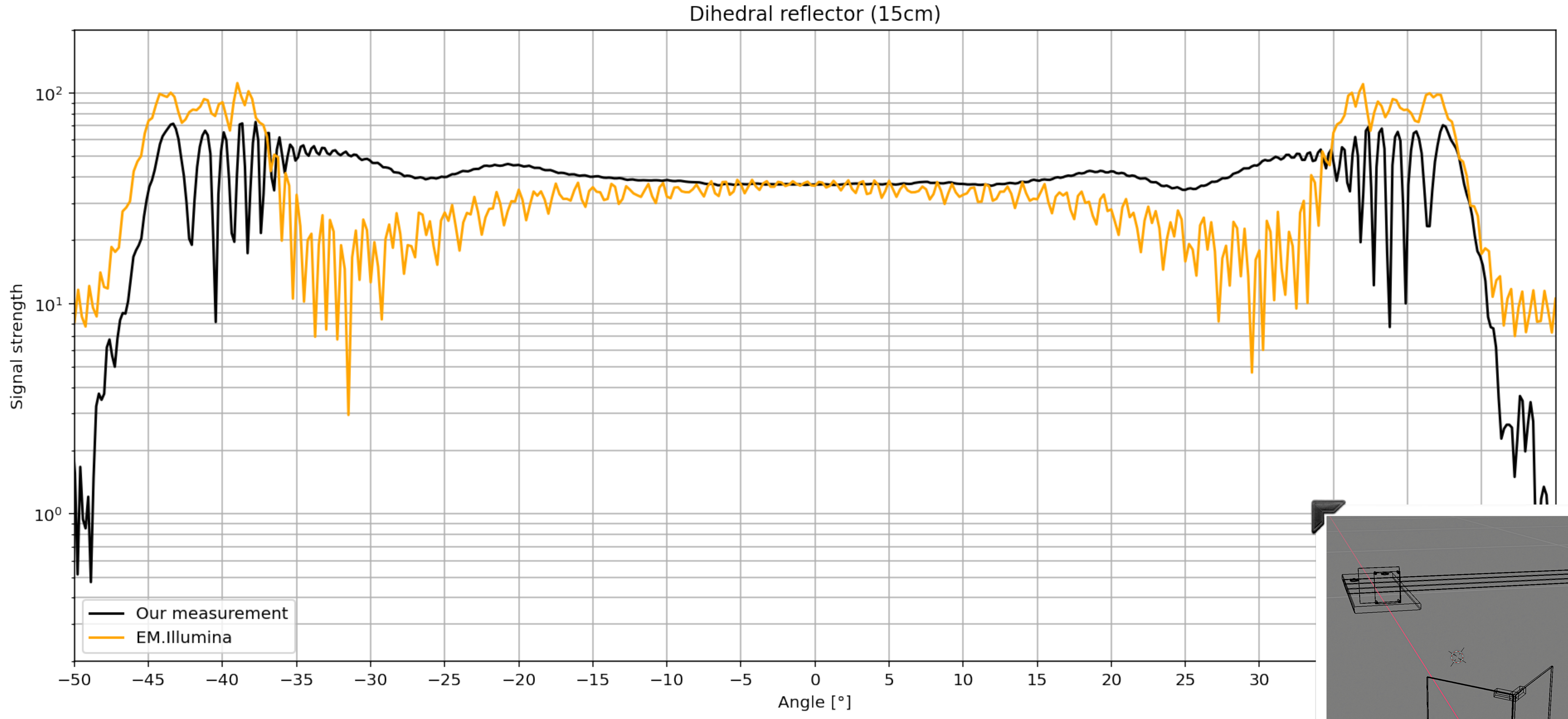
- In the following, we will look at a slightly harder test scene: a dihedral reflector made of aluminum

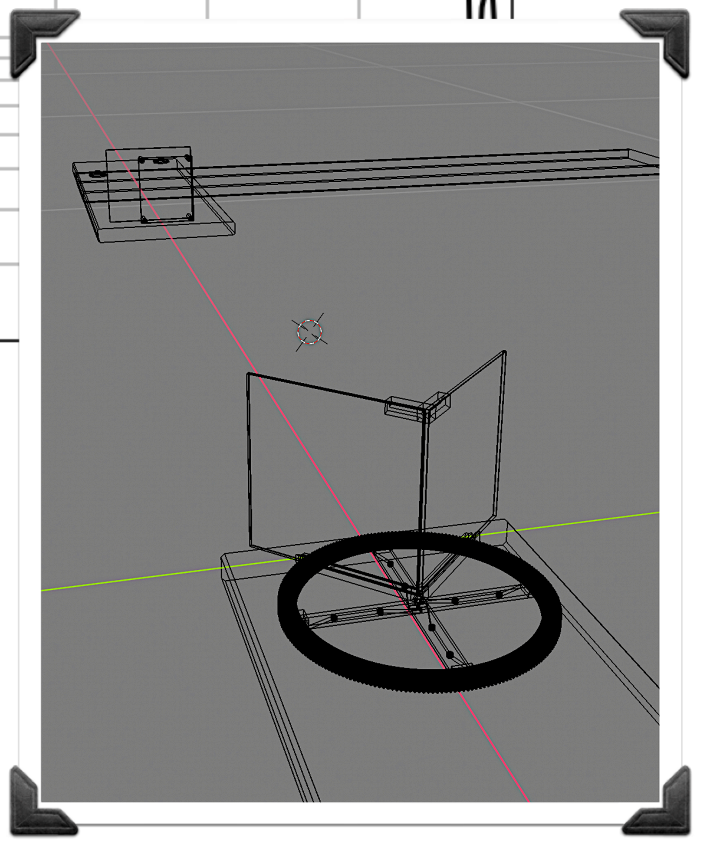




RESULTS

EM.Illumina (Physical Optics + Finite Elements)

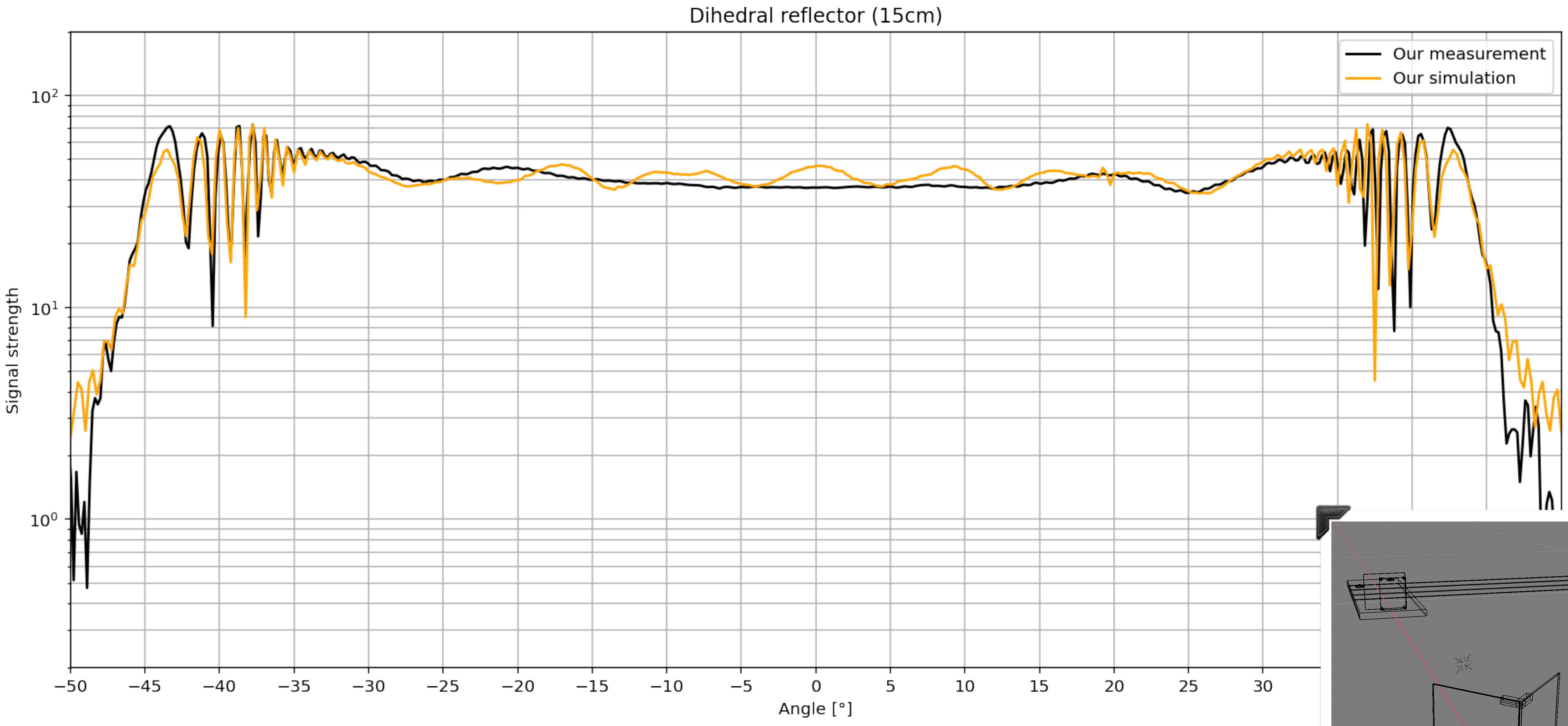


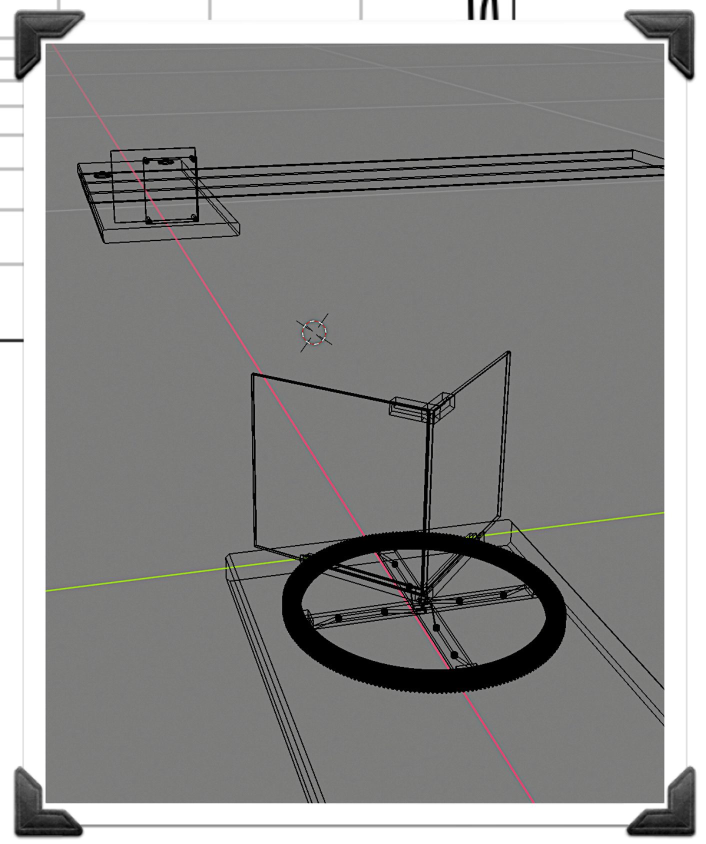


runtime: 13.4 hours

RESULTS

Ours (Physical Optics + Monte Carlo)

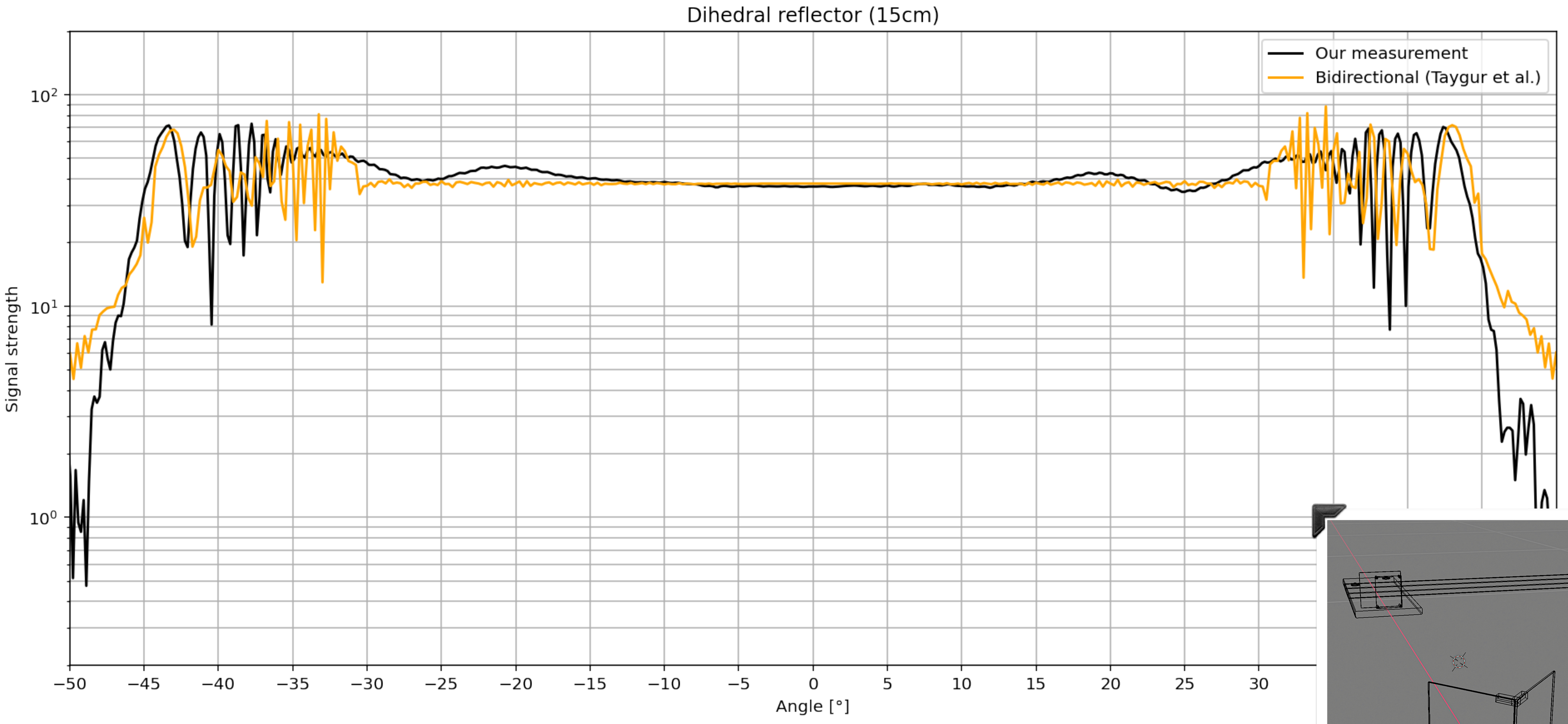


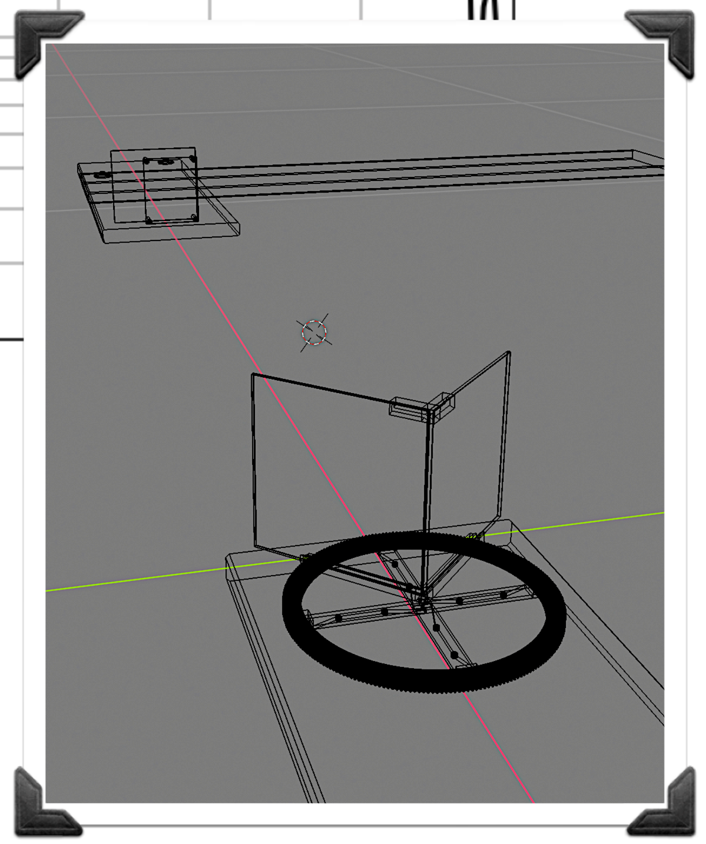


runtime: 33 seconds

RESULTS

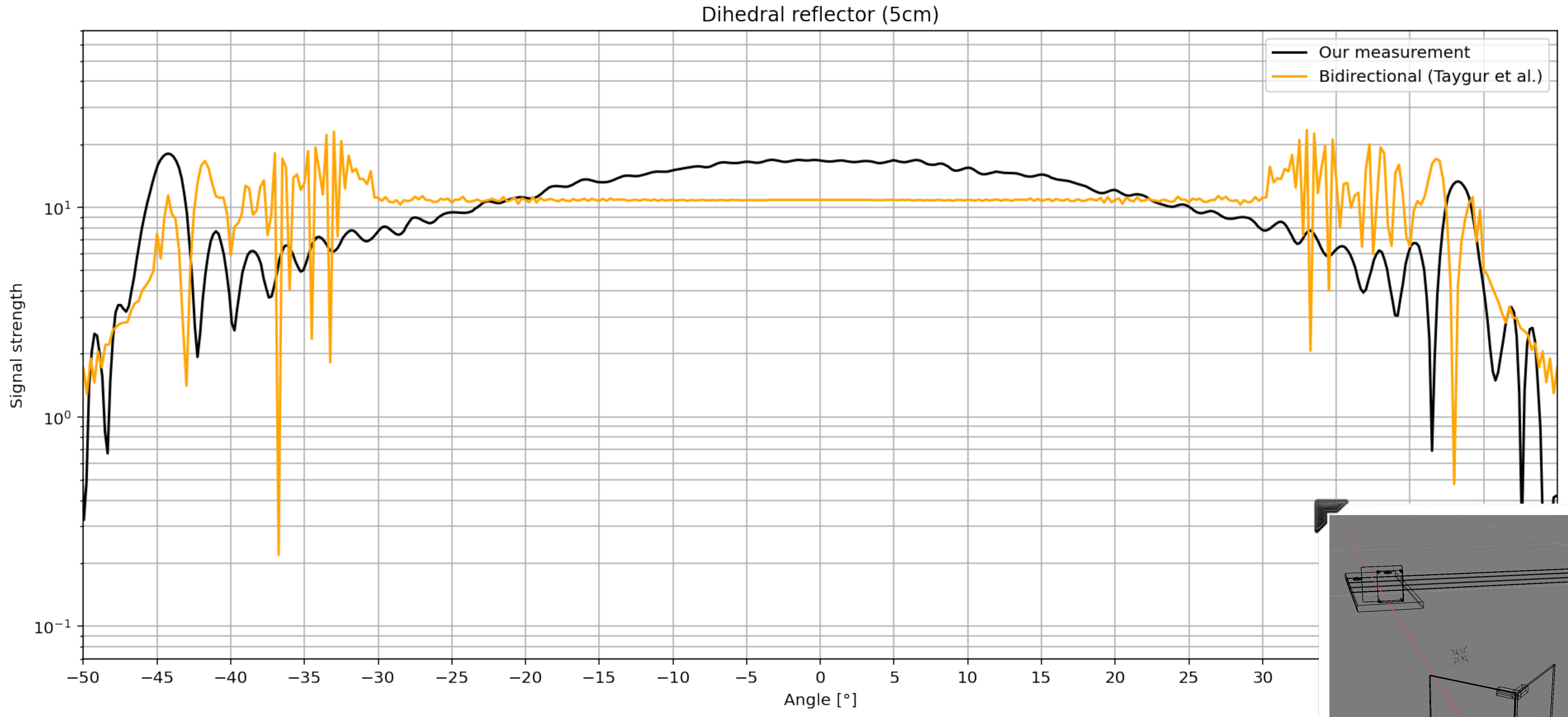
Bidirectional Antenna Coupling (Taygur et al.)

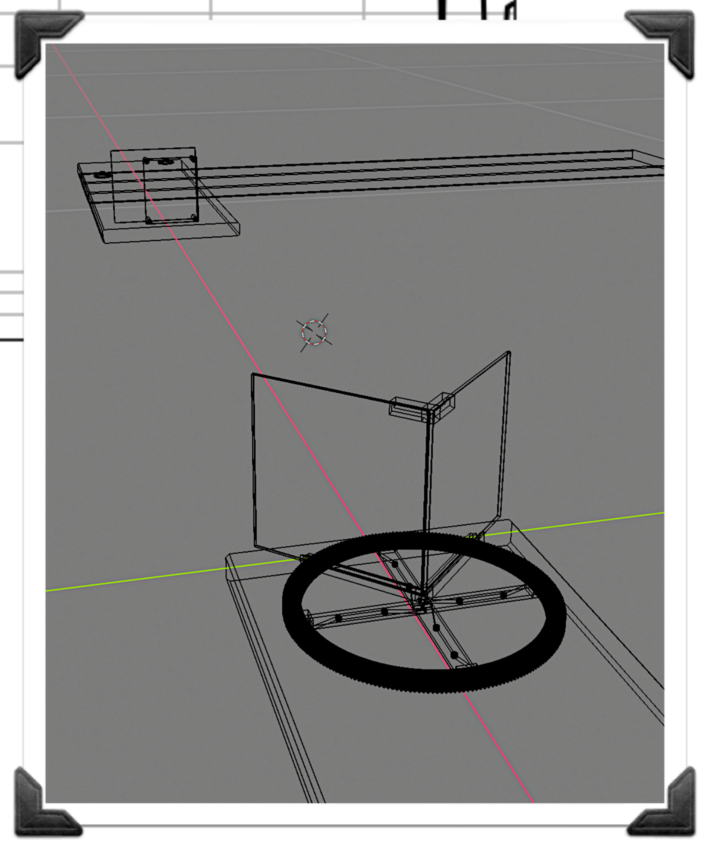




RESULTS (SMALLER DIHEDRAL REFLECTOR)

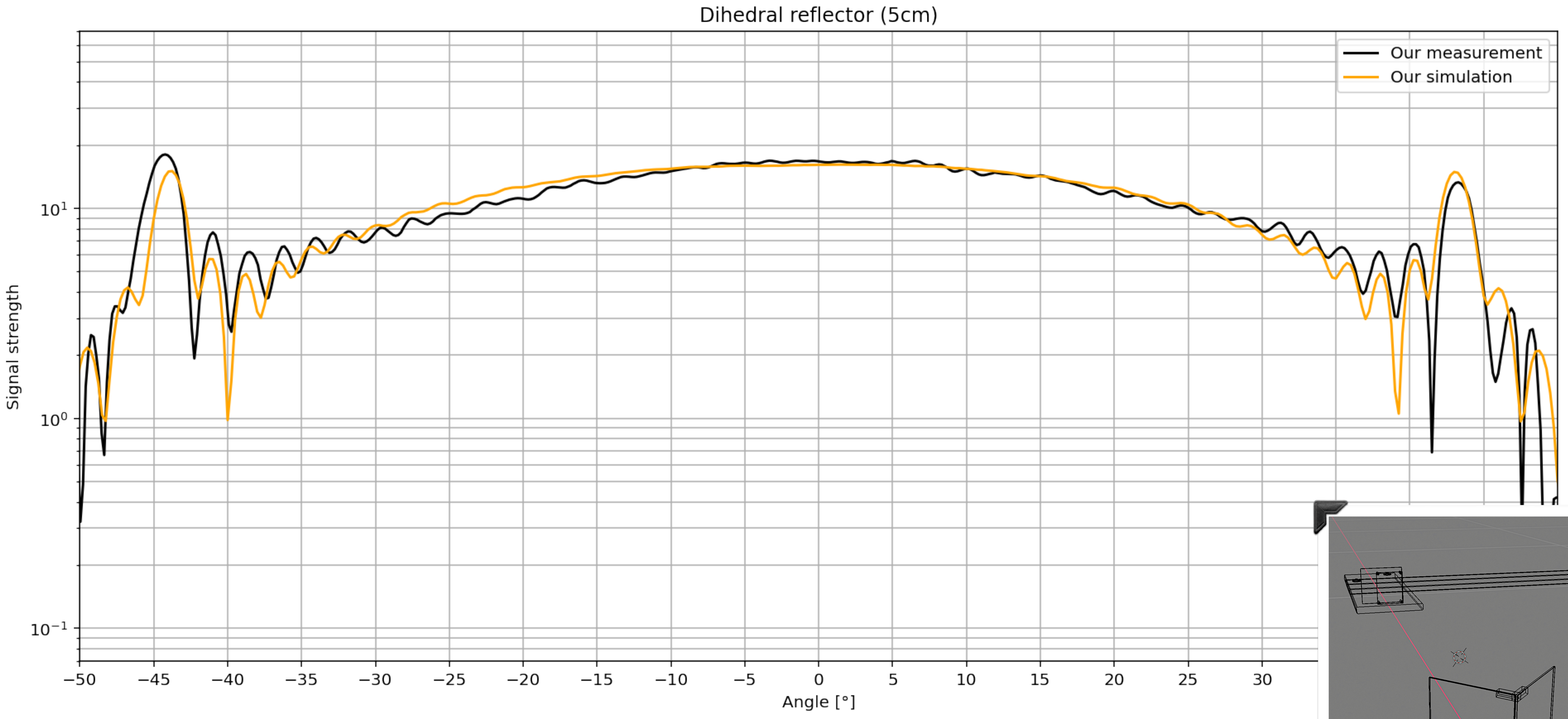
Bidirectional Antenna Coupling (Taygur et al.)

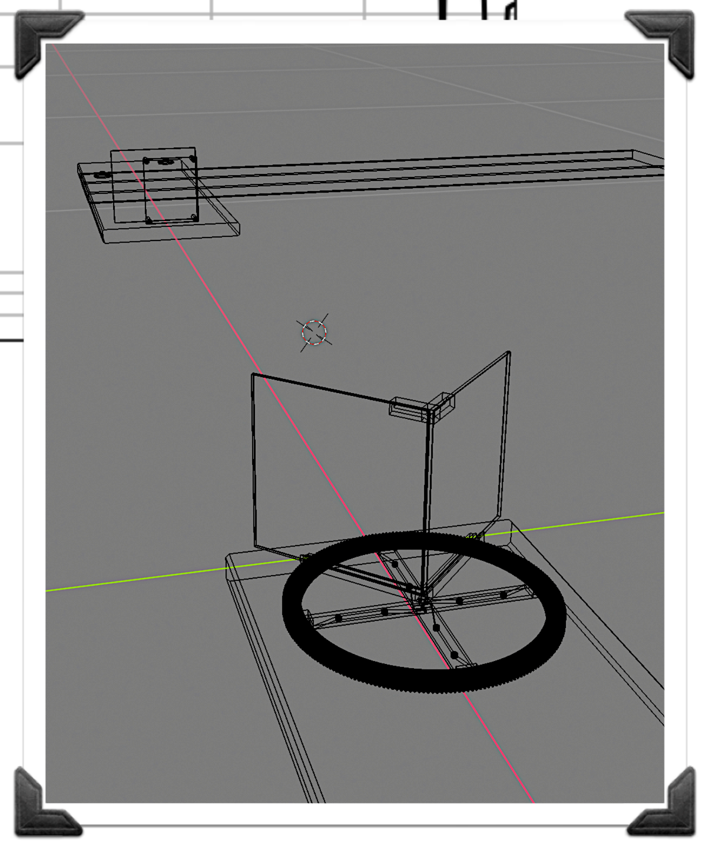




RESULTS (SMALLER DIHEDRAL REFLECTOR)

Ours (Physical Optics + Monte Carlo)





CONCLUSION

Radar Simulation

CONCLUSION

- We have shown that Radar simulation and Light Transport are not that different after all
- With some adjustments to the Rendering equation, we were able to transfer ideas like Path Guiding and Texture Filtering
- There are a lot more sophisticated methods that sound promising for Radar simulation still left to explore:
  - Volumetric rendering, Denoising, Gradient Domain methods, Spectral rendering, Manifold Exploration, Bi-directional methods, Metropolis, ...
- Our research lays the foundation to transfer these (and future) ideas to Radar simulation

NEXT STEPS

- There is lots of work still to be done (and help is always welcome ;-))
- For example, we are always interested in transferring more sophisticated algorithms to the Radar context
- Right now we are in the works of evaluating larger scenarios (entire cars, street crossings, ...)



CONCLUSION

- Source code, documentation, measurements and results are available on GitHub:

https://github.com/cg-saarland/hussar