Optimization of Phased Array for RET-CR

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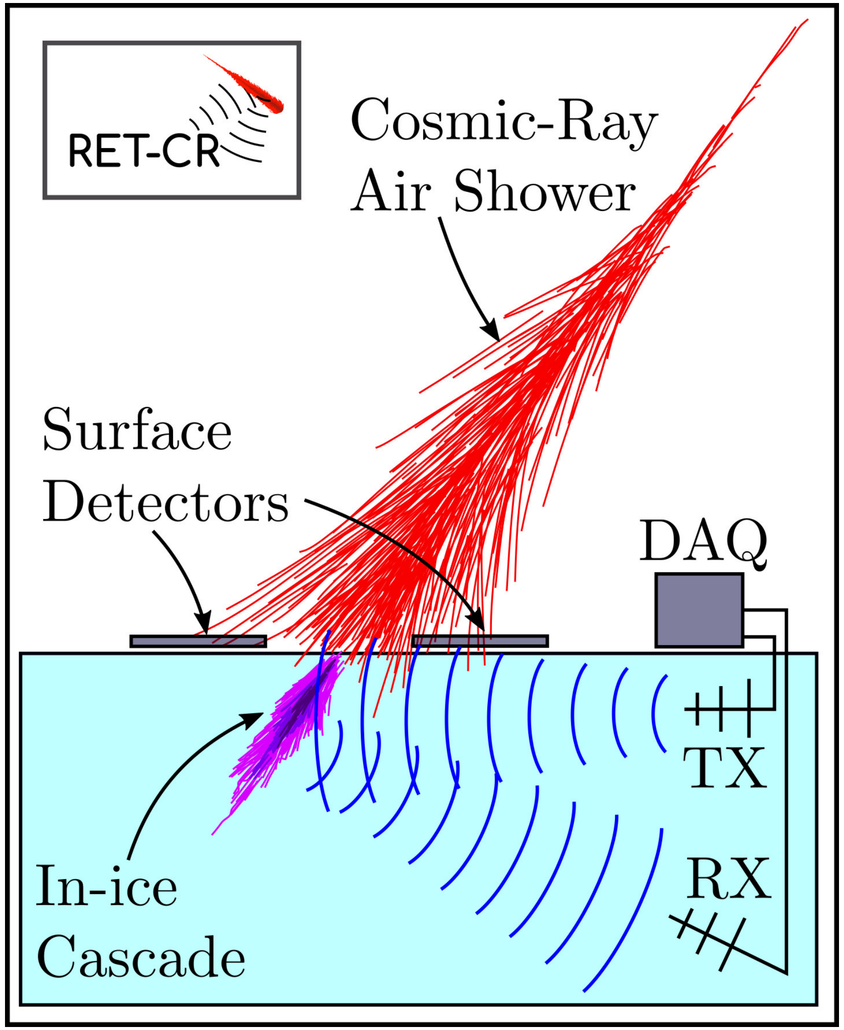
* This project overview is adopted from two presentation given to the RET collaboration. I’ve adapted it to be more accessible.

Project overview

Build a piece of software that optimizes the design of a transmission phased array antenna (TX) for the Radar Echo Telescope experiment. That is, find the best parameters for the design of the phased array.

To do this, I simulated the electric field of a variety of phased array designs using numeric EM solvers and took that data to see which design will give the rest of the experiment the best results.

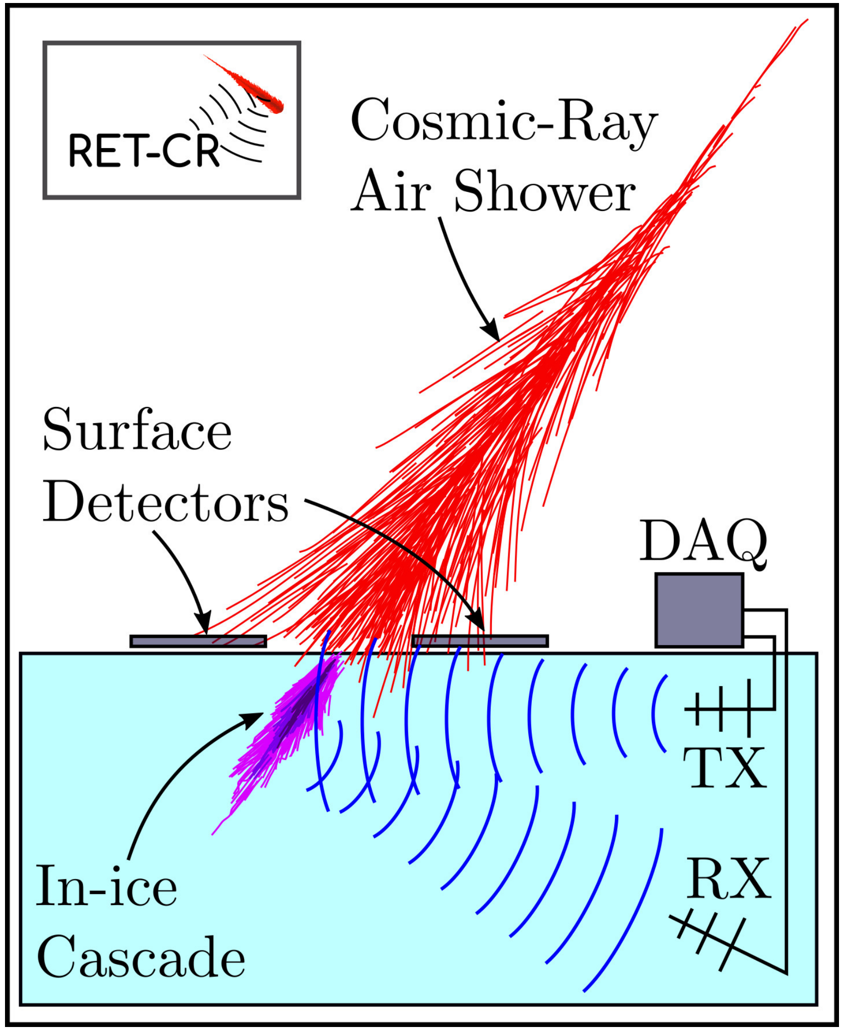


RET overview

Radar Echo Telescope (RET) is a collaboration with the purpose of detecting ultra-high energy neutrinos in Antarctica.

When neutrinos come down from the atmosphere and hit the ice, they cause a dense in-ice cascade of particles. Radio waves have characteristic wavelengths such that they can reflect off these in-ice cascades.

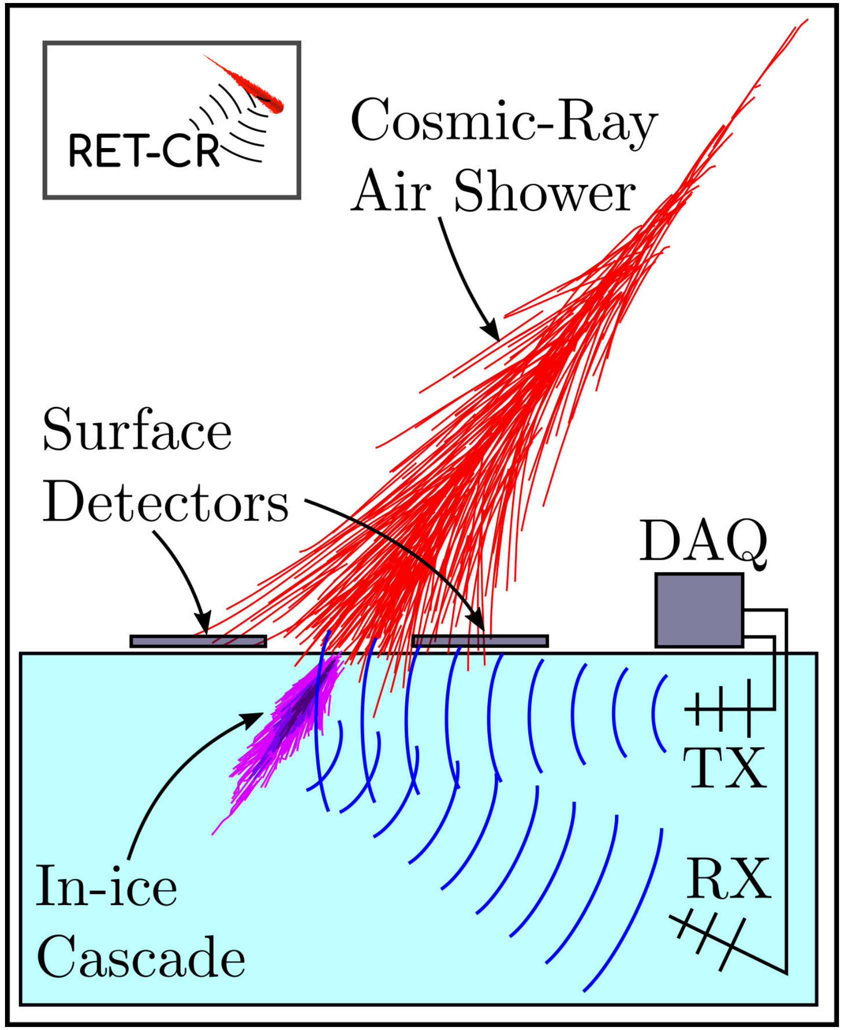
So, RET designed an experiment to detect these reflections



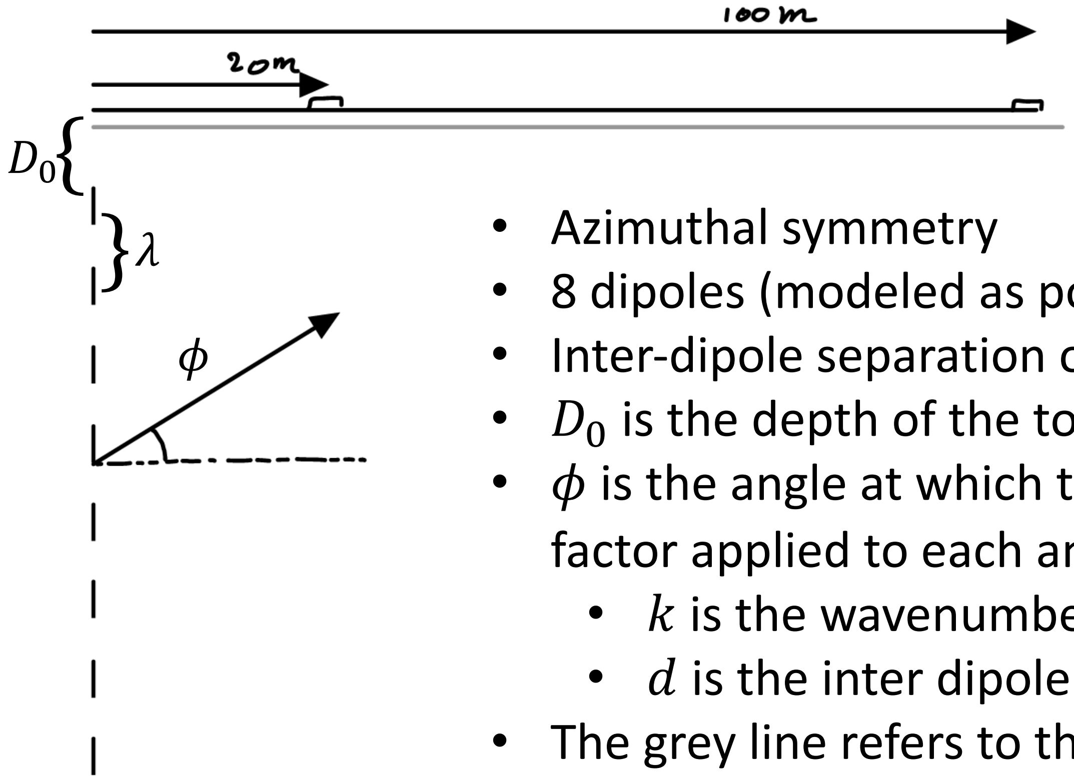
RET overview

A simplified version of the experiment goes like,

1. Use surface detectors to detect when and where there is an in-ice cascade.
2. Use a phased array transmission antenna (TX) to send out a signal directed at the surface.
3. That signal will bounce off the in-ice cascade and get detected by a receiver antenna (RX).



More details on the transmission phased array

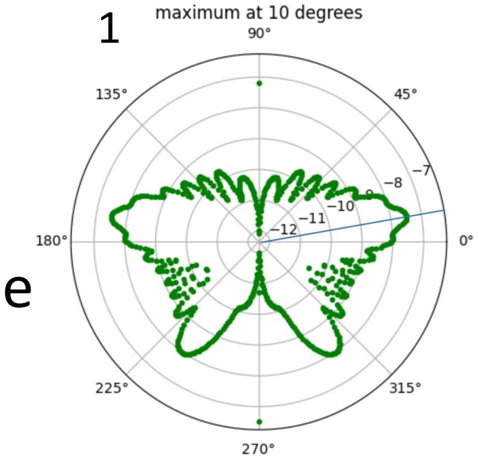


- Azimuthal symmetry
- 8 dipoles (modeled as point like)
- Inter-dipole separation of one λ (wavelength)
- D_0 is the depth of the top dipole
- ϕ is the angle at which the phased array is steered in vacuum from a phase factor applied to each antenna. The factor for the l^{th} dipole is: $e^{-il(k\phi d)}$
  - k is the wavenumber of the antenna
  - d is the inter dipole separation ($d = \lambda$ in our case)
- The grey line refers to the depth at which we measure the E-field corresponding the maximum of the cascade shower.
- *we have modeled the detectors at 20m and 100m.

Reason for optimizing

- When we steer a phased array in vacuum, we lose power output to side lobes[1,2]. So, steering the array directly at the surface may cause a weak signal at the surface.
- In addition, Antarctica has a non uniform index of refraction which causes the electric field to bend[3]. We want to control this bending so the field doesn't drop off along the surface.
- So, we want to find the optimal depth and steering angle of the array that minimize these effects and get a large power output along as much of the surface as possible.

1



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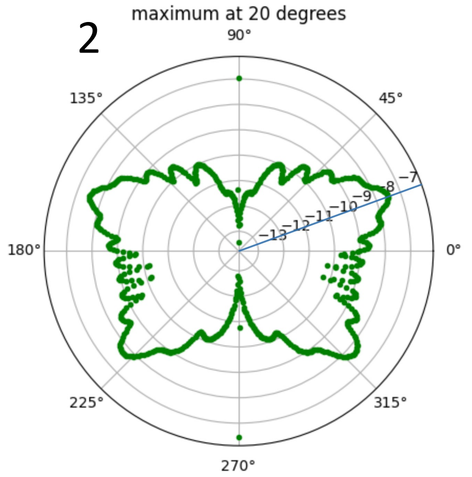

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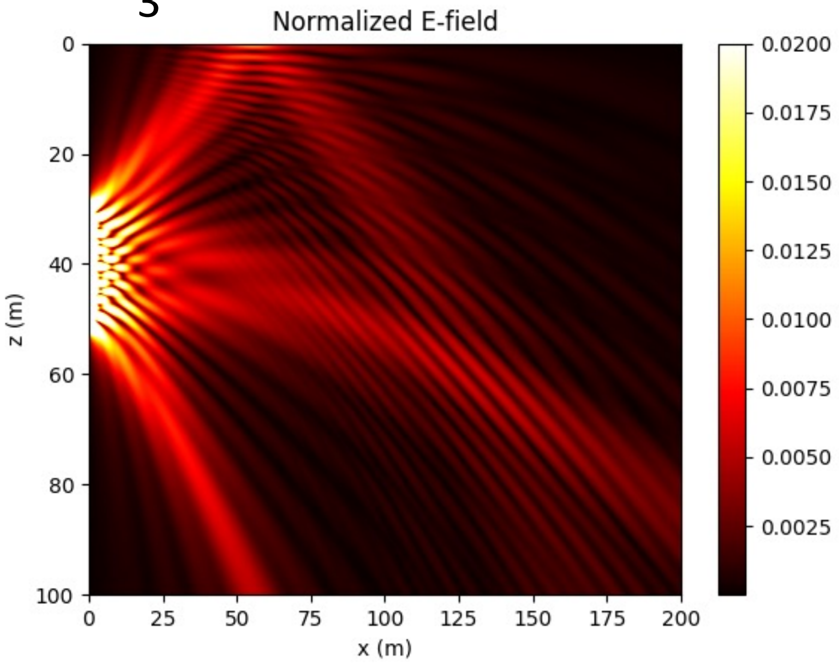


Optimization metric

- We want to maximize a weighted area of the region along the surface where the power output from the phased array is above some threshold.

$$\int_{\Omega} w(r)da$$

- To find the region Ω where the power output is above a certain threshold, we use two methods

1. Absolute threshold

$r \in \Omega$ if,

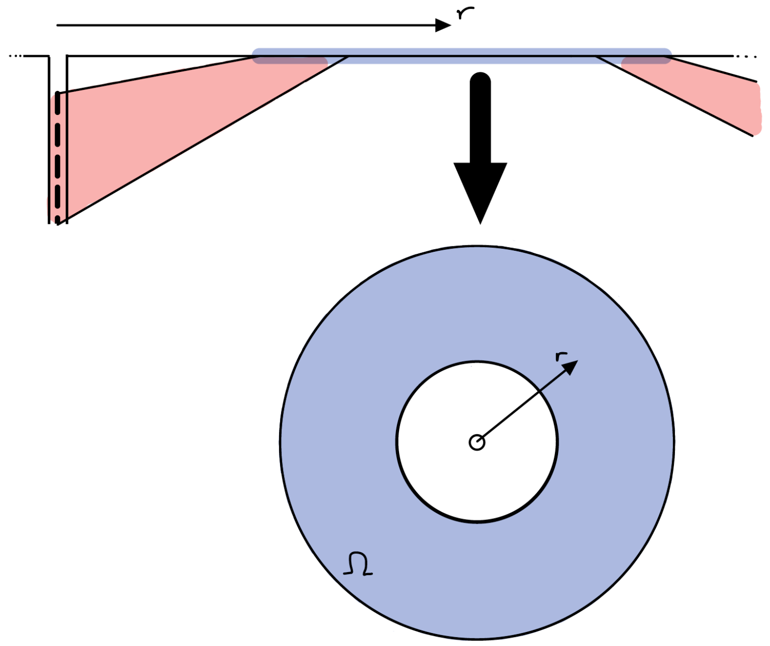
$$C_{abs} < 10\log_{10}\left(\left(E_{array}(r)\right)^2\right)$$

2. dBd threshold

   - Compare the phased array to a dipole.

$r \in \Omega$ if,

$$C_{dBd} < 10\log_{10}\left(\left(\frac{E_{array}(r)}{E_{dipole}(r)}\right)^2\right)$$



* We tested with different values for C_{dBd} and C_{abs}

Optimization metric

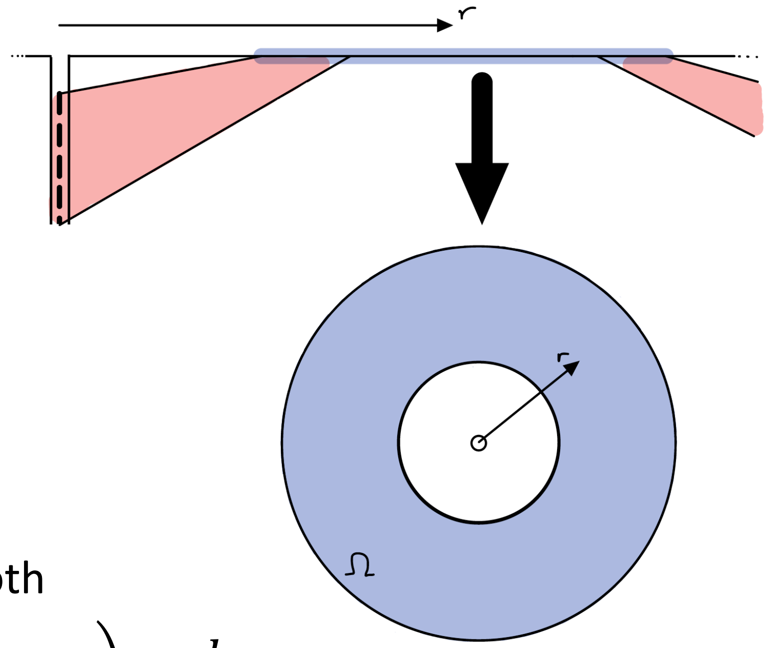
- We will use four methods for the weights $w(r)$. These are used because we want to weight the regions close to the surface detectors higher.
- The different methods

1. **Actual Area**: Ignore the detectors and just calculate the actual area of Ω
$$Area_{AA} = 2\pi \int_{\Omega} 1 \cdot rdr$$

2. **Punished Short:** Punish the area elements further from the short-range detector
$$Area_{PS} = 2\pi \int_{\Omega} \frac{1}{\sqrt{(r-r_{sd<})^2+z_m^2}} \cdot rdr$$

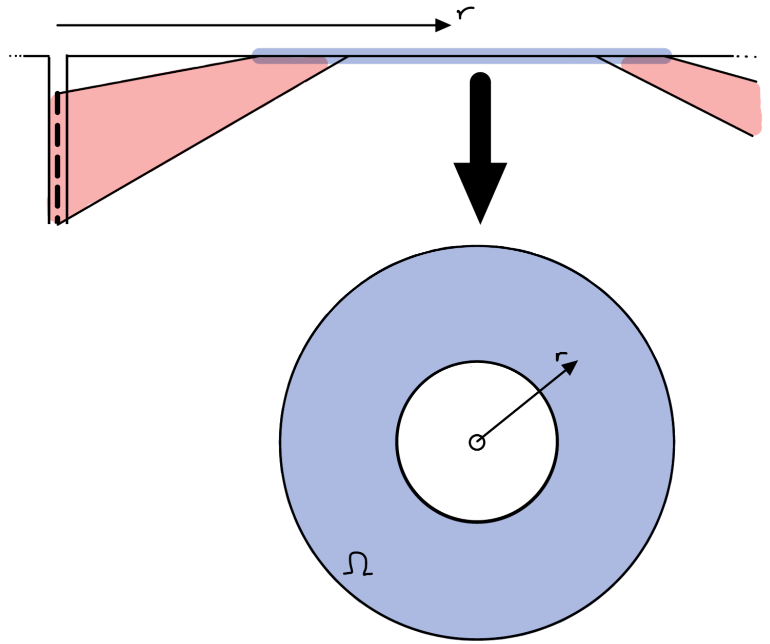
3. **Punished Long:** Same for the long-range detector
$$Area_{PL} = 2\pi \int_{\Omega} \frac{1}{\sqrt{(r-r_{sd>})^2+z_m^2}} \cdot rdr$$

4. **Averaged Punished**: Punish the area elements further from both detectors
$$Area_{AP} = 2\pi \int_{\Omega} \frac{1}{2}\left(\frac{1}{\sqrt{(r-r_{sd>})^2+z_m^2}} + \frac{1}{\sqrt{(r-r_{sd<})^2+z_m^2}}\right) \cdot rdr$$



Optimization

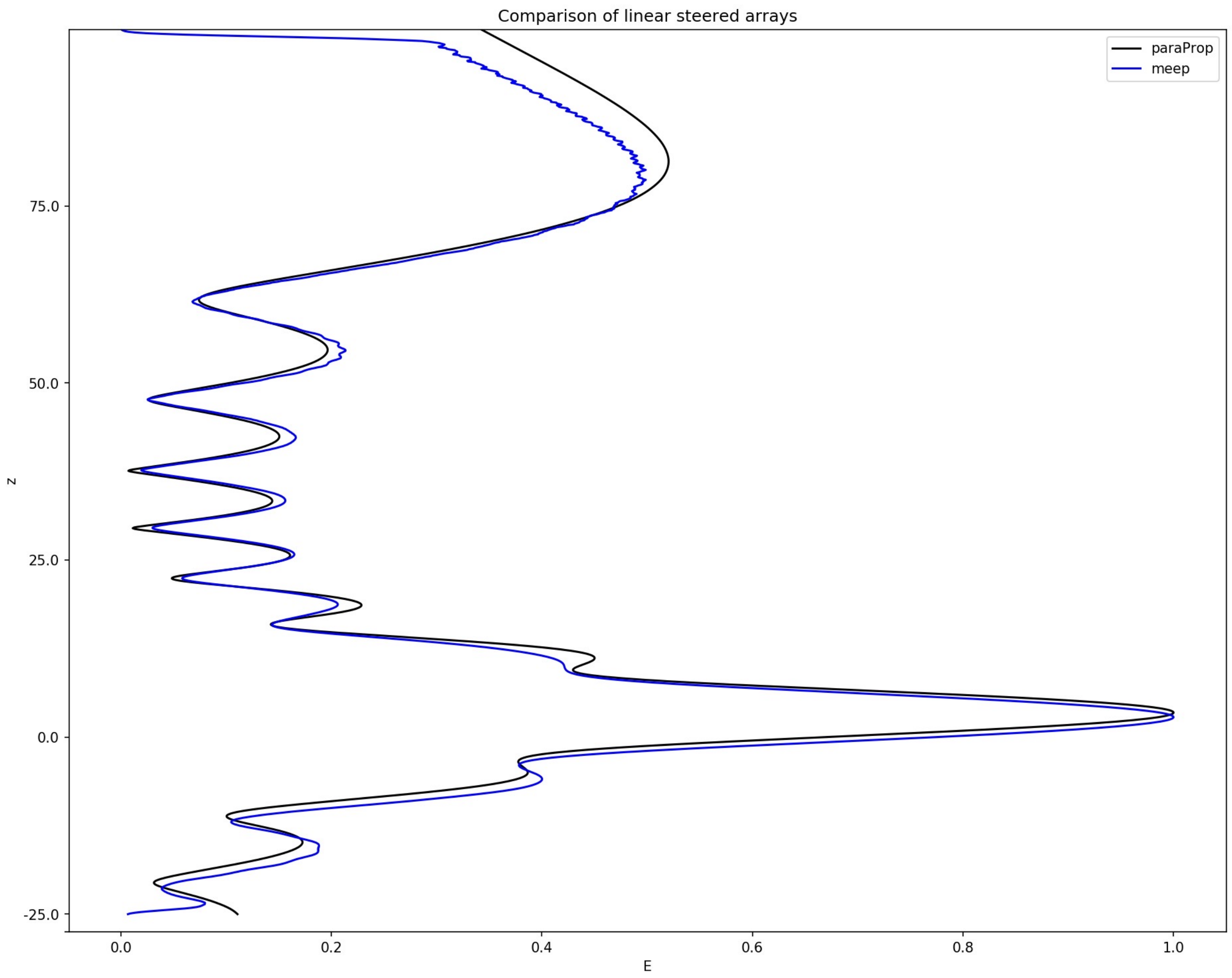
- We will use heat maps to view the area calculated by each combination of depth and steering angle.
- We will start be comparing the simulations using finite difference time domain software[1] and with ParaProp[2]. ParaProp is much faster, though less accurate than FDTD to the actual results.
- In these initial tests we just used the actual area method to find the areas. And used a course scan of parameters



1: We used Meep and the code for this is found in optimizerNAnpyMeep1.py and optimizerNAnpyMeep2.py
2: This code is found in ParaPropPhasedArrayOptimization.ipynb

Verify ParaProp

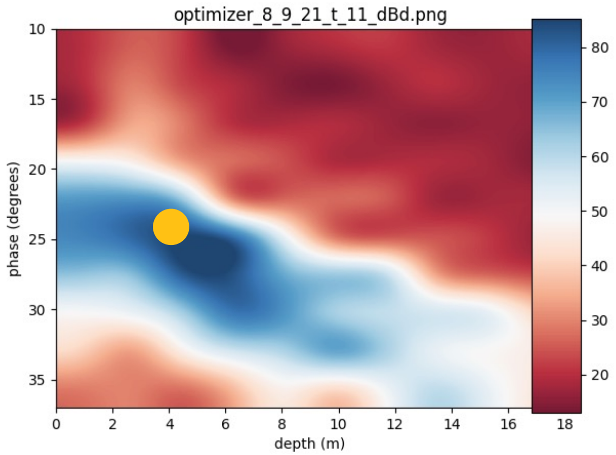
- We initially looked at a slice of the electric field taken at a range $r = 50m$ using both ParaProp and FDTD (Meep).

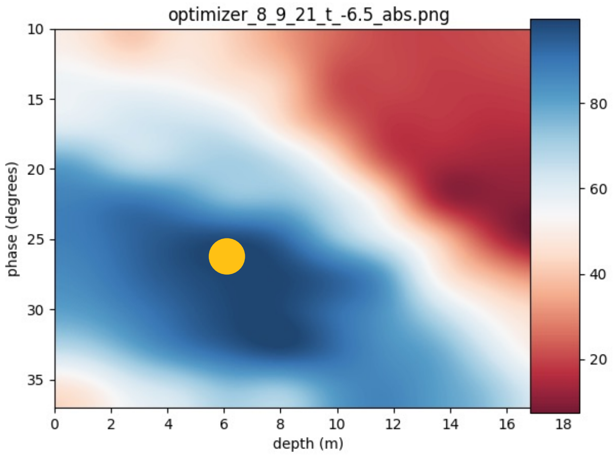


Verify ParaProp

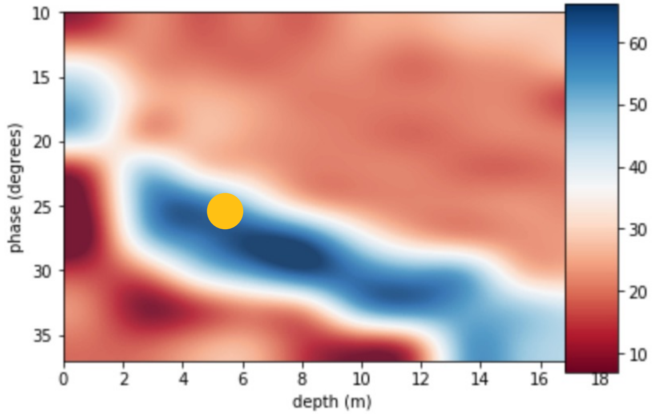
- We then looked at heat maps using both solvers.

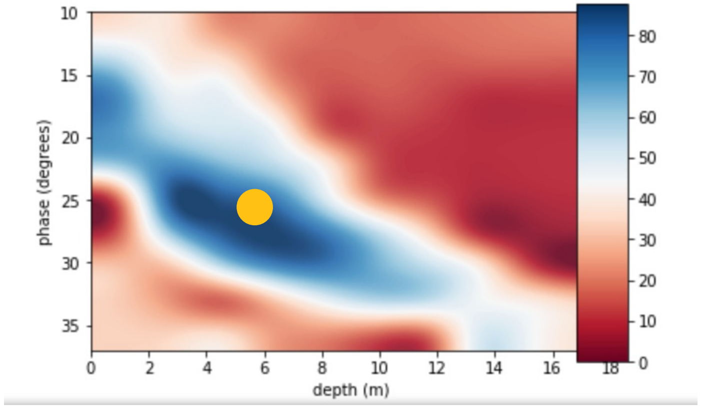
FDTD





PProp





DbD

Db

Verify ParaProp

- I have highlighted the best designs i.e. the designs with the maximized area in yellow from both solver methods.
- We found good matchup between the two solver methods and will therefore use ParaProp throughout the rest of the optimization.

Optimization results overview

- I ran optimizations using all area methods and a more detailed set of parameters
  - Depths [0m:20m by 1m] and angles [10°:40° by 1°]
- Since there is no theoretical value for the threshold cutoff value, we tried multiple values.
- We looked at the heat maps generated from each run. We got 4 maps for a given threshold.
- Here's how I analyzed the results
  - I only looked at threshold values higher than a critically low value C^*. C^* is the lowest possible value that gives a single best design that gives the maximum area.
  - I took the mode of all the designs from the different area methods from these thresholds.
  - I then took the mode of the designs each area method converged at its critical threshold.

Optimization results overview

- I found that the optimal parameters were

Depth: 6m Angle: 27°

- This is mode of all the designs from all area and thresholds methods.
- This is also the value all the "abs" threshold area methods converge on at the critical thresholds C^*_{abs}.
- The "dBd" threshold area methods don't all converge on this design at the critical threshold C^*_{dBd}. But during the course of the project, we had felt that "dBd" was not as useful or accurate as "abs". So, we excluded it from further use.

Optimization results analysis

- To see the convergence, I’ll show GIFs of the heat maps for each area method at different thresholds.
- Also, I converted each best area configuration from a given threshold and area method to a numerical code and plotted them against the thresholds.

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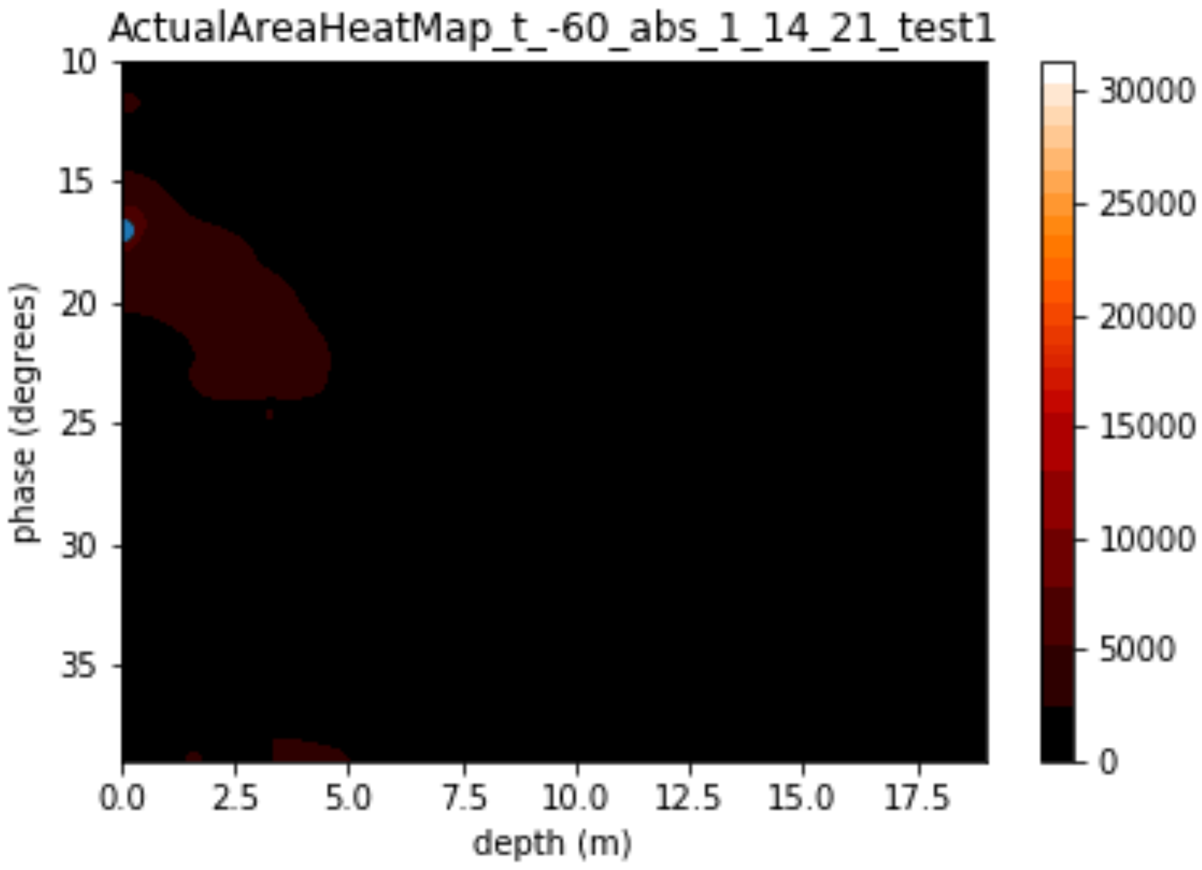
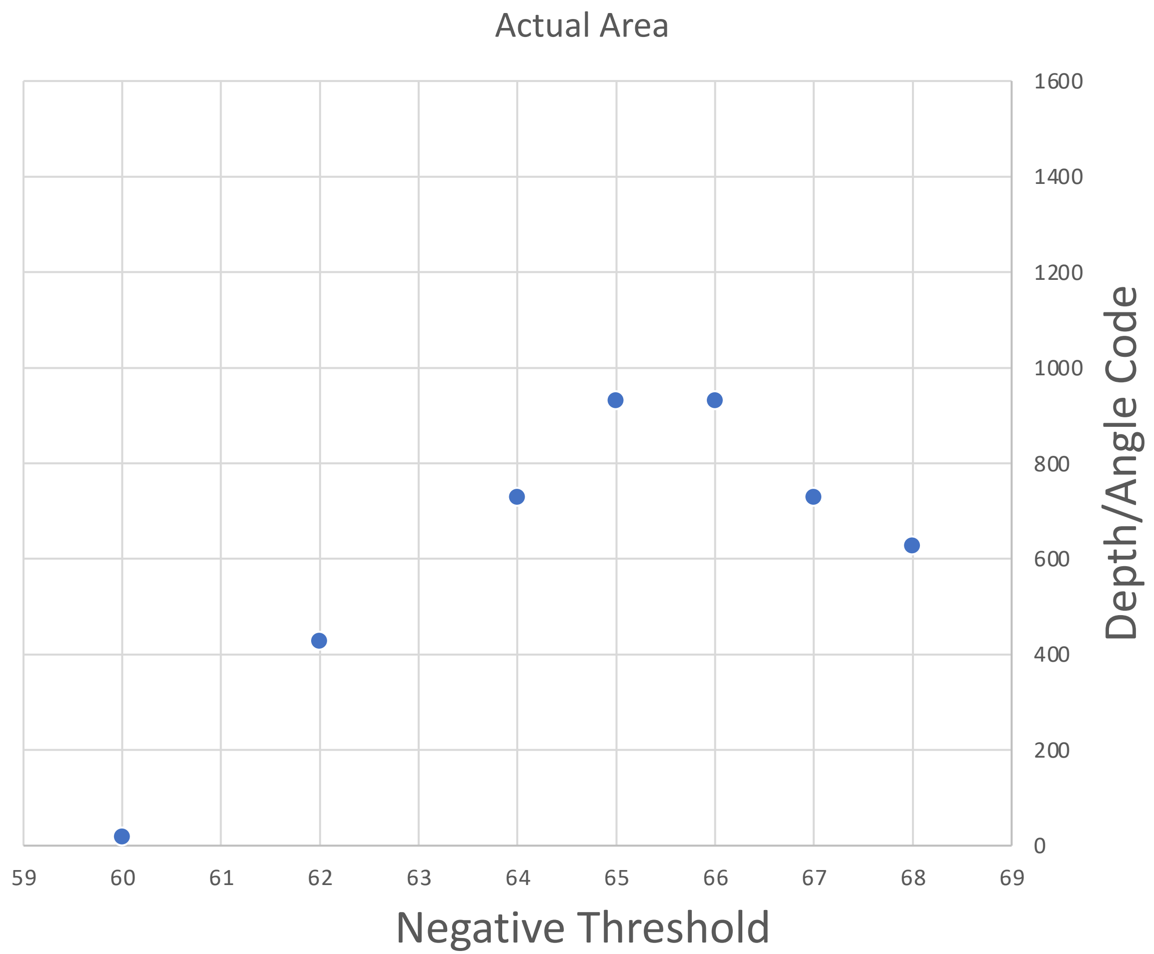
Depth Angle

Heat Maps (Actual Area)

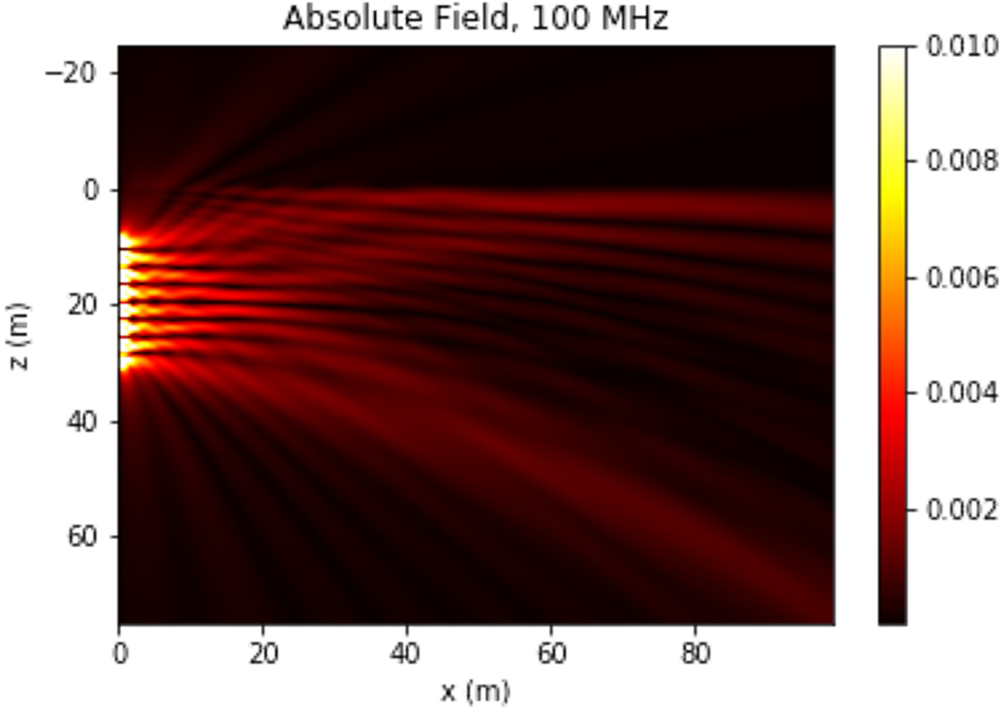


Code vs. Threshold (Actual Area)

- This shows the convergence of the design code at the critical threshold ($C^*_{abs} = -68$)



Best E Fields



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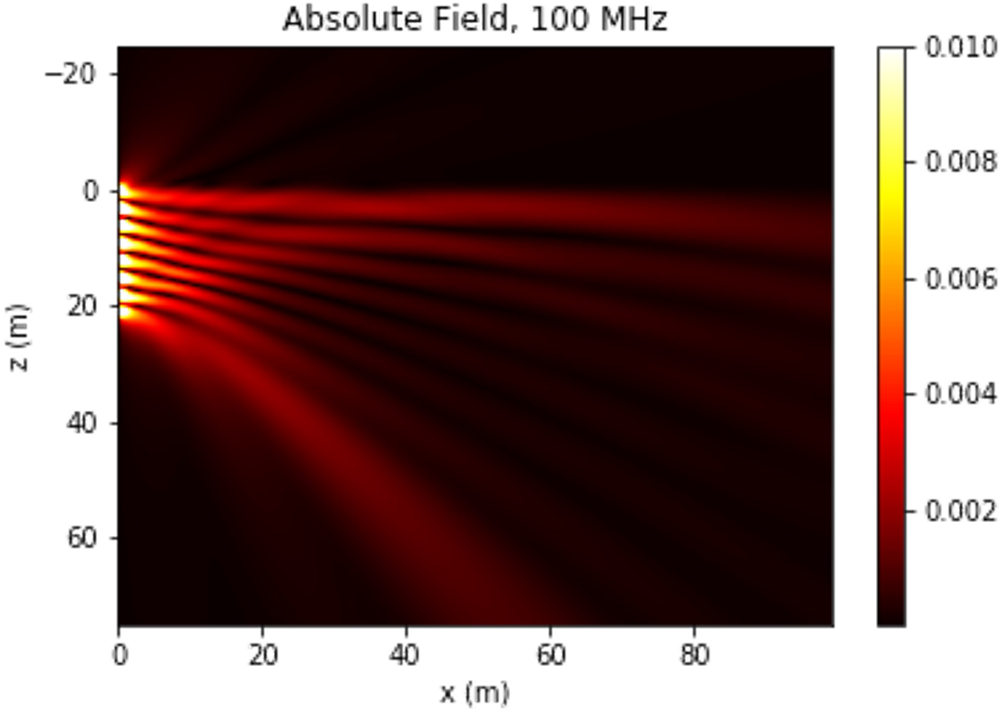

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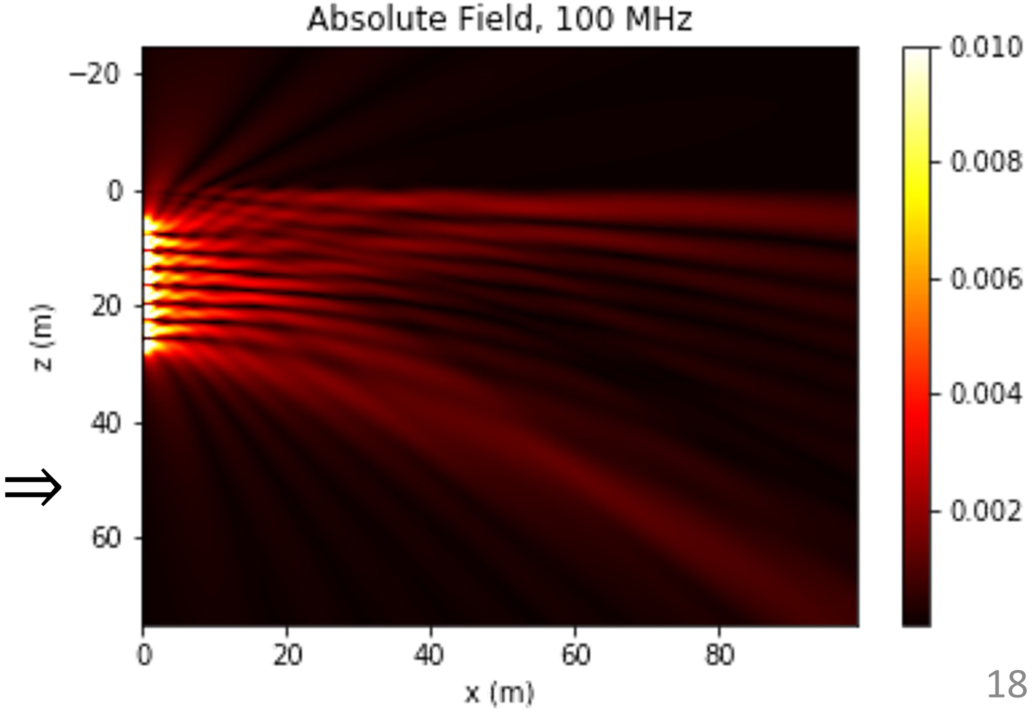
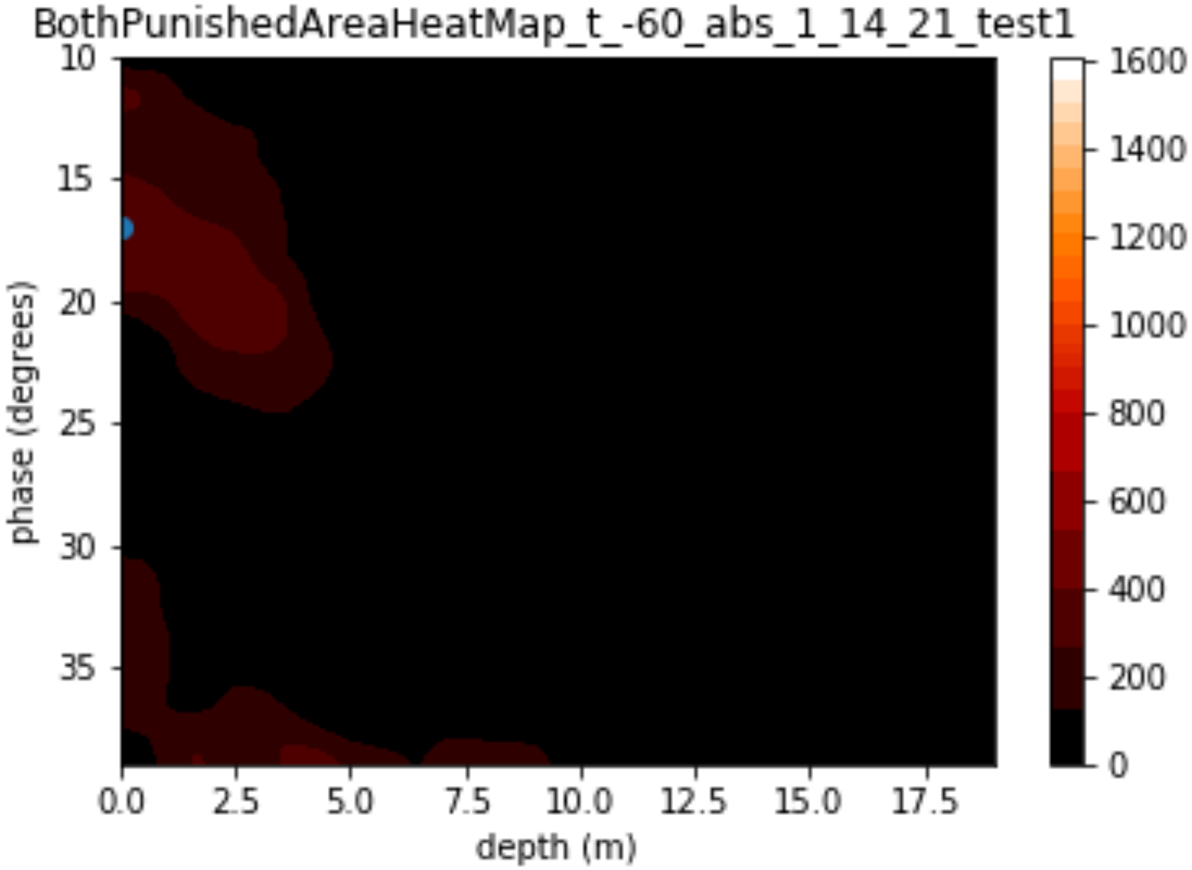
627 ⇒

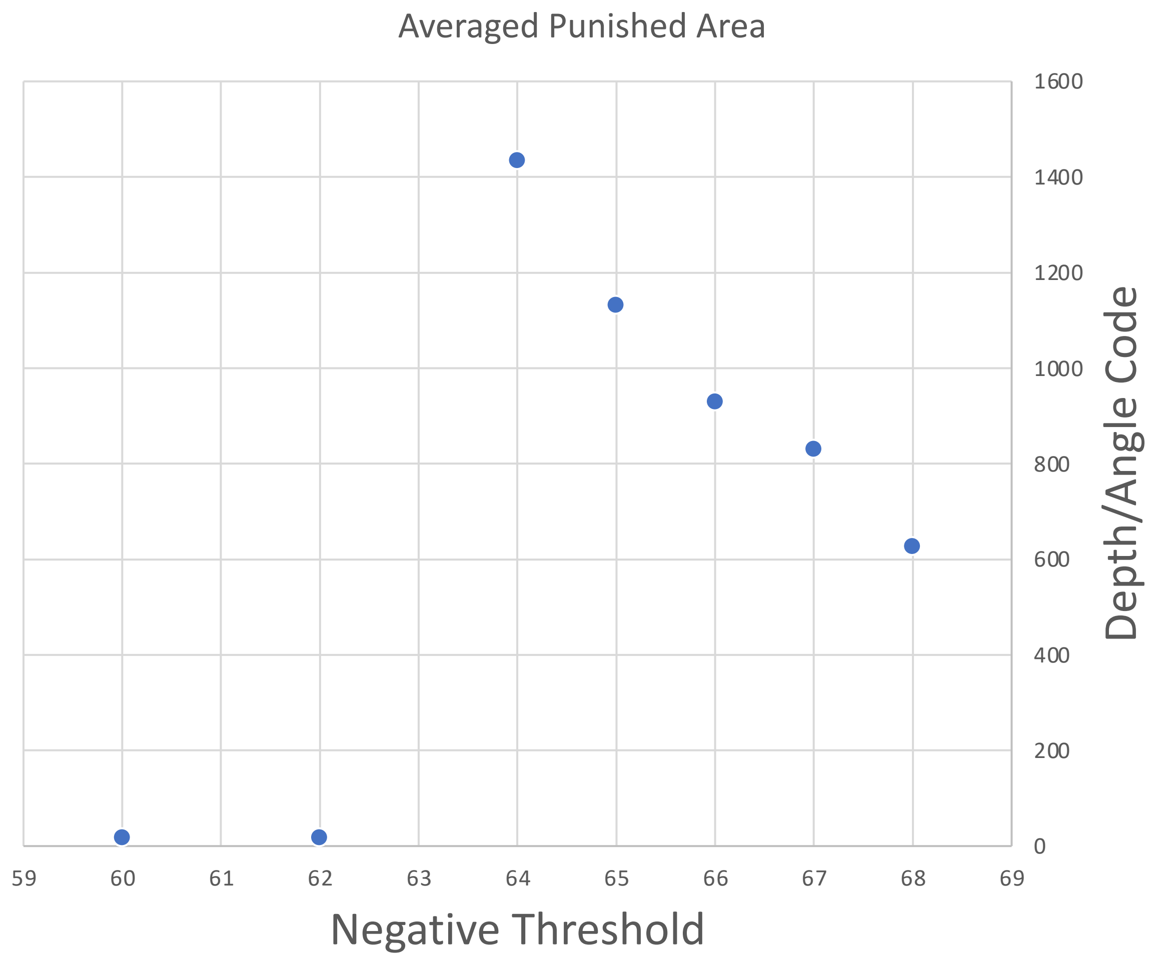


Heat Maps (Averaged Punished Area)

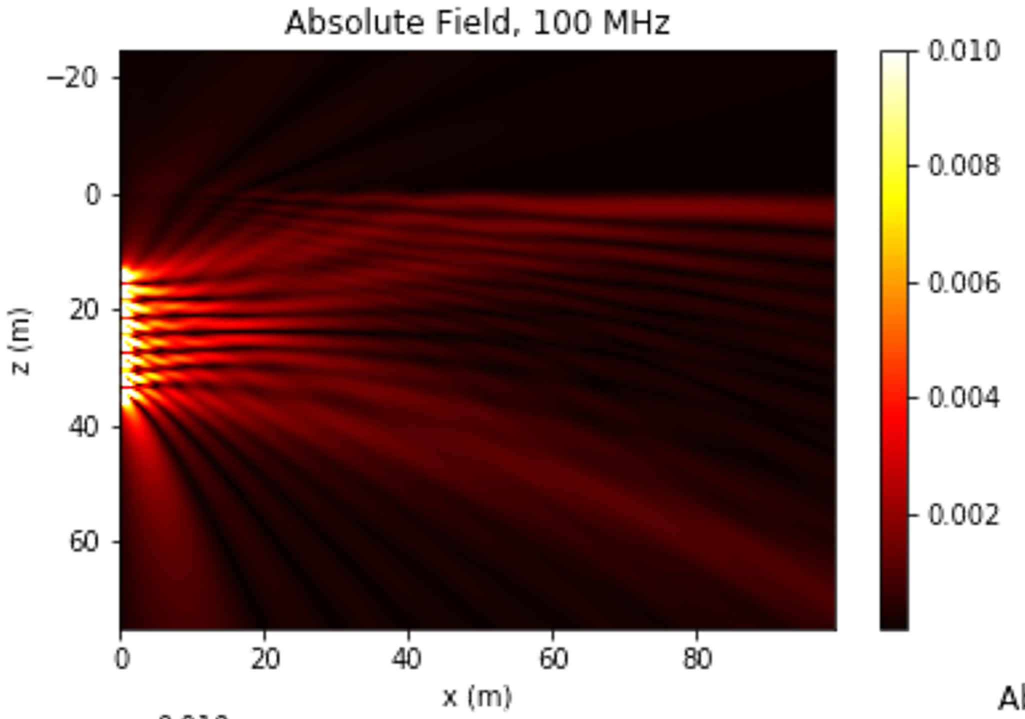


Code vs. Threshold (Averaged Punished Area)

- This shows the convergence of the design code at the critical threshold ($C^*_{abs} = -68$)



Best E Fields



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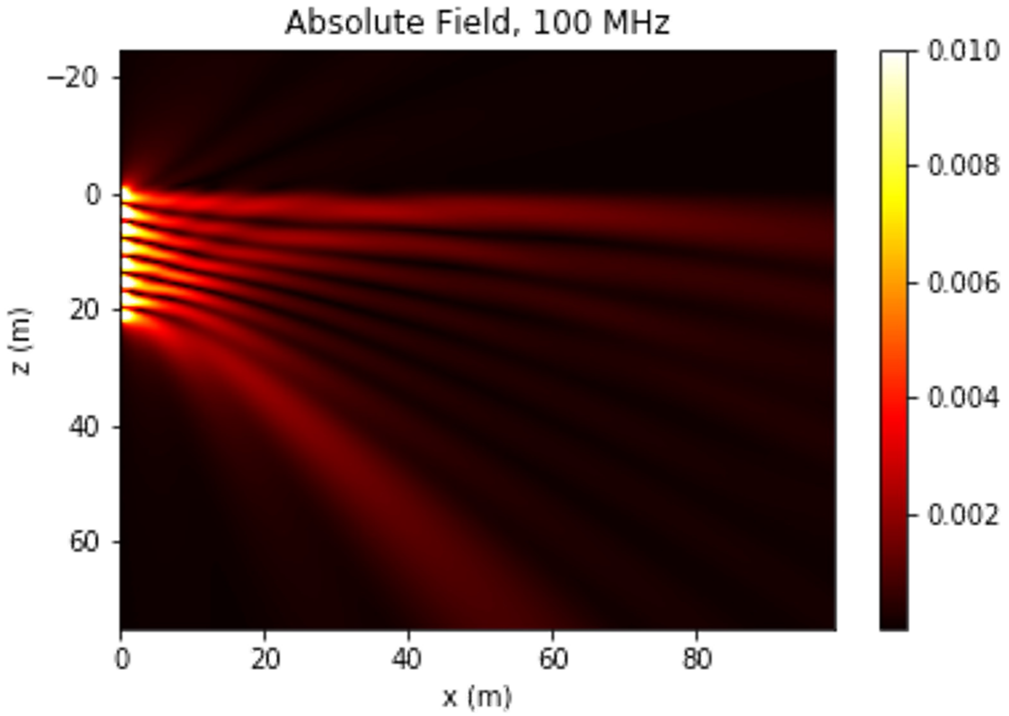

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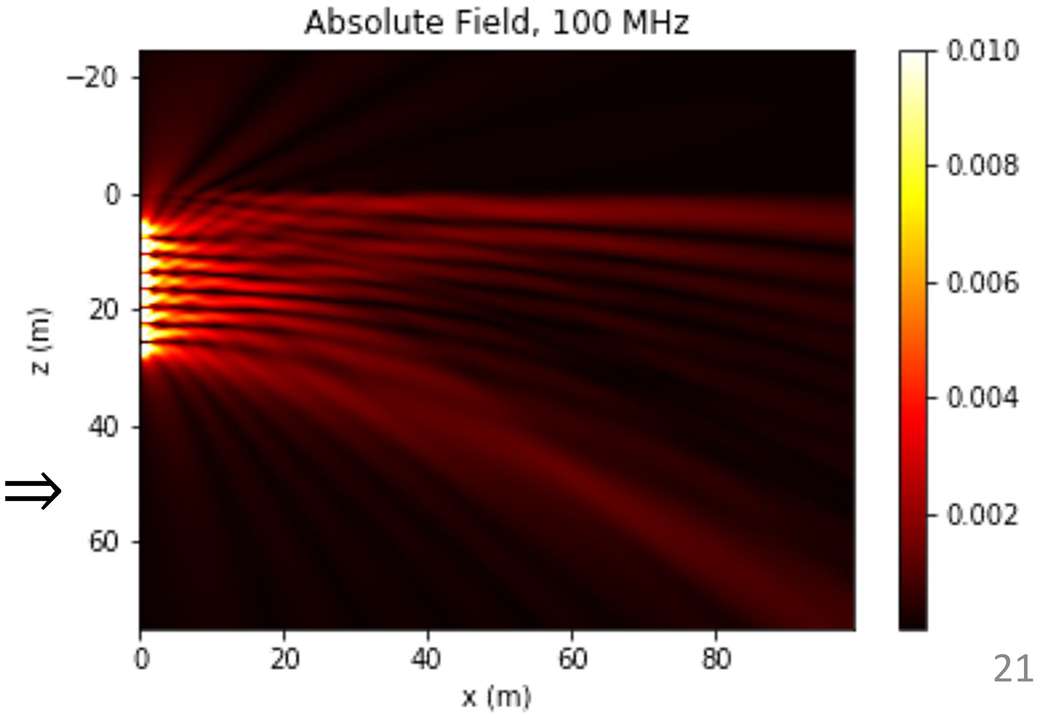
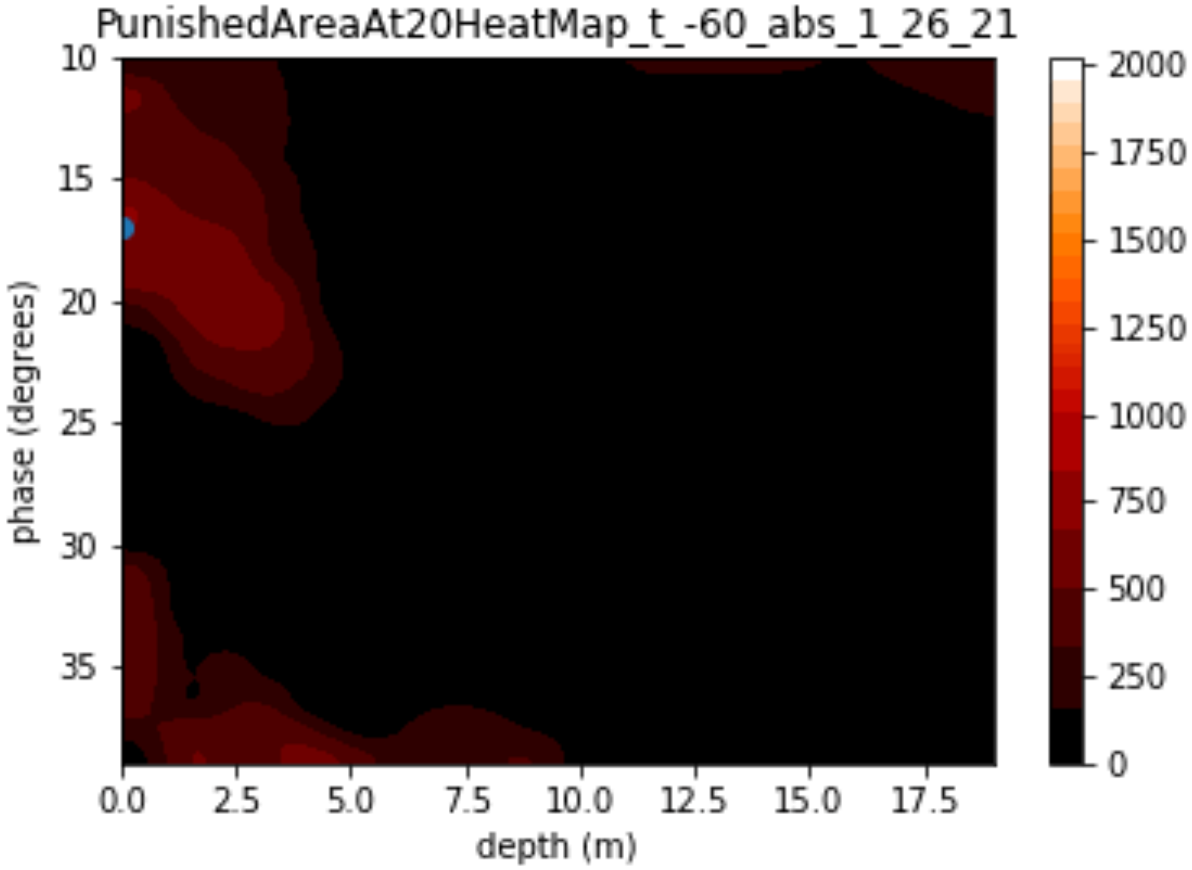
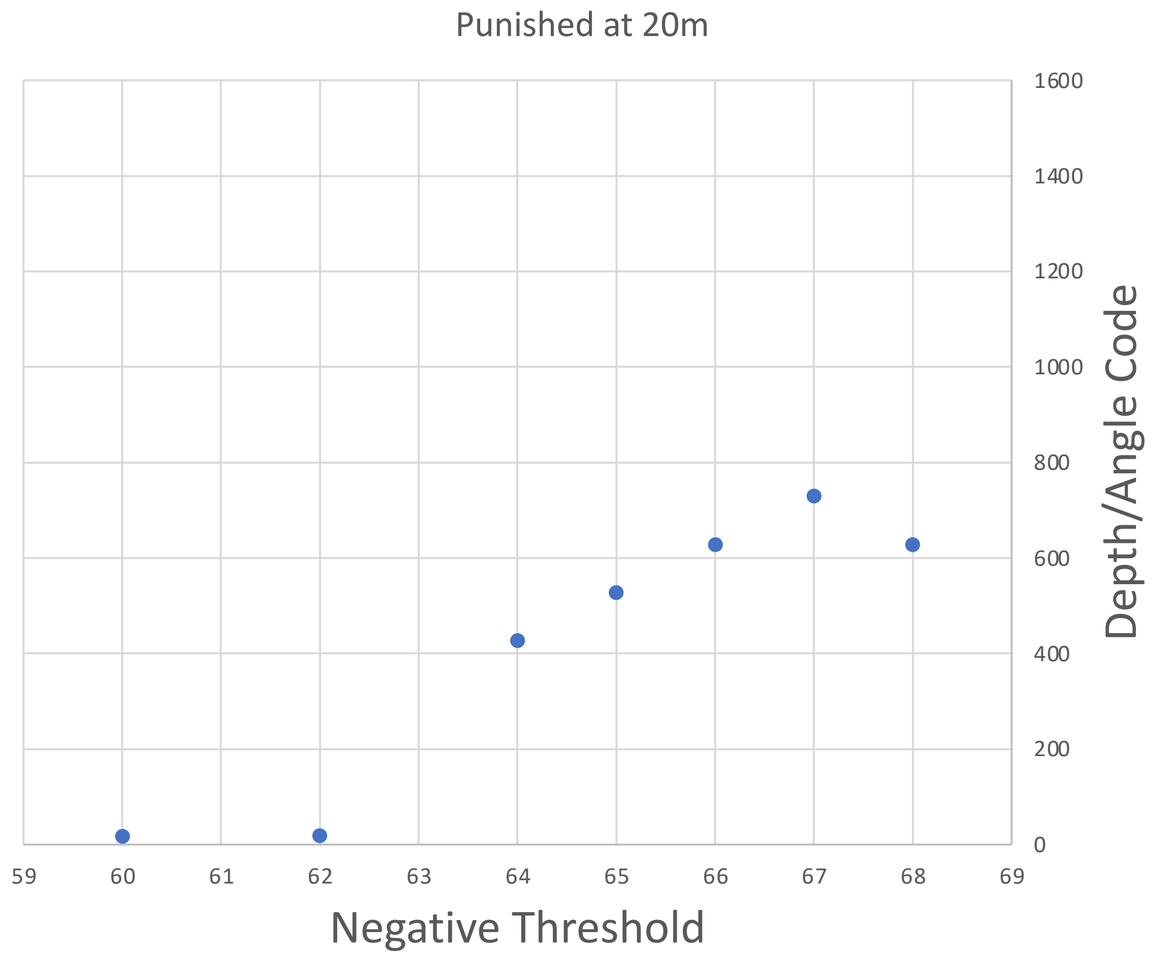


Heat Maps (Punished @ 20m Area)

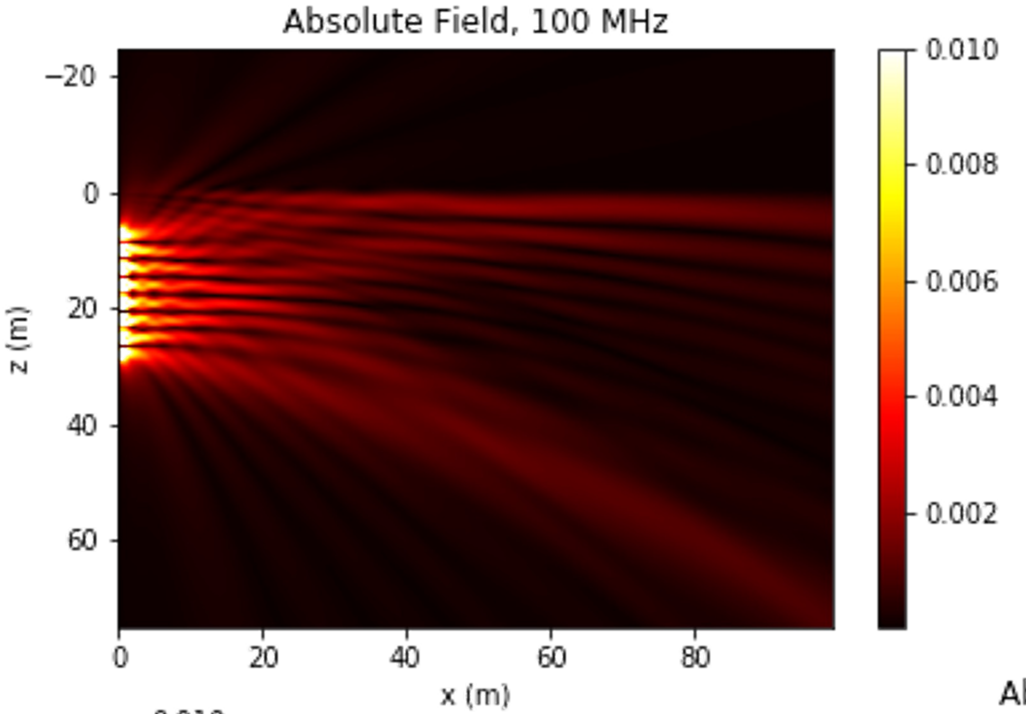


Code vs. Threshold (Punished @ 20m Area)

- This shows the convergence of the design code at the critical threshold ($C^*_{abs} = -68$)



Best E Fields



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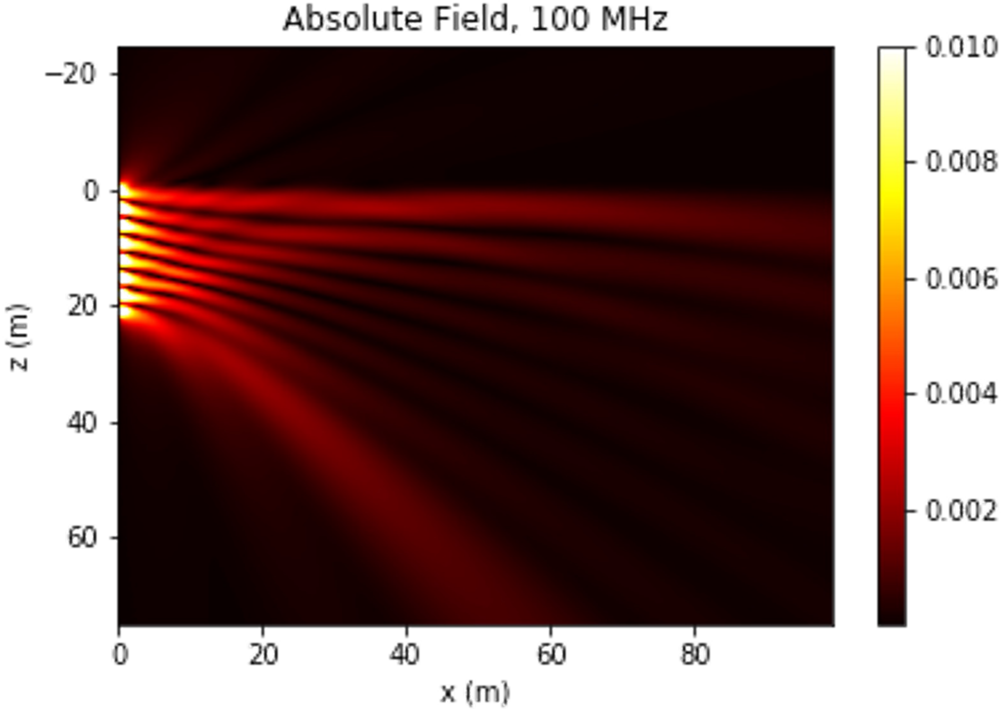

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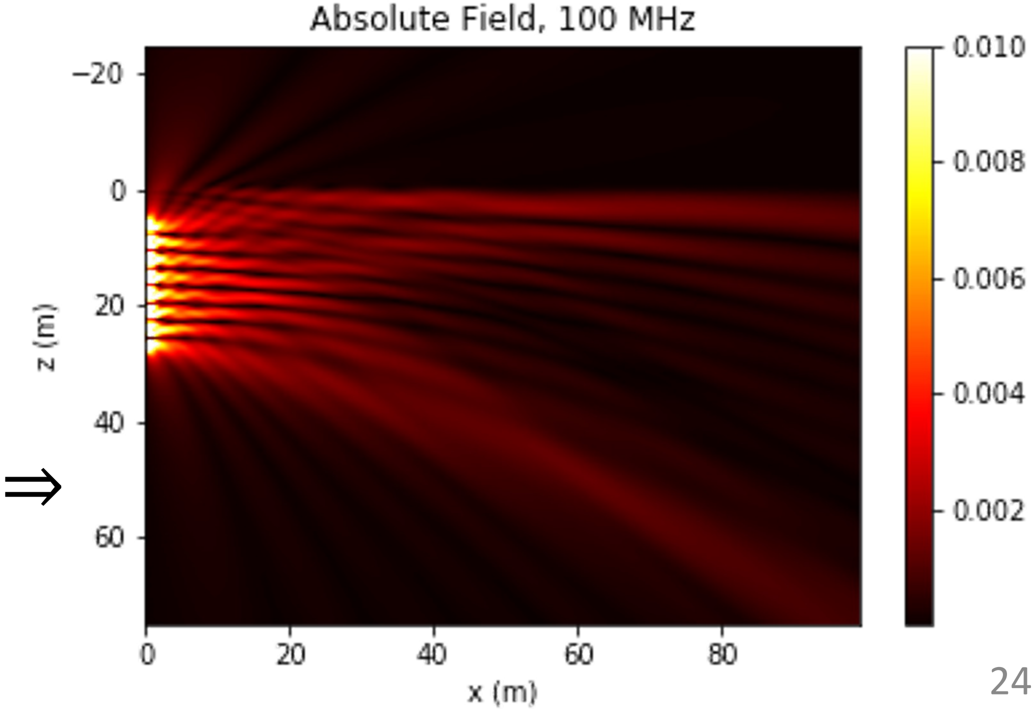
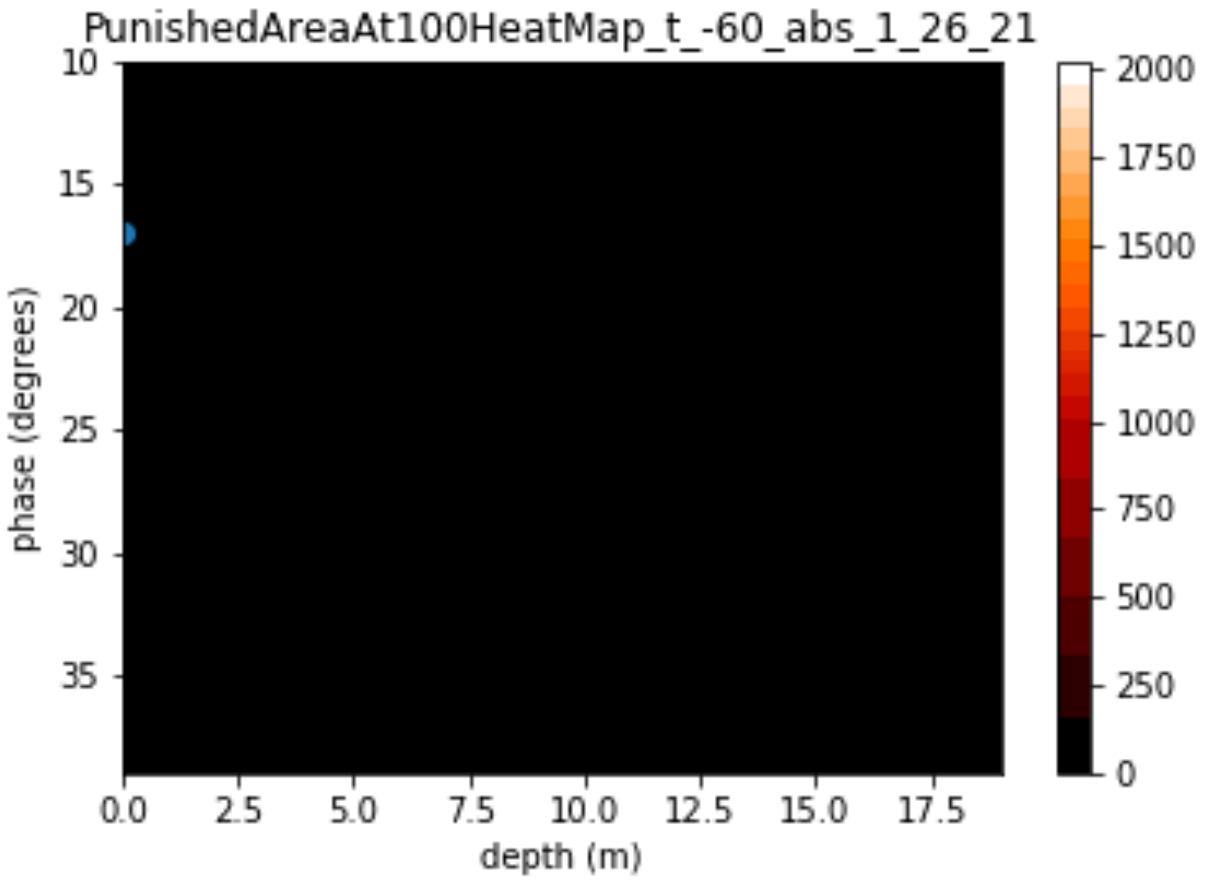
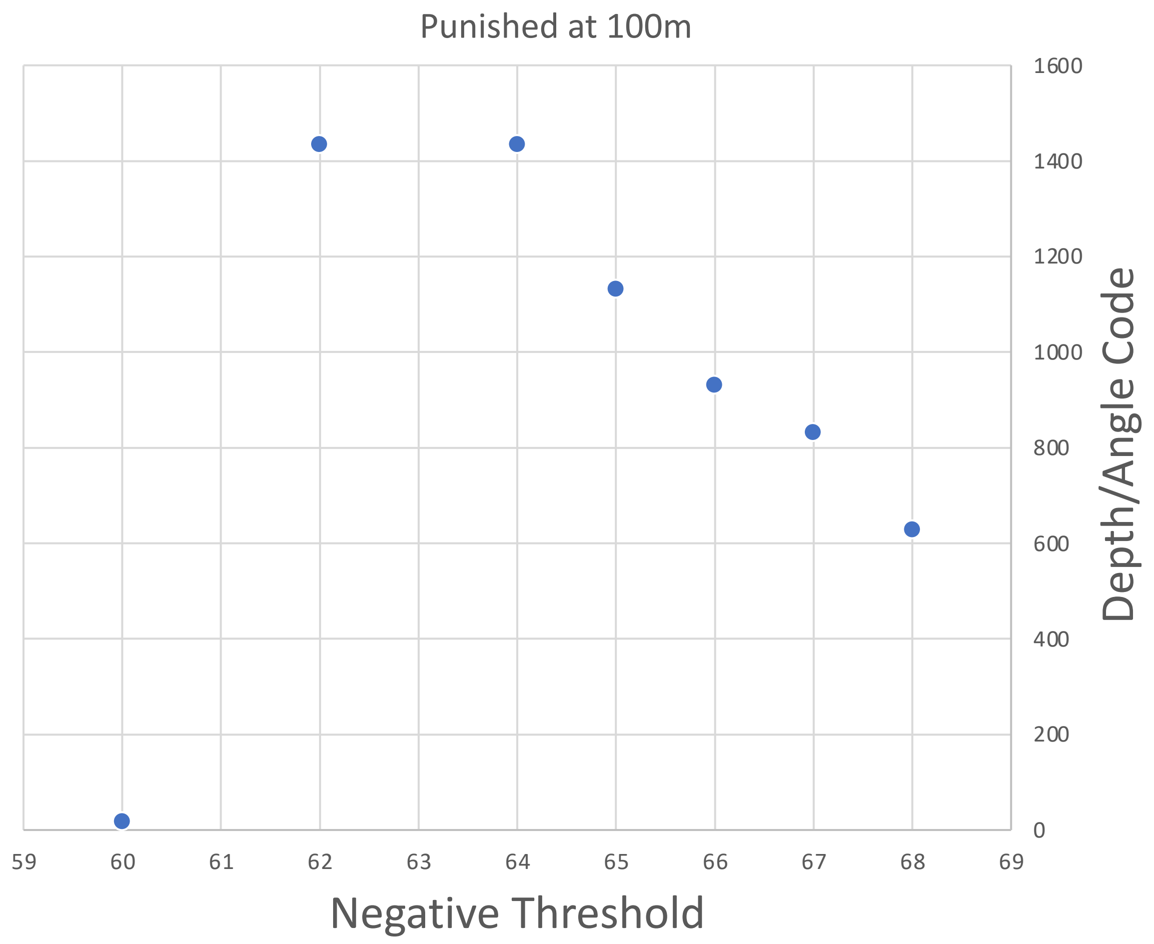


Heat Maps (Punished @ 100m Area)

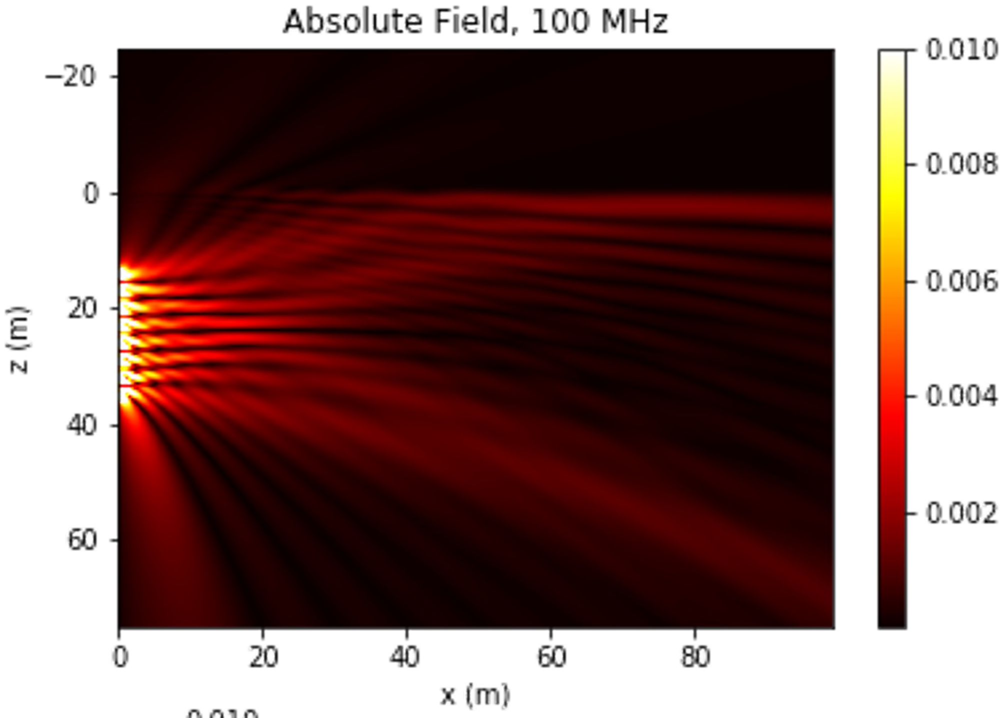


Code vs. Threshold (Punished @ 100m Area)

- This shows the convergence of the design code at the critical threshold ($C^*_{abs} = -68$)



Best E Fields



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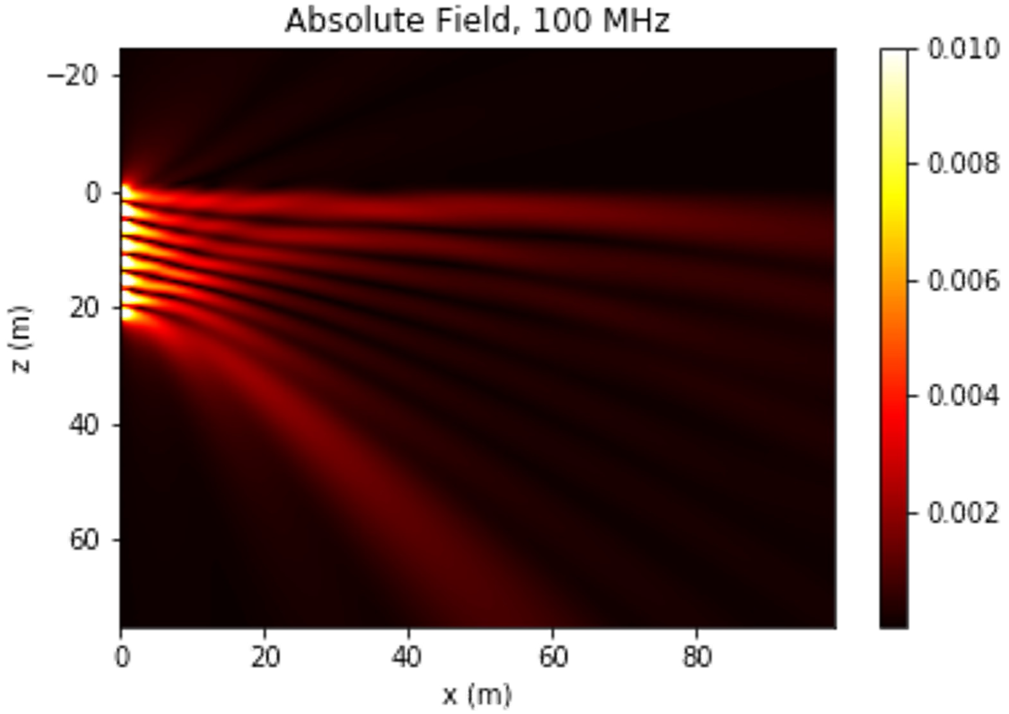

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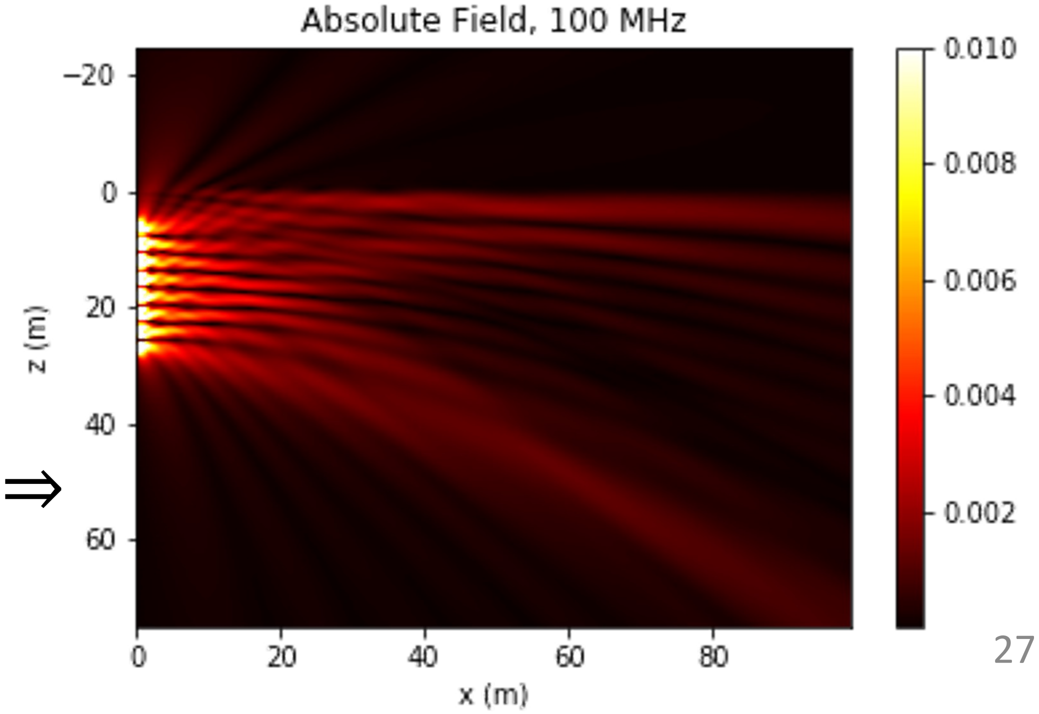


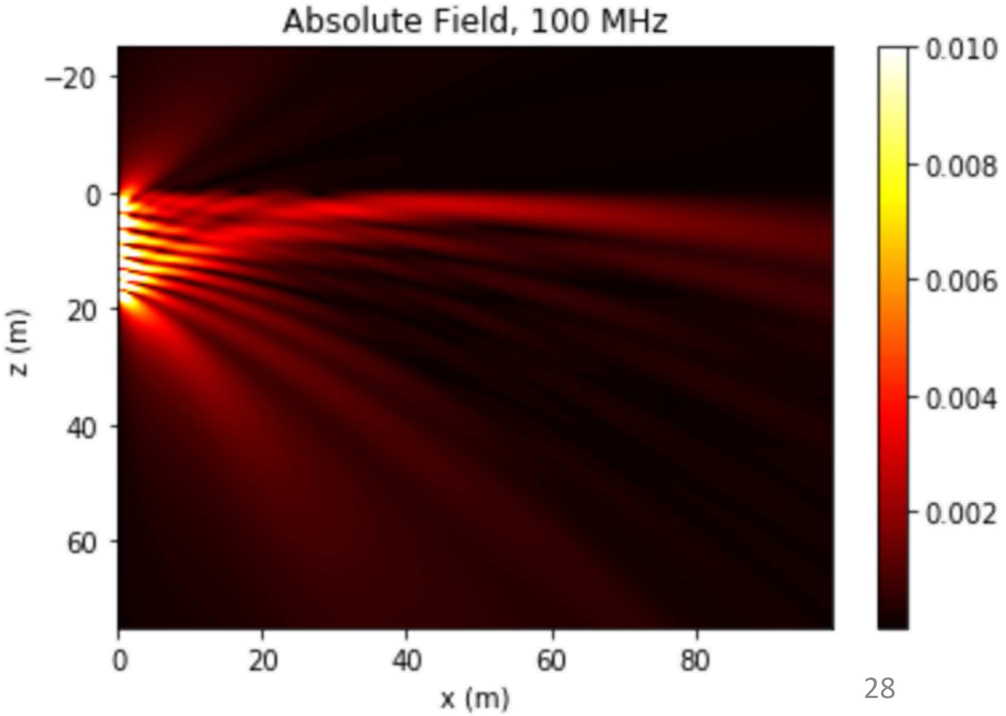
Next Steps

- Using an exponential function for the dipole depths of the form,

$$D(l) = D_o + \lambda_o \cdot a \cdot (1 - \exp\left(-\frac{l}{a}\right))$$

seems to suppress side lobes and concentrate more power towards the surface.

  - l refers to the l^{th} antenna in the array
  - λ_o is the dipoles wavelength
  - D_o is the depth of the top antenna which would still be optimized
  - a is a new optimized parameter.



Conclusion and Next Steps (cont.)

- Using an exponential function for the dipole phases of the form,

$$\text{Phase}(l) = e^{-ik\phi b\cdot\left(1-\exp\left(-\frac{l}{b}\right)\right)}$$

  seems to concentrate the two beams power
  - l refers to the l^{th} antenna in the array
  - b is a new optimized parameter
- Adding the detectors into the simulation and simultaneously optimizing them and the phased array could improve the overall design.