# Automated Pixelated Unit Cell Design for Reflectarray Antennas and Reconfigurable Intelligent Surfaces

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May 2024

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# Background

- Reflect and transmitarray antennas require many iterations of a unit cell to generate the necessary reflected phases to create an array.
- Unit cell iterations are typically done by changing a physical dimension, rotation of the structure, or true time delay to generate the required phases for an array
- Unit cell optimizations take a significant amount of time to run
- A solution to this is to use a subwavelength pixel structure coupled wit

# Motivation

- By using a randomly generated series of subwavelength structures and automating the simulation and data processing its possible to produce unit cells that meet the phase and magnitude requirements to be used in a reflect or transmitarray configuration.

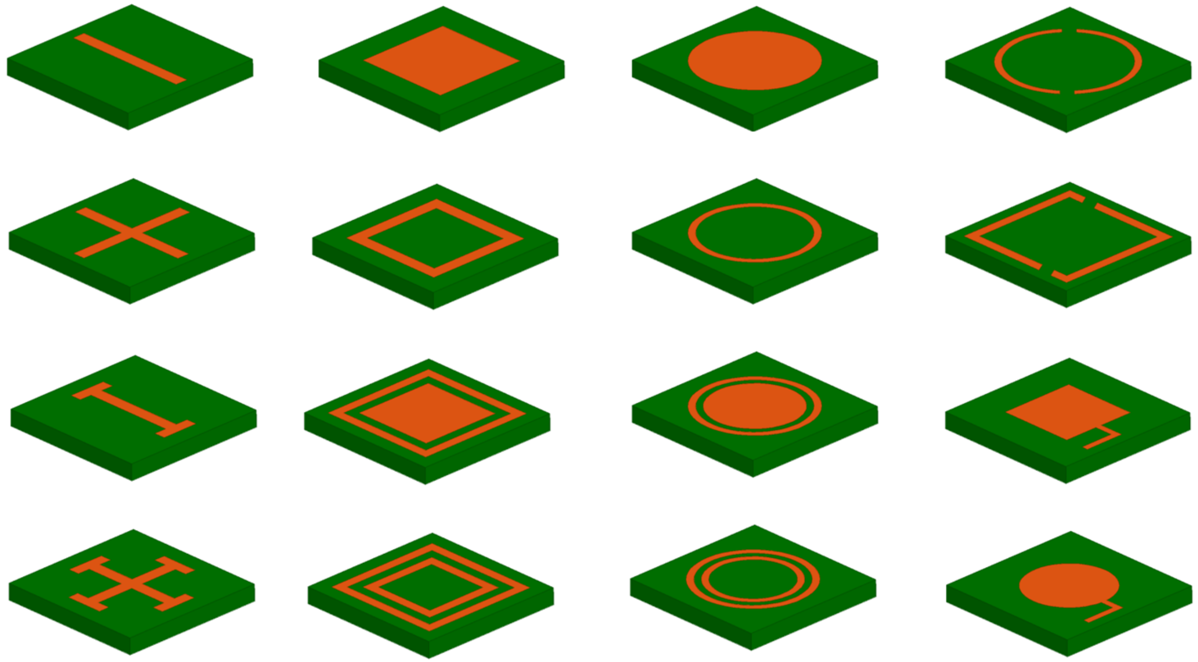
# Presentation Outline

- Background
- Motivation
- Model Overview
  - Historical unit cell construction
  - Analytical array design
  - Subwavelength unit cell construction and generation
  - Traditional Square Patch Generation
- Simulation Process
  - MATLAB-HFSS API Overview
  - Unit Cell Stack Up
  - HFSS Boundary Conditions
- Results
  - Reflected phase over frequency and associated magnitude
  - Array Unit Cell Phase Distribution Plots
  - Analytical Array Gain Plots
- Conclusion

# Model Overview

# Historical Unit Cell Configurations

- Historically to generate the necessary reflected phase and magnitudes required for a reflect or transmistarray 3 parameters are adjusted:
  - Physical dimension is changed
    - E.g. square patch sides are changed, or dipole arms are adjusted
  - True time delay is changed
    - E.g. a transmission line on the unit cell is modified to achieved necessary delay with respect to reflected phase requirement
  - Rotation of a gap in a ring or square
    - E.g. a split ring resonator gap is optimized then rotated to to achieve the necessary phase



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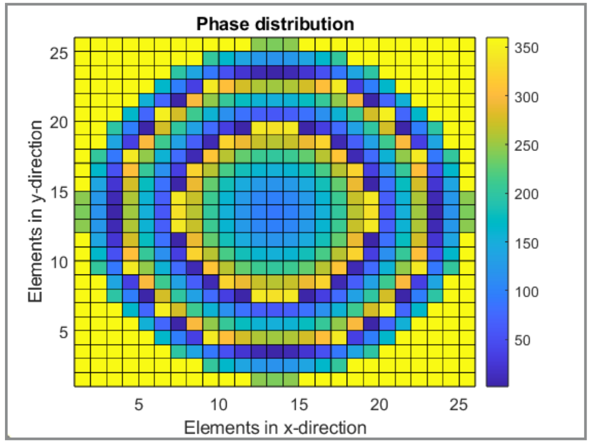
# Analytical Array Design Procedure

1. Calculate the phase distribution for a given beam direction

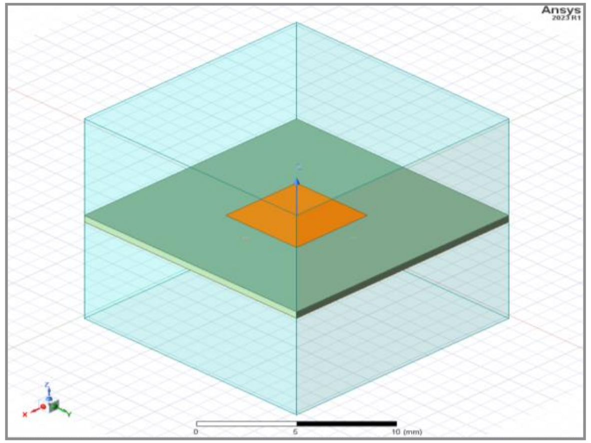
2. Use an EM solver to optimize a unit cell
   - Note: When optimizing a unit cell a physical parameter is varied (size, rotation, ect) to produce a change in phase, or an S-Curve, at a given frequency

3. Analytically calculate the gain of the array
   - Note: You can use an EM solver to do this, but the simulations can take hours to run

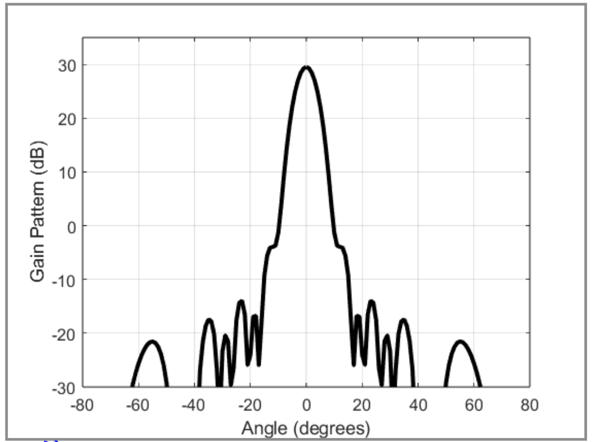
Step 1: Phase Distribution




Step 2: Unit Cell Optimization




Step 3: Gain Calculations

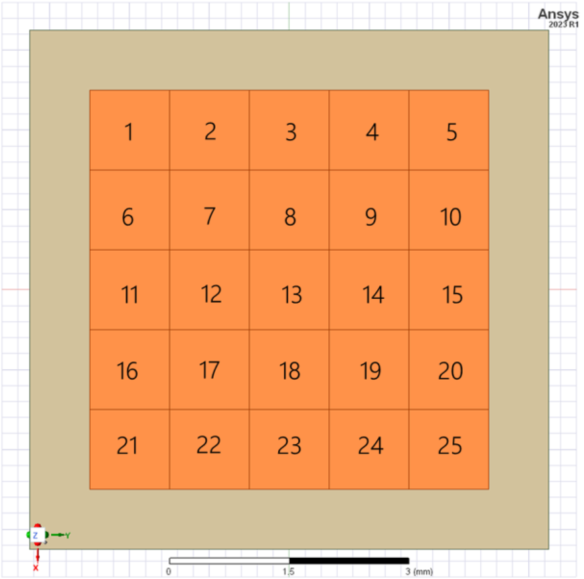


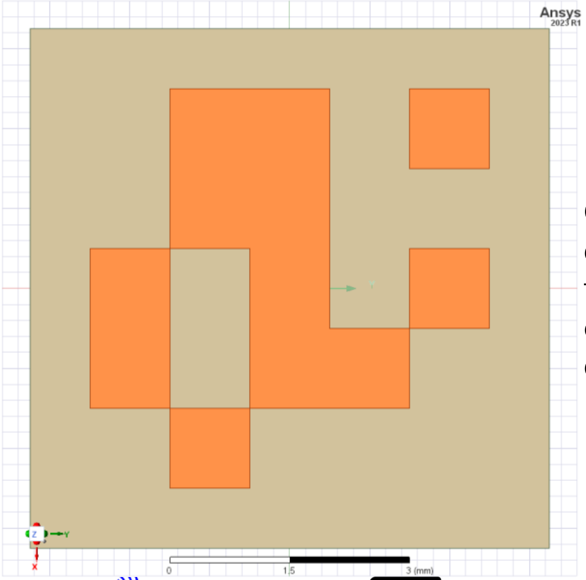
# Subwavlength Unit Cell Structure and Generation

- Current unit cell generation is based on a simple random number generator, although other more advanced algorithms can be used.

1. Generate array of length 25, each element is either 1 or 0.
2. Compare new configuration with a *.mat database file to see if configuration has been run before
3. If configuration has not been run pass array of 1s and 0s to main function
   - The array is length 25 of randomized 1s and 0s. The position of the array corresponds to a pixel. For example, randomUnitCell(13) = 1 that means that the 13th pixel will be generated. However, if randomUnitCell(7) = 0 then the 7th pixel will not be generated. Reference the figure for pixel naming convention.
4. Lastly, the new randomized configuration is saved to *.mat configuration database

Initial model starting location and naming convention

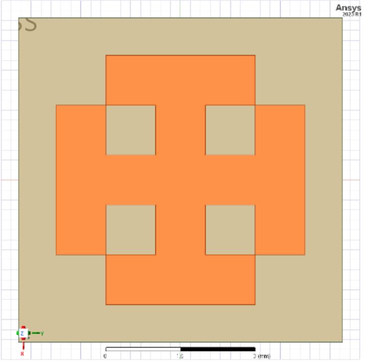


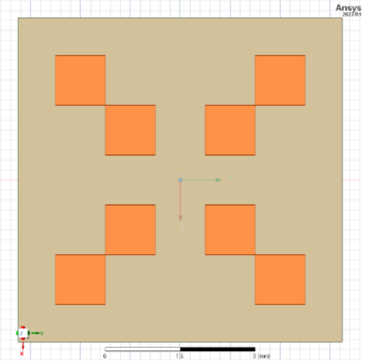

Configuration generated by the randomized configuration generator

# Unit Cell Designs 29 to 36

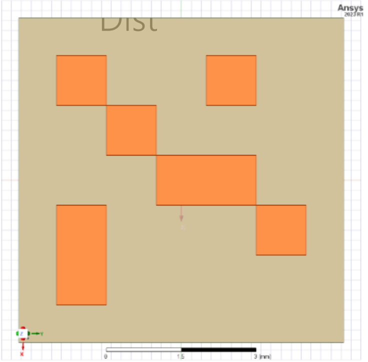
Case 29 | Jerusalem Cross



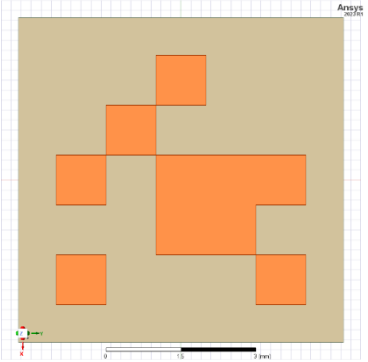
Case 30 | Inverse Jerusalem Cross



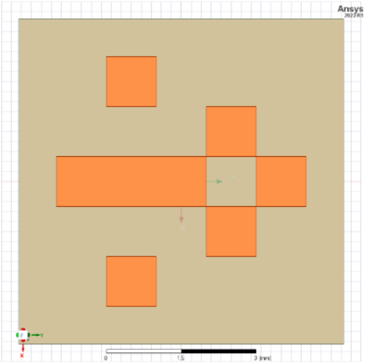
Case 31 | Random Dist



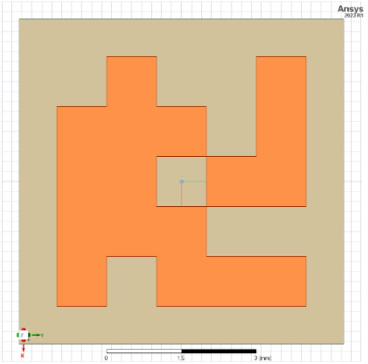
Case 32 | Random Dist



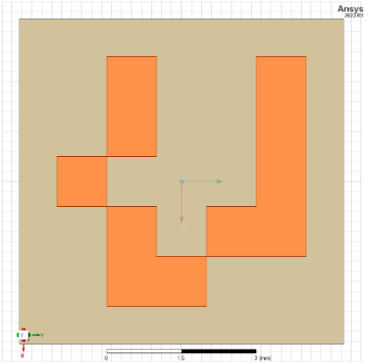
Case 33 | Random Dist



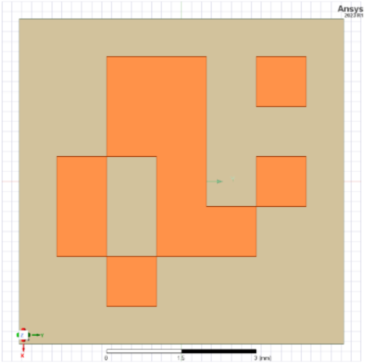
Case 34 | Random Dist



Case 35 | Random Dist

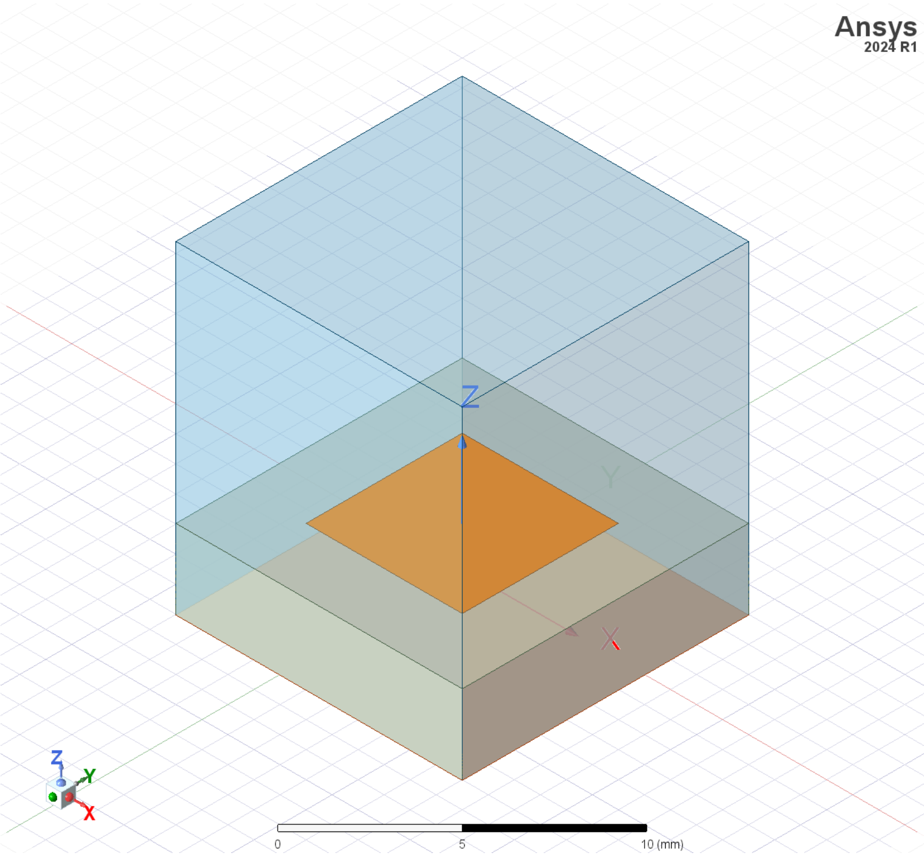


Case 36 | Random Dist



# Square Patch Generation

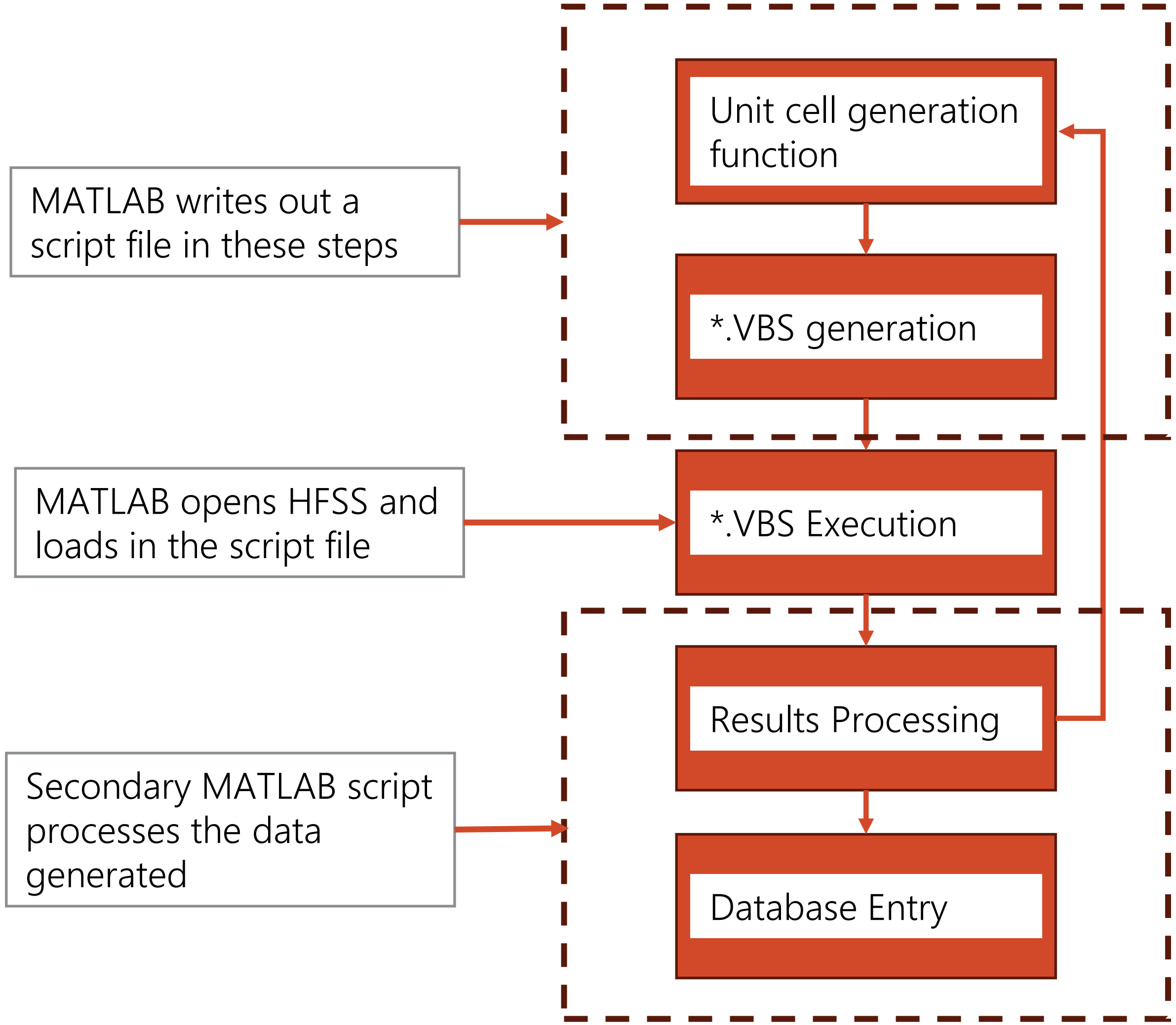
- The square patch shares the substrate, ground plane, boundary conditions with the pixelated unit cell
- The surface conductor, shown, was changed to a patch
- The patch was swept from 0mm : 1mm : 6mm
  - The sweep magnitude of 1mm was chosen as a fair comparison to the pixel configuration. Each pixel is 1 mm x 1 mm



# Simulation Process

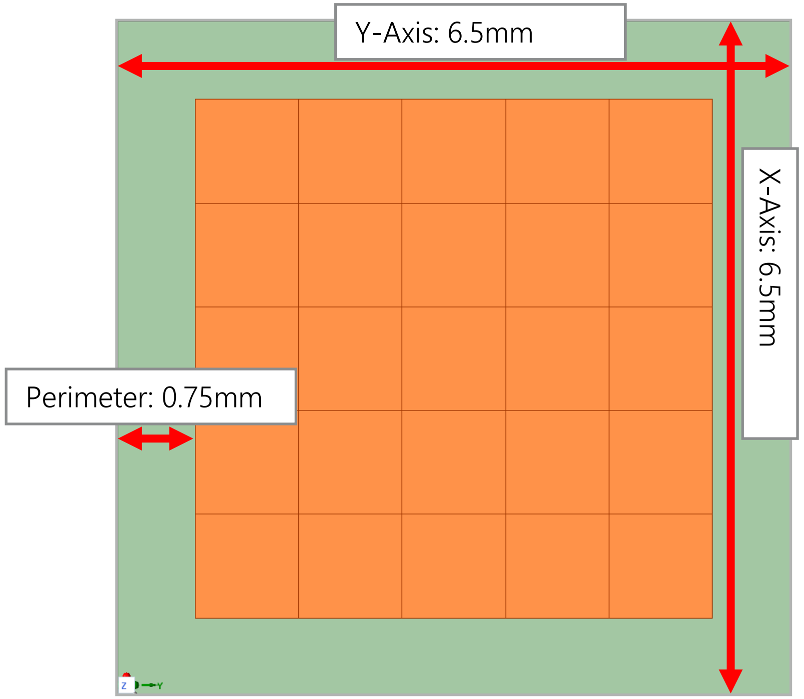
# MATLAB-HFSS API Overview

- MATLAB interface translates MATLAB code into VB scripts (scripting interface used by HFSS).
- The MATLAB code generates the randomized pixelated unit cell, geometric orientation, applies material parameters, boundary conditions, and solution parameters
- MATLAB launches HFSS and executes the simulations
- Post-processing and results database management are handled once the simulation has been run and the data has been exported



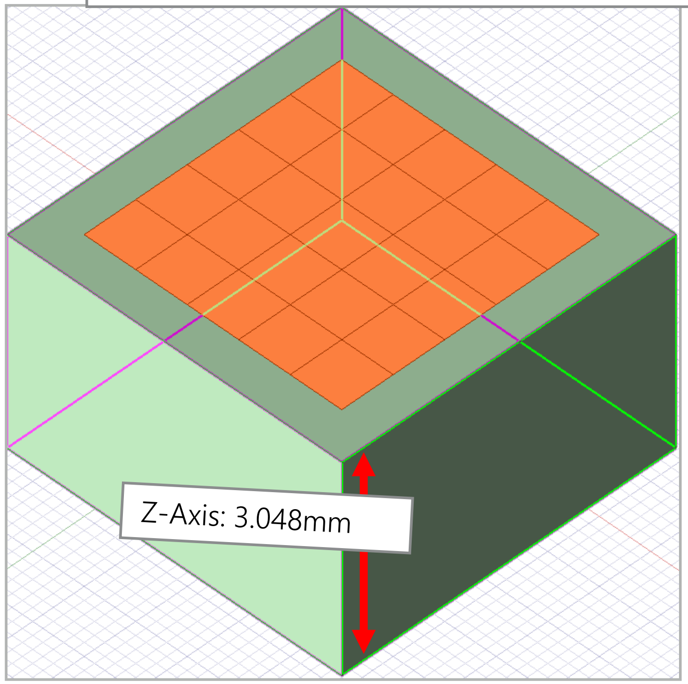
# Unit Cell Stack Up

- Physical Dimensions
  - Substrate: 6.5mmx6.5mmx3.048mm
  - (WxLxH)
  - Pixel: 1mmx1mm (WxL)
    - Note: The patch was simulated as a sheet body with a Perfect E boundary
  - Dielectric Constant: 3.4
  - Tan Delta: 0.02
- Port Setup
  - Floquet port with periodic boundary conditions to excite unit cell
  - Plane Wave Direction: +Z to –Z
- Simulation Setup
  - Frequency: 8GHz to 12 GHz in 100 MHz steps
  - Mesh Frequency: 12GHz




Template design featuring 5x5 pixels for rapid modification

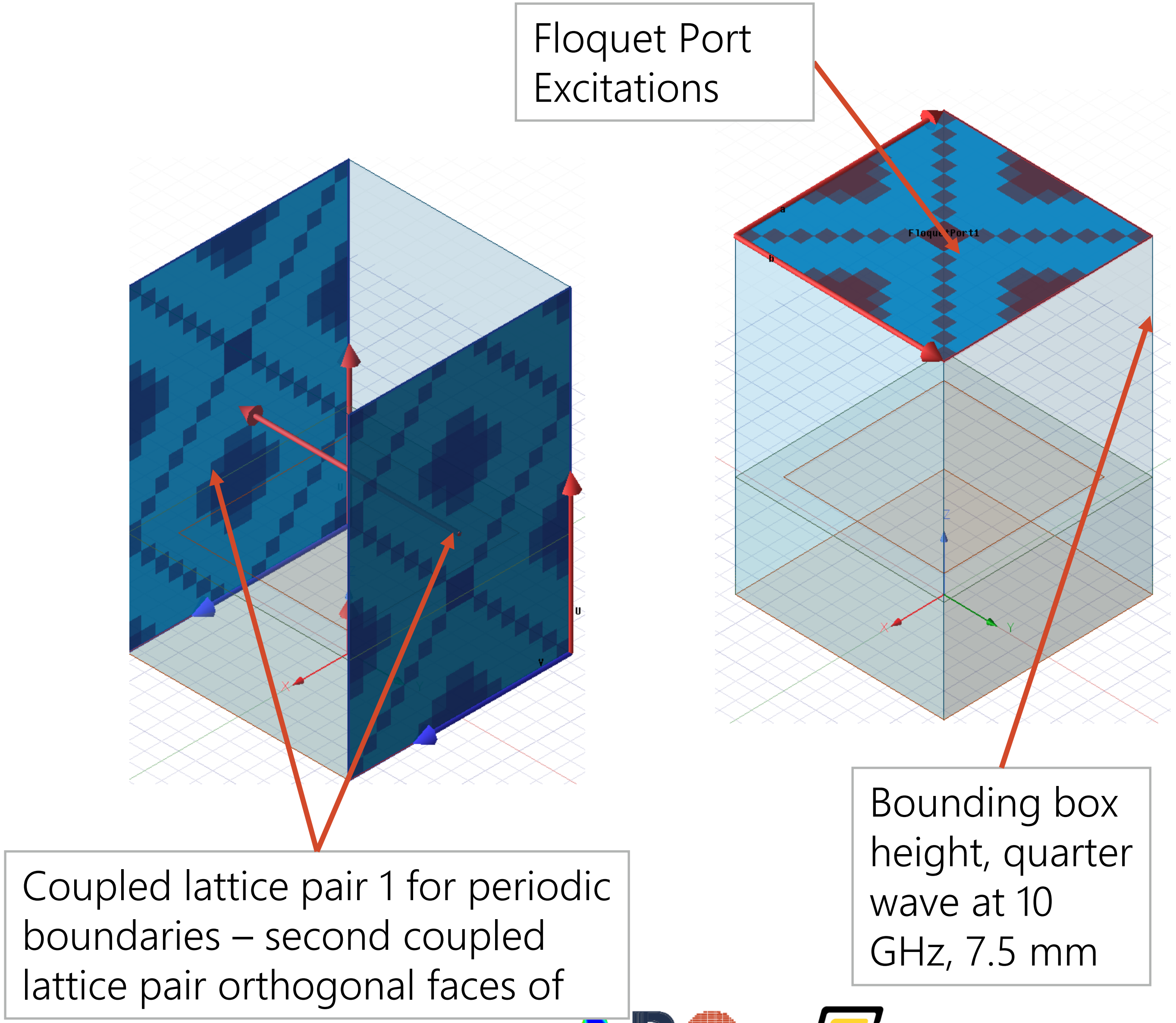
Isometric view of unit cell stack up



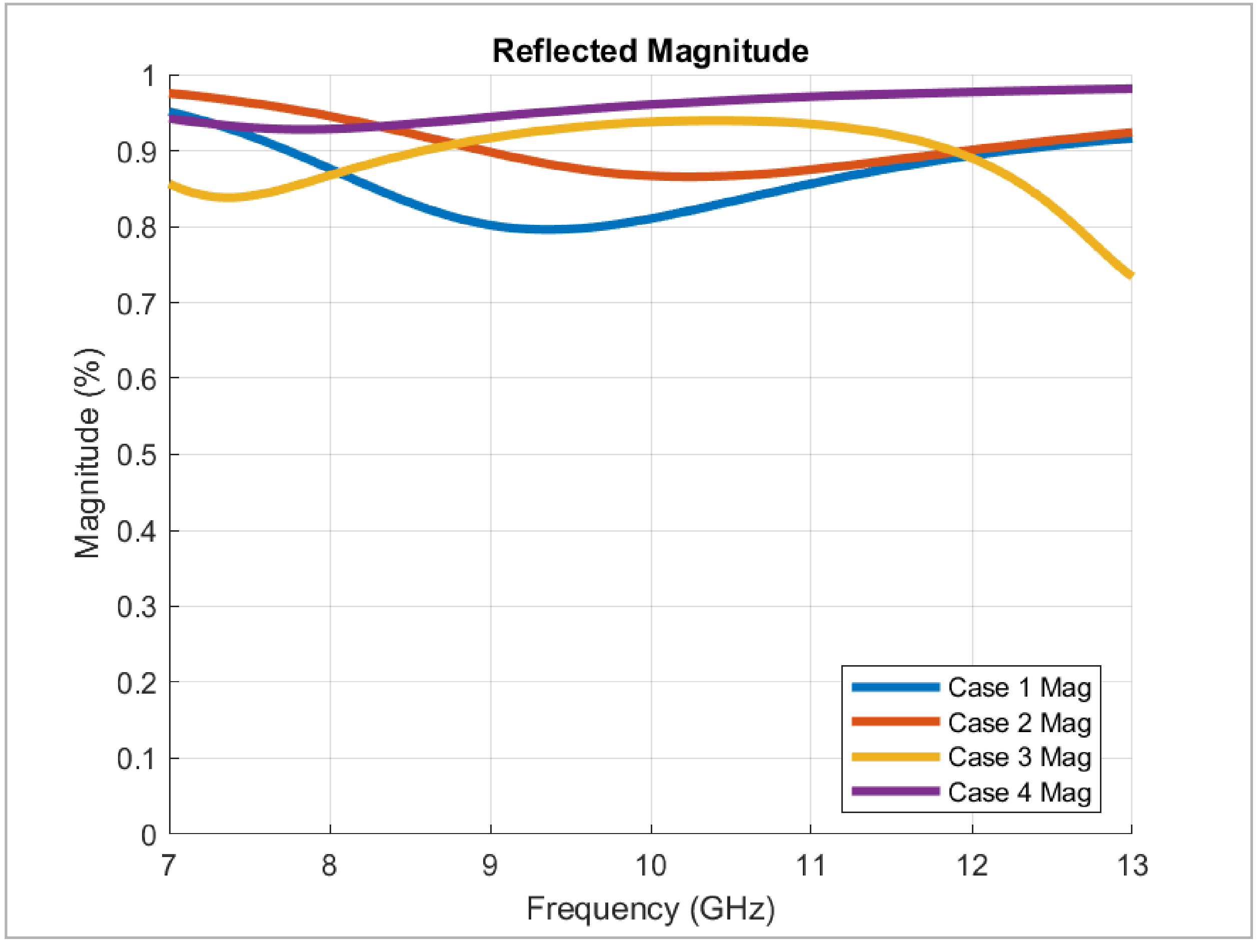
# HFSS Boundary Conditions

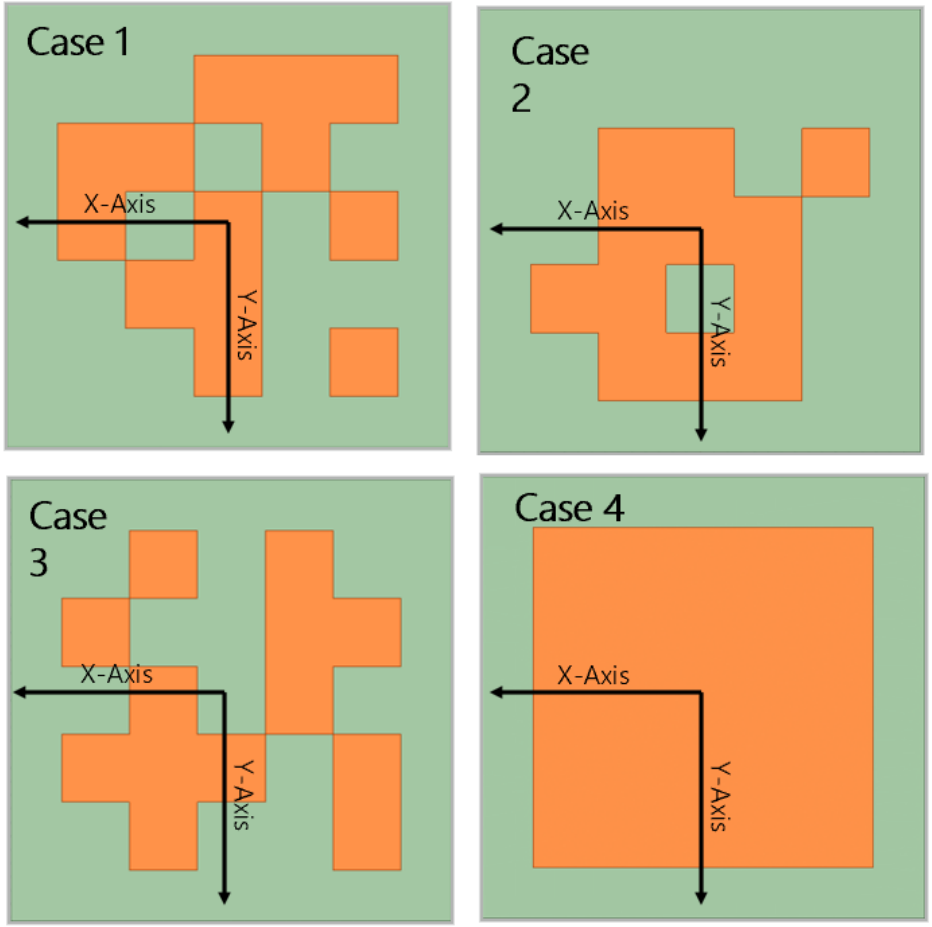
- HFSS requires manual definition of coupled lattice walls

- Floquet port is defined on the face of the bounding box normal to coupled lattice walls
  - Bounding box was defined as a quarter wave at 12 GHz, 6.25 mm
  - Since there is an integrated ground plane only one Floquet port was defined
  - Note: a & b vectors defined as part of Floquet port assignment set periodicity in lattice directions



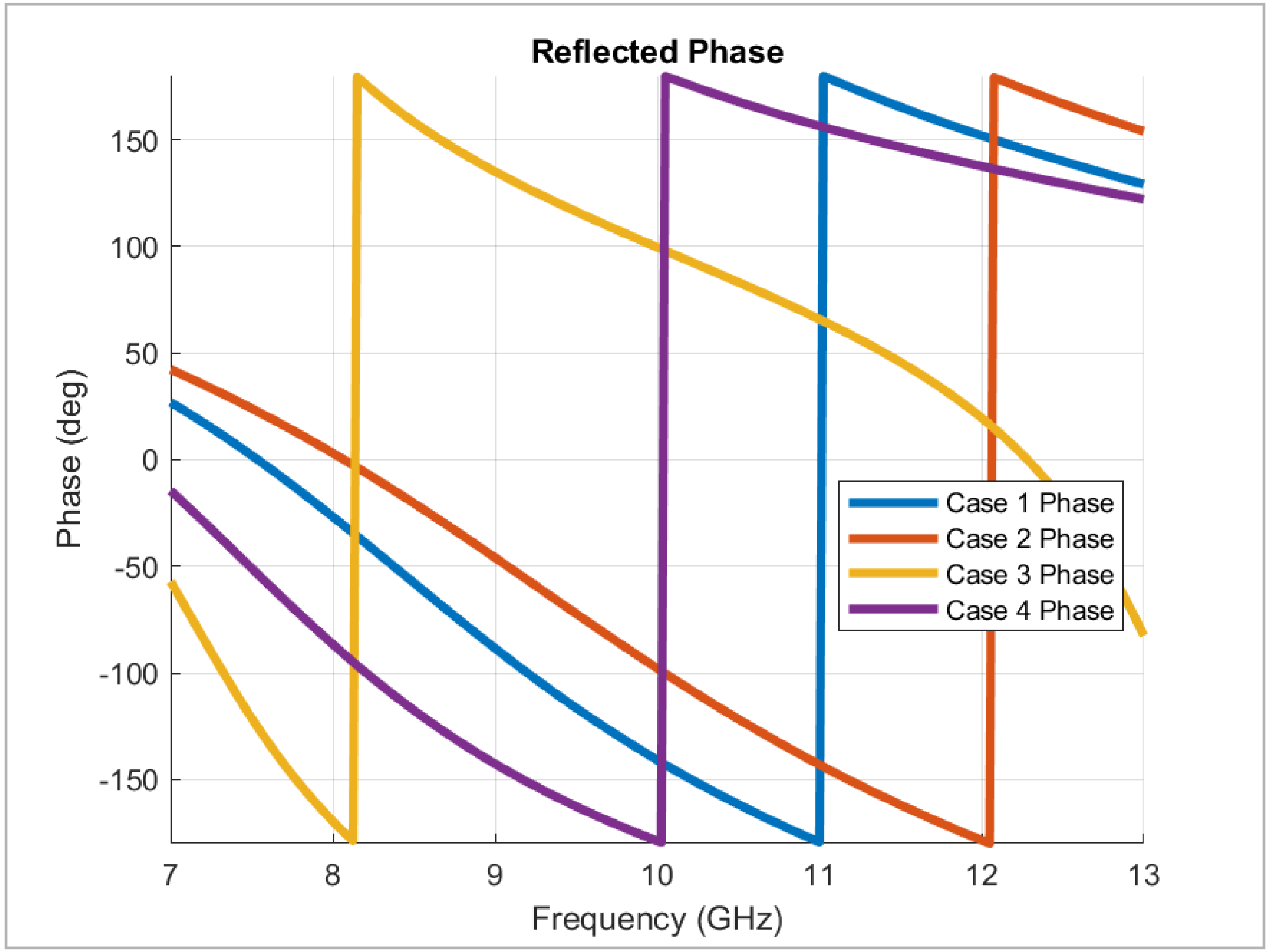
# Sample Reflected Magnitude

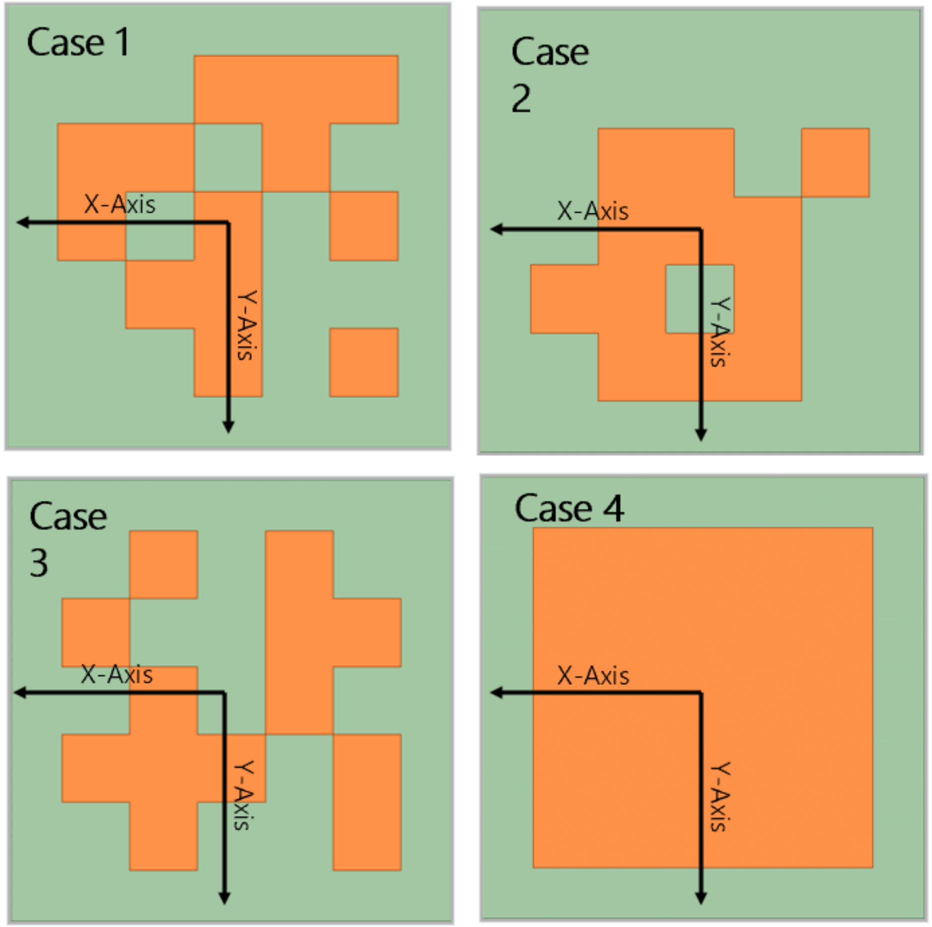



Floquet port S11 data is being plotted.
Note: Magnitude is in percent reflected.

# Sample Reflected Phase



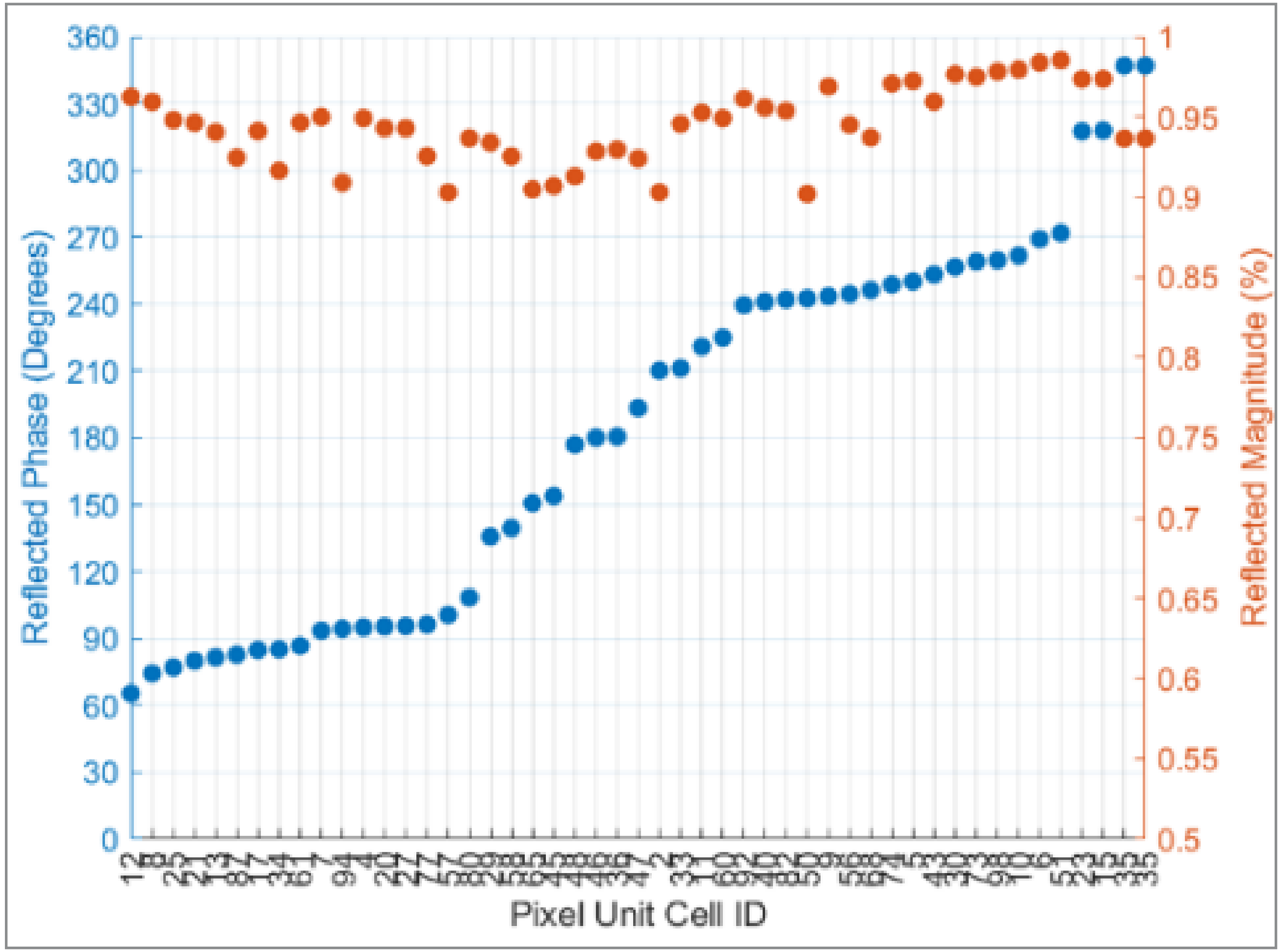




Floquet port S11 data is being plotted.
Note: Magnitude is in percent reflected.

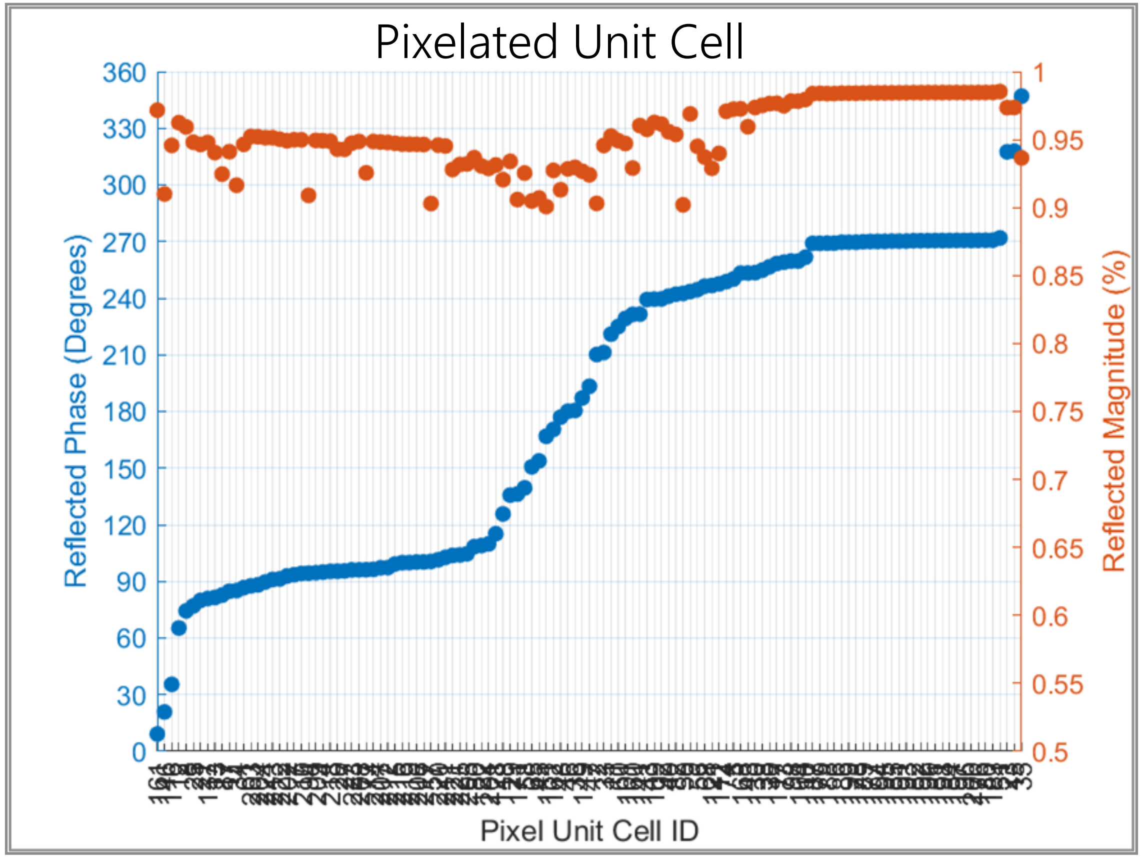
# Results

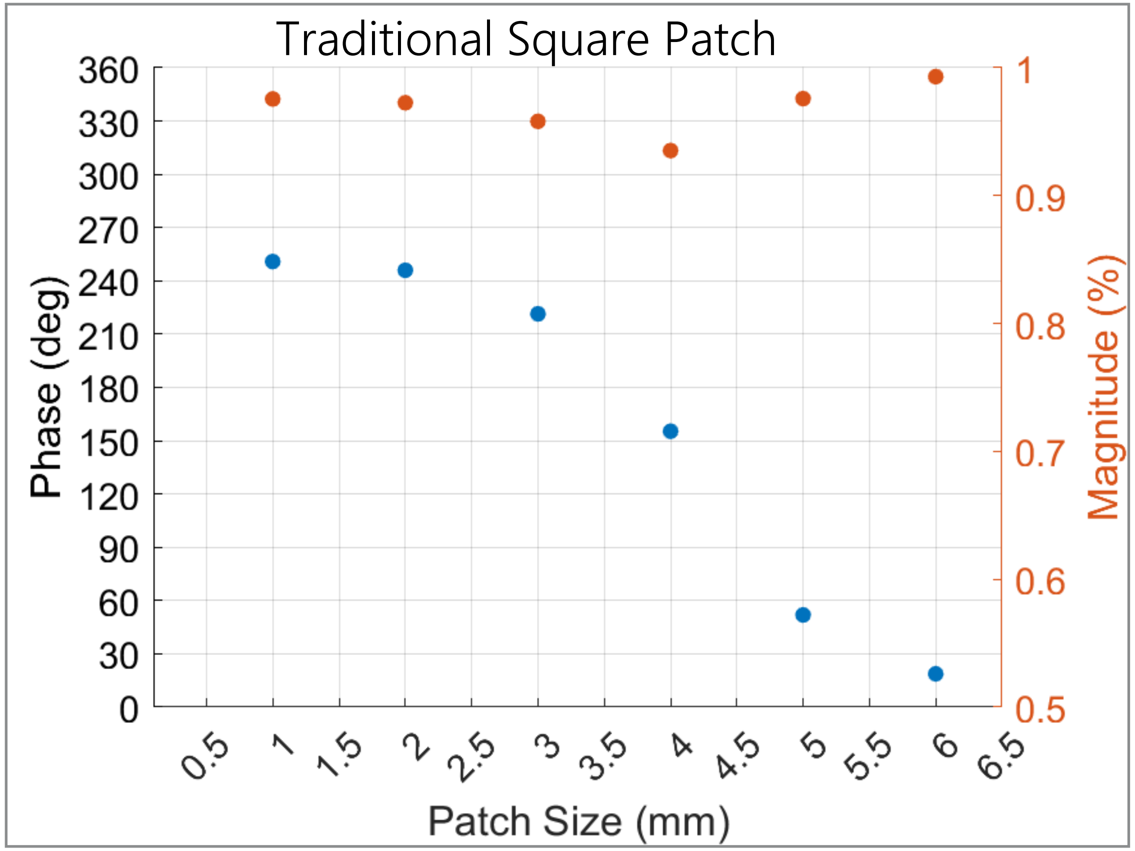
# Reflected Phase versus Frequency and Associated Magnitudes

- Results consist of 100 randomly generated cases at 9 GHz
  - Data was generated from 8.0 GHz to 12.0 GHz in 100 MHz steps
- Of the 100 generated cases 50 cases met the magnitude requirement, mag > 0.9%
- The solution space consists of 2^25 cases, ~33.5 million configurations



# Unit Cell Phase Range – 10 GHz




- Given that the unit cell parameters for both cases are the same the unit cell with the traditional square patch is not large enough to support a full 360 degrees of phase change.
- Unit Cells were simulated from 8.0GHz : 0.1GHz : 12.0GHz data presented is at 10.0 GHz.

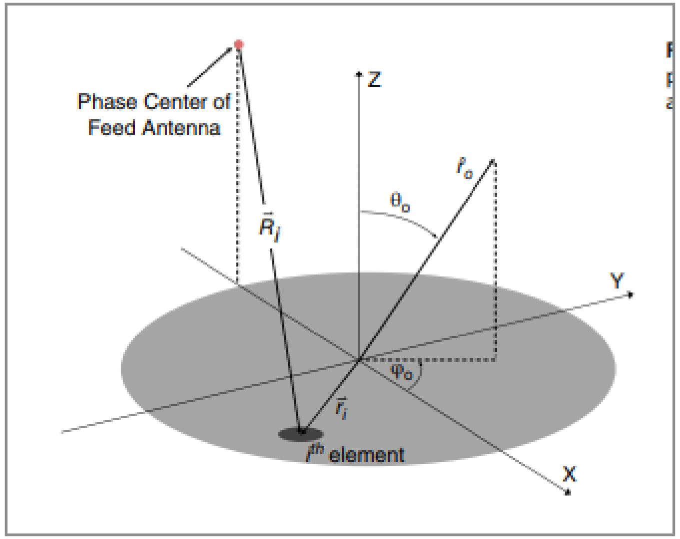
# ReflectArray Designs

- The following slide present data for 3 reflectarray sizes
  - 11x11 unit cell array phase distribution and array gain
  - 30x30 unit cell array phase distribution and array gain
  - 125x125 unit cell array phase distribution and array gain
- We've generated a set of configurations assuming ideal phase is achieved and will use those as a base line of comparison
- In addition, we've created 6 configurations using our simulated reflected phases for the pixelated unit cell and a traditional square patch unit cell
- By substituting the closest phases from each unit cell type into the ideal case we can determine what the array phase profile will look like as well as the new configurations achieved gains.

# Element Phase Distribution Calculation

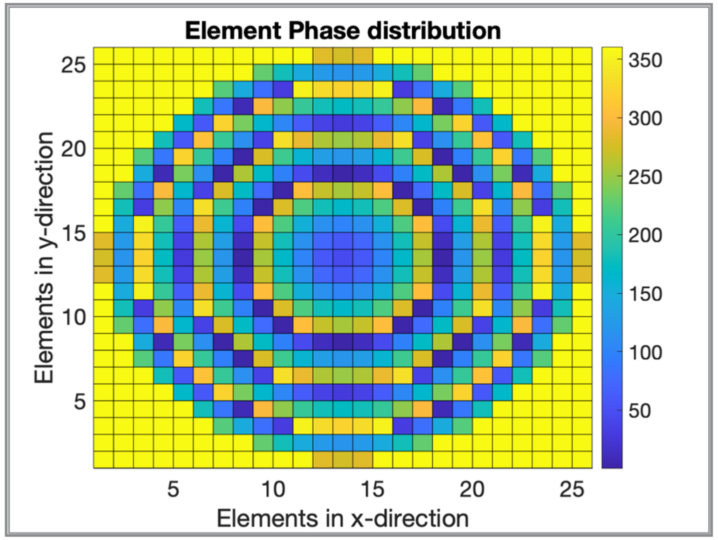
$$\phi_{RA} = K_o(R_i - sin\theta_o(X_i Cos\varphi_0 + Y_i Sin\varphi_0)) + \phi_0$$ [1]

- $K_o$ is the wave number
- $R_i$ is the radial distance from the center of the element to the feed horn
- $\theta_o$ & $\varphi_0$ Are beam location in spherical coordinates
- $X_i$ & $Y_i$ are the position of each element in the array at the element's center
- $\phi_0$ Is a relative phase constant term
- Note: This element phase distribution can be used for either a reflect OR transmitarray




Geometric representation of element phase with respect to the feed antenna

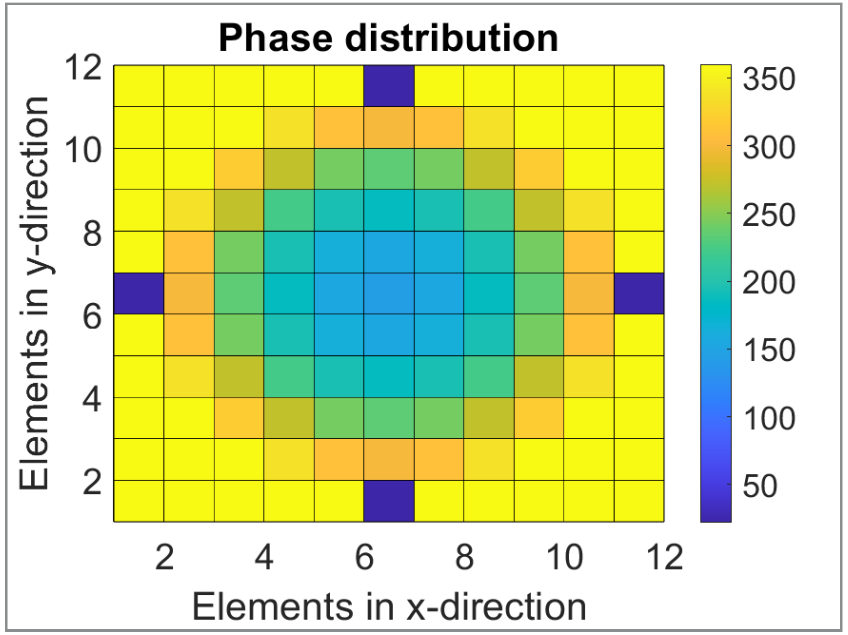
Resulting element phase distribution plot



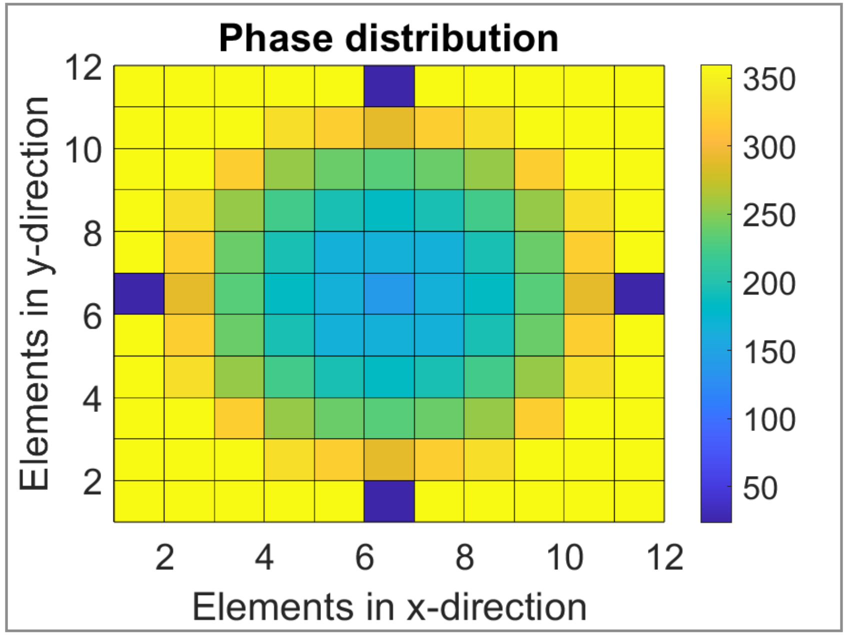


[1] P. Nayeri, F. Yang, A. Elsherbeni (2018) "Reflectarray Antennas Theory, Design, and Application" – Equation 2.4

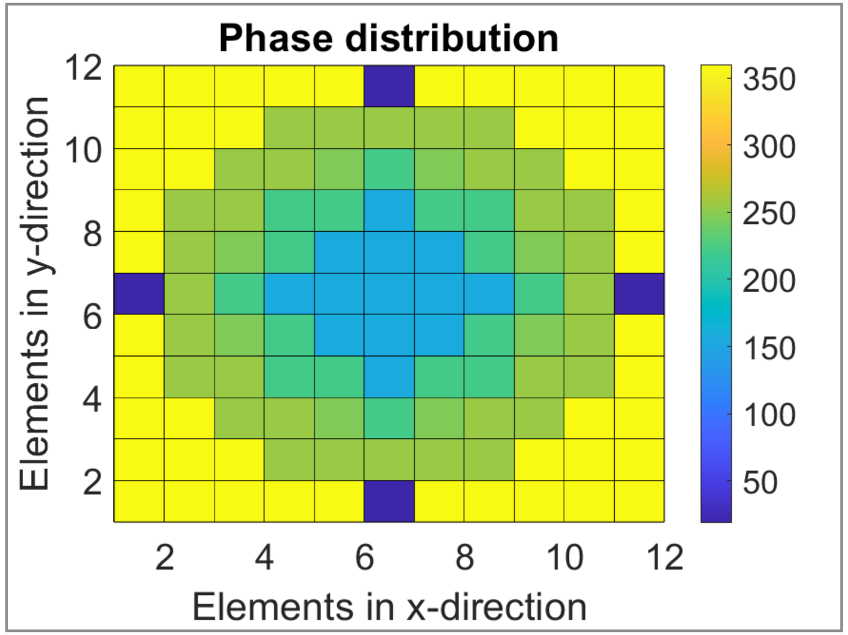
# 11 x 11 Unit Cell Phase Distributions




Ideal Phase Distribution




Pixelated Phase Distribution




Patch Phase Distribution

- With a small array of unit cells there are too few required phases to show differences between the ideal phase distribution and the pixelated phase distribution
- Its evident even with a small array of unit cells that the square patch does not have enough fidelity to produce an adequate phase distribution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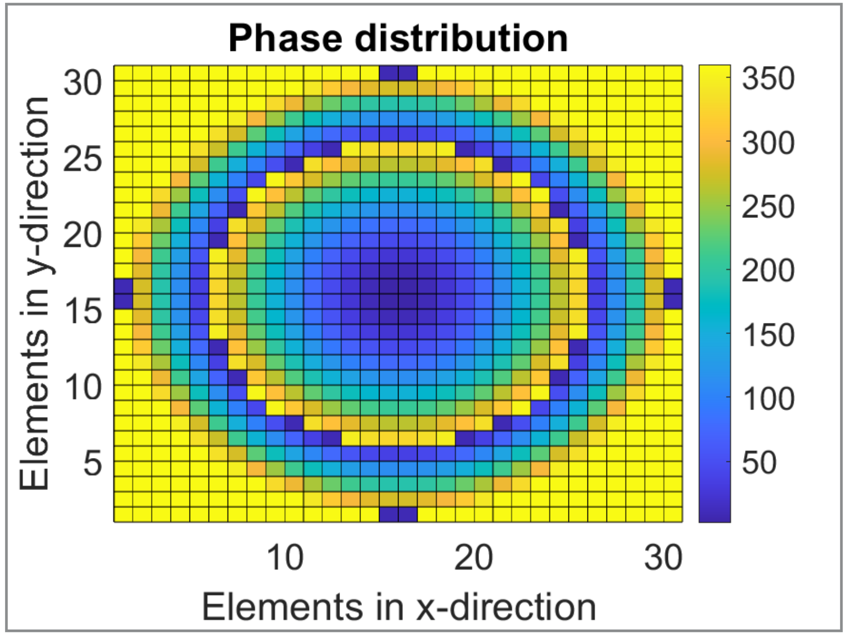
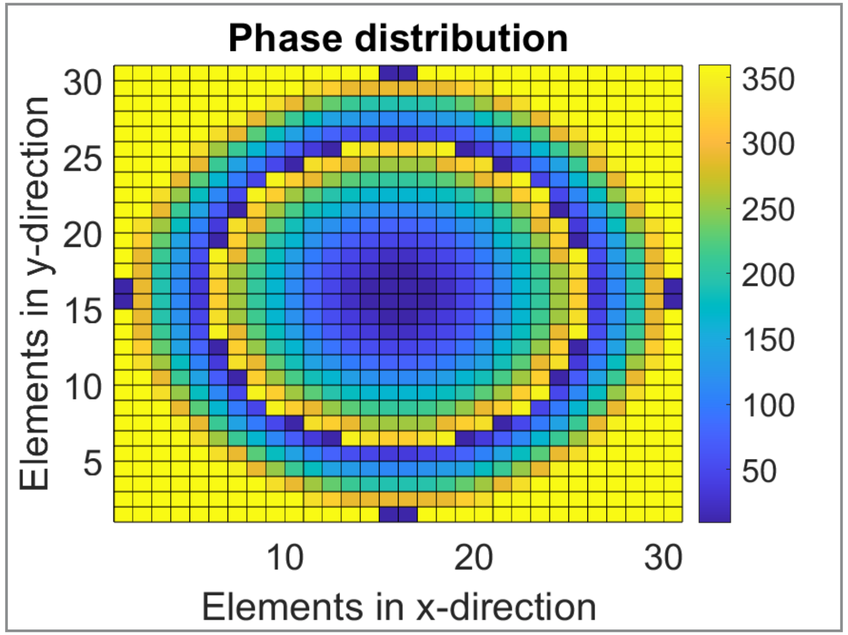
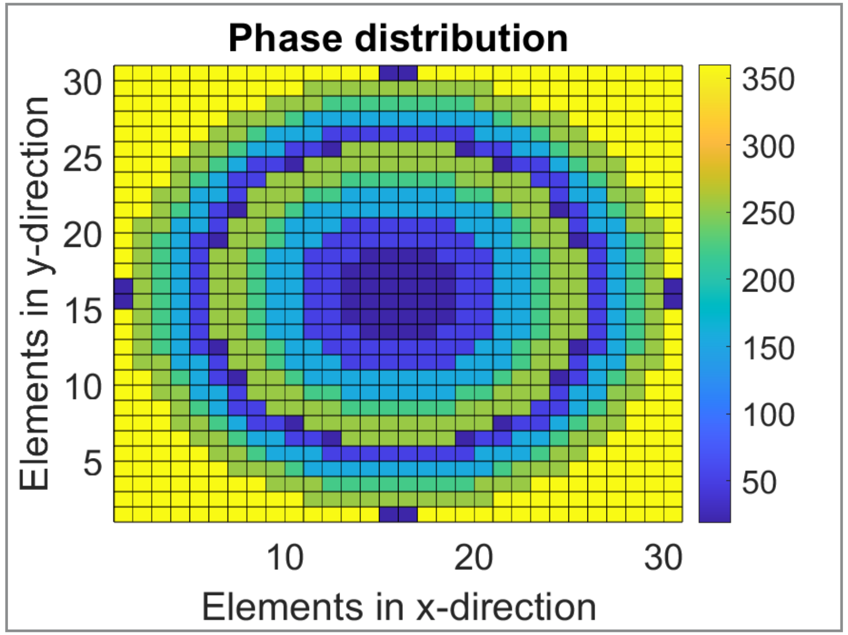
# 30 x 30 Unit Cell Phase Distributions




Ideal Phase Distribution



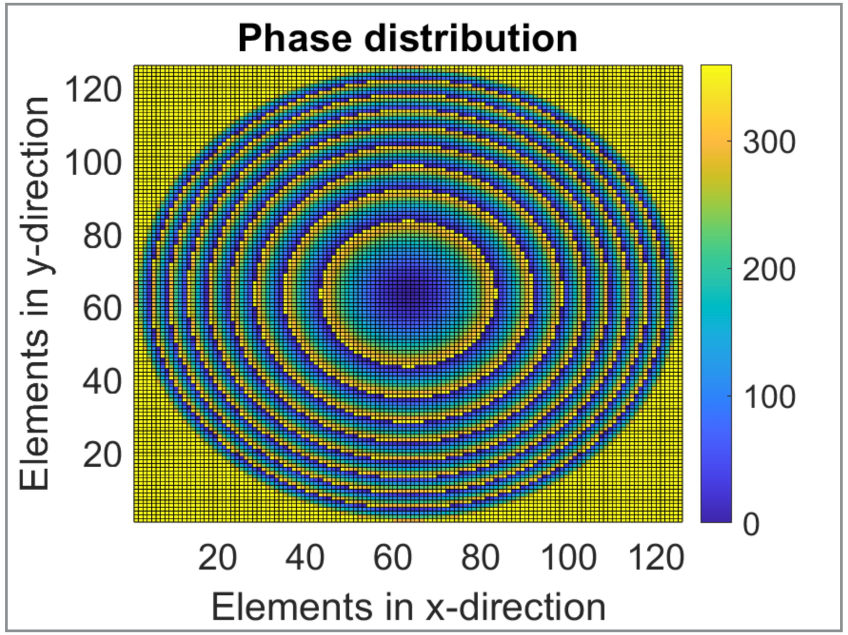

Pixelated Phase Distribution



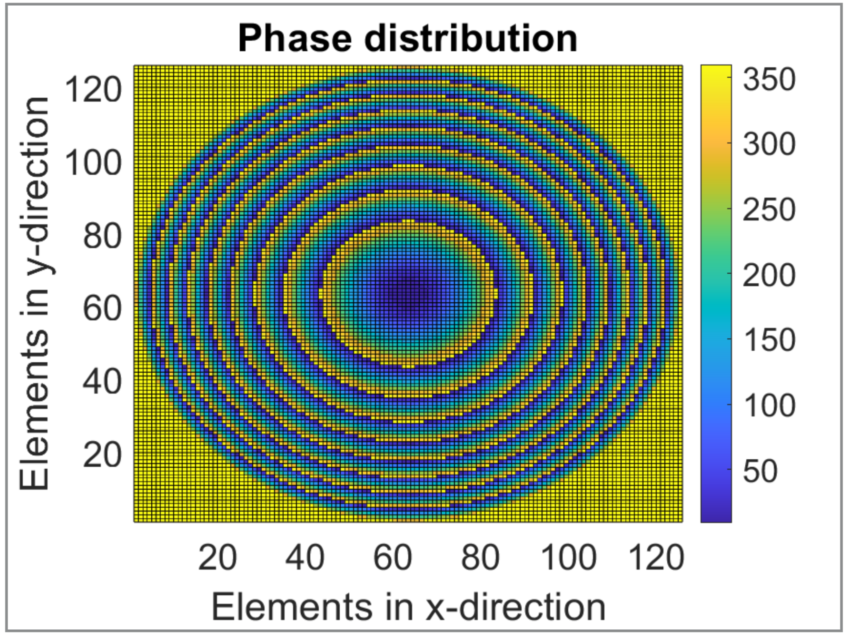

Patch Phase Distribution

- At a larger array size the differences between the square patch and the ideal phase distribution is distinct..

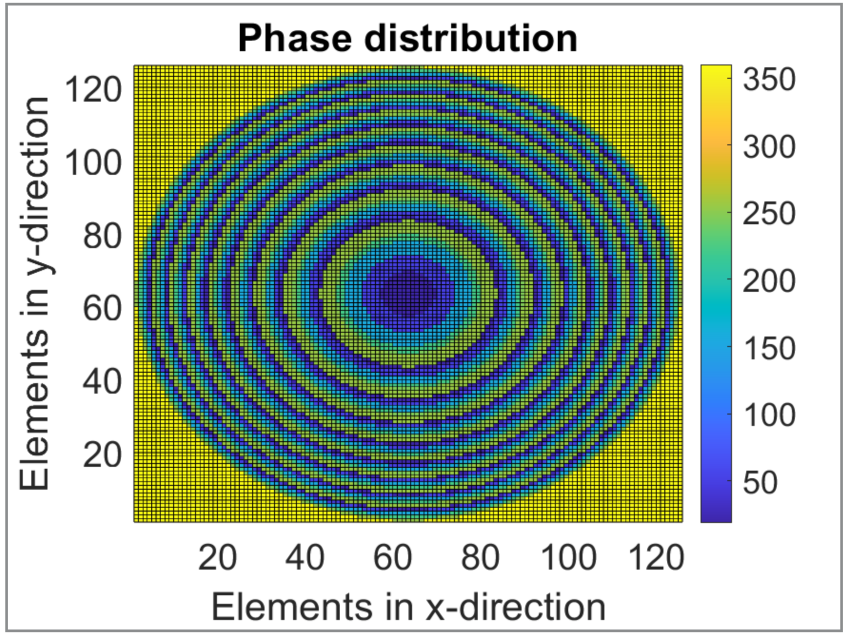
# 125 x 125 Unit Cell Phase Distributions




Ideal Phase Distribution



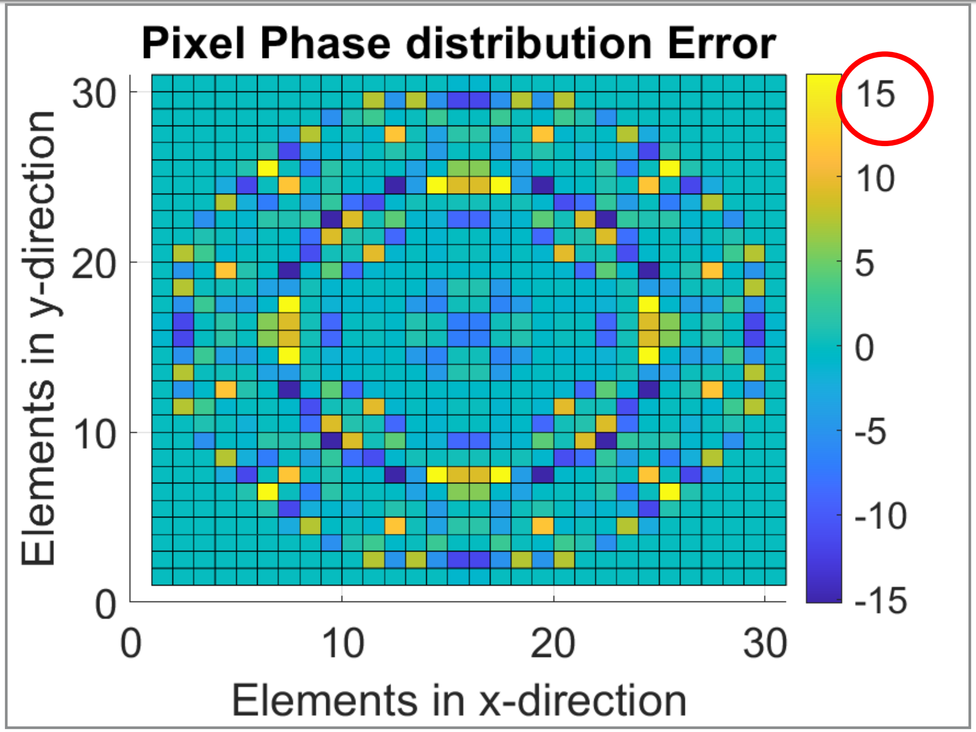

Pixelated Phase Distribution

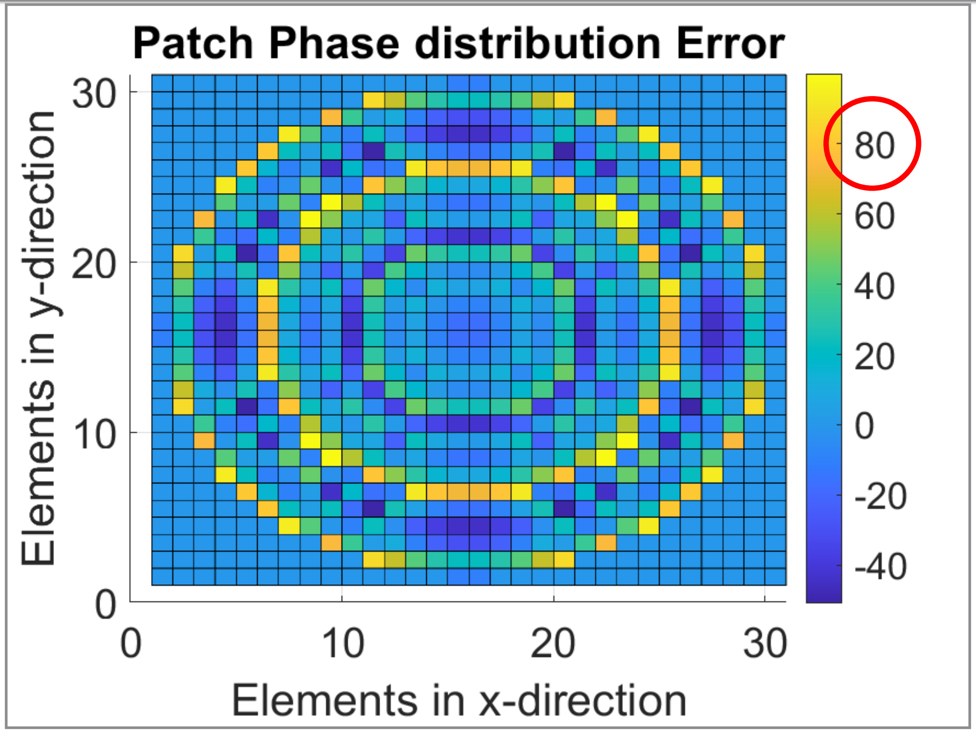



Patch Phase Distribution

- The square patch figure has a hue of green implying that the majority of the unit cells are in the range of 200 degrees of phase.

# 30 x 30 Phase Distribution Error Plots



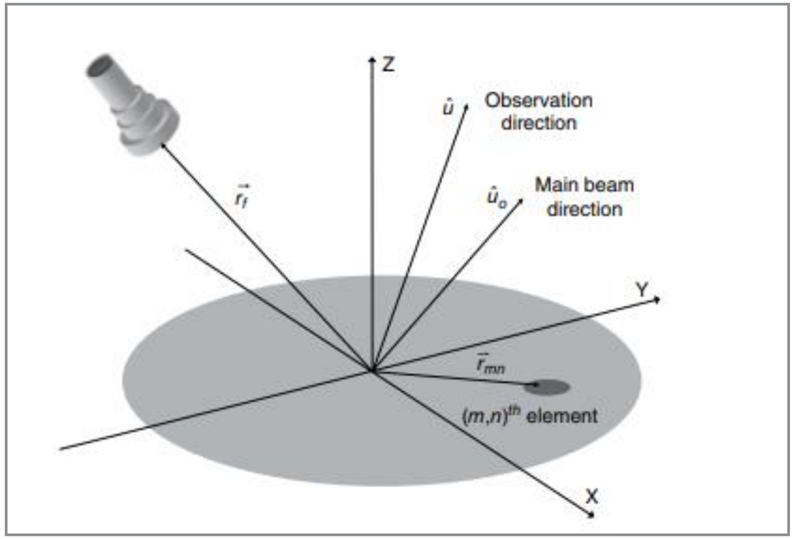

- Left plot is pixelated discrete phase for 30x30 array minus Ideal discrete phase for 30x30 array
- Right plot is square patch discrete phase for 30x30 array minus Ideal discrete phase for 30x30 array
- By subtracting the ideal discrete unit cell phase from the discrete unit cell phase distributions for the pixelated array and the patch array, we can visualize the variation of phase across the array surface.
  - Negative phase values means that closest phase to ideal was larger
  - Positive phase values mean that the closets phase to ideal was smaller
- Its clear to see the pixelated array has a closer match to the ideal discrete phase distribution
- Using the simulated patch phases there are greater than 80 degrees of phase error

# Radiation Pattern based on the Array Elements Distribution

$$E(\theta,\varphi) = \sum_{m=1}^{m}\sum_{n=1}^{n} Cos^{q_e}\theta \frac{Cos^{qf}\theta_f(m,n)}{|r_{mn}-r_f|} e^{-jk(|r_{mn}-r_f|-r_{mn}.U)} Cos^{q_e}\theta_e(m,n) e^{j\phi_{mn}}$$ [2]

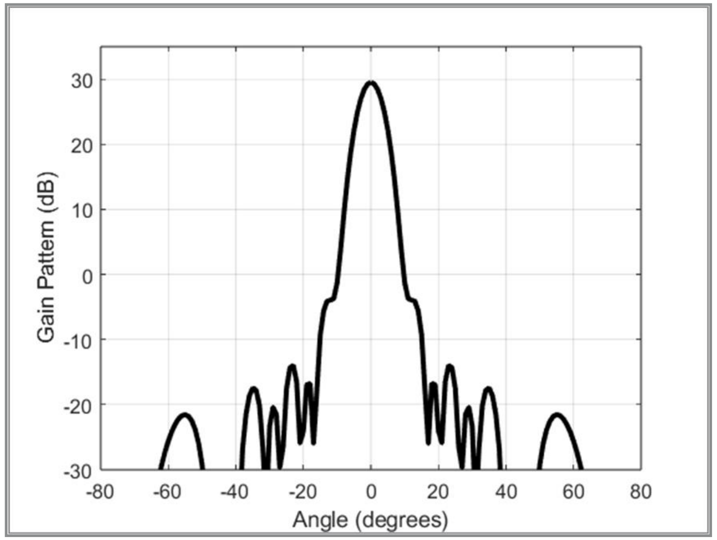
- $q_e$ & $q_f$ Are cosine weighting factors to simulate the element and feed radiation patterns respectively
- $\theta_e$ & $\theta_f$ Are the angles from the element to the feed and the feed to the element respectively
- $\phi_f$ Is phase distribution calculated in step 1
- $r_{mn}$ Is the radial vector from the center of the array to the center of element
- $r_f$ Is the radial vector from the phase center of the feed to center of each element

- This equation was implemented in MATLAB to produce to presented plot



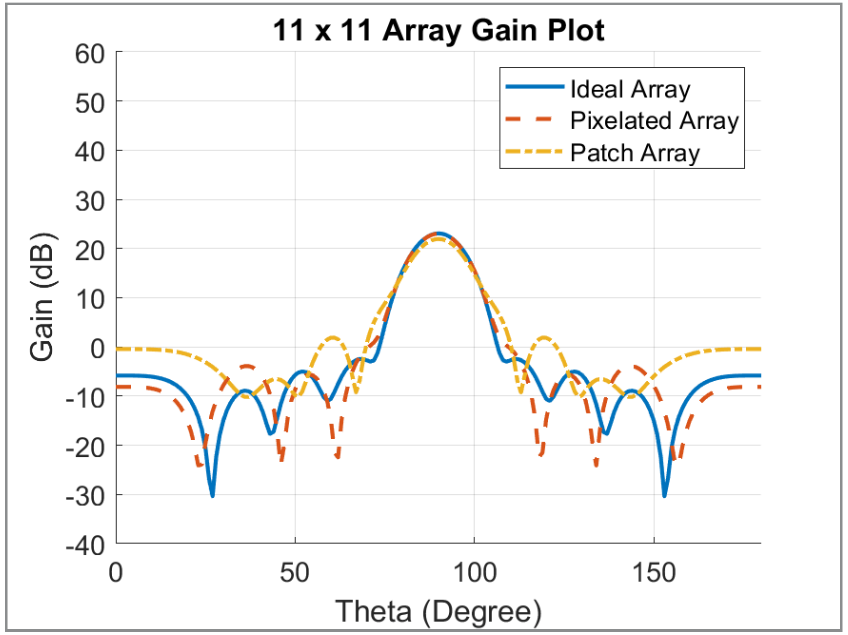

Geometric representation of element phase with respect to the feed antenna

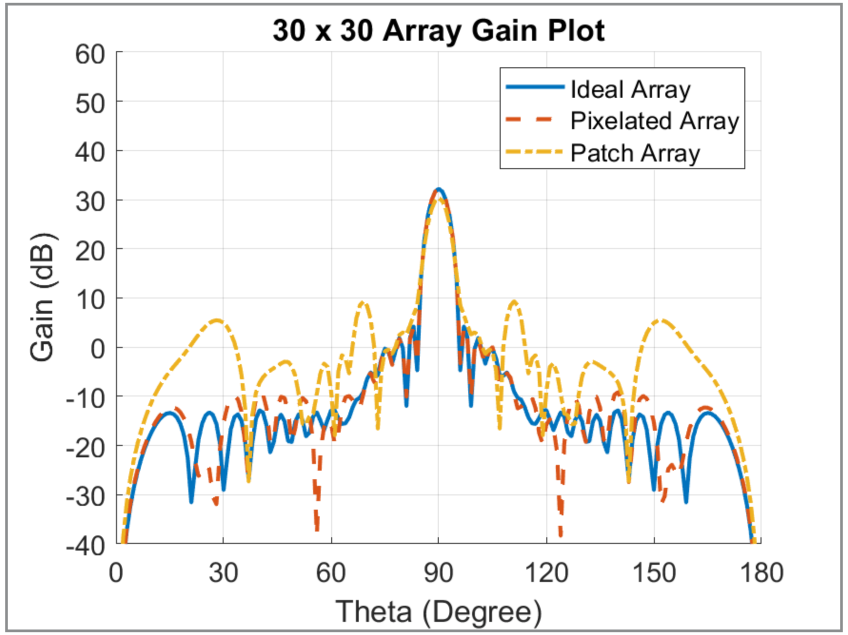
Resulting array gain based on element phase distribution

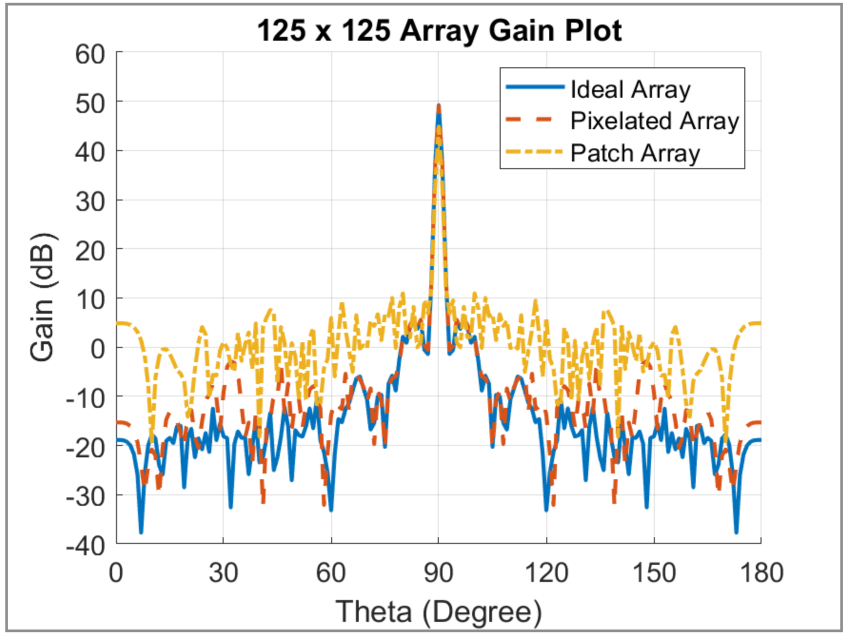



[2] P. Nayeri, F. Yang, A. Elsherbeni (2018) "Reflectarray Antennas Theory, Design, and Application" – Equation 4.7

# Analytical Array Gain Comparisons




- Sidelobe levels are the largest impact to the array performance with degraded unit cell phase.

# Conclusion

# Conclusion

- With this approach a designer can create a single model and iterate through configurations while building up a database of results.
- These results can be coupled with an analytical element reflected phase distribution to create a reflect or transmitarray.
- In addition, the current results demonstrate the ability to have a large reflected phase range while maintaining a compact size.
  - To achieve a similar reflected phase range using a patch type element the unit cell size would have to be doubled
- Lastly, this approach lends itself to building a database of results for future reuse or machine learning approaches.

# Observations

- Pros
  - The pixelated unit cell can achieve a wide range of reflected phases with acceptable reflected magnitudes in a compact size.
    - To achieve similar range of reflected phases the unit cell needs to be doubled in size
  - The pixelated until cell is less sensitive to manufacturing variation
    - Based on the steep nature of the square patch reflected phase curve a minor tolerance variation in PCB manufacturing can have a large change in reflected phase.
    - Standard etch tolerances are +/- 0.1 mm
    - Depending on the reference reflected phase a 0.1 mm change can lead to a reflected phase change of 5 degrees.
  - Based on current data, pixelated unit cell can achieve more discrete leading to a more gradual reflected phase profile.

- Cons
  - Due to large solution space (33.5 million combinations of pixels) generating reflected phases is a lengthy process to simulate configurations

Comments and Questions are Welcome