Simulation of mutual Coupling in Aperiodic Arrays

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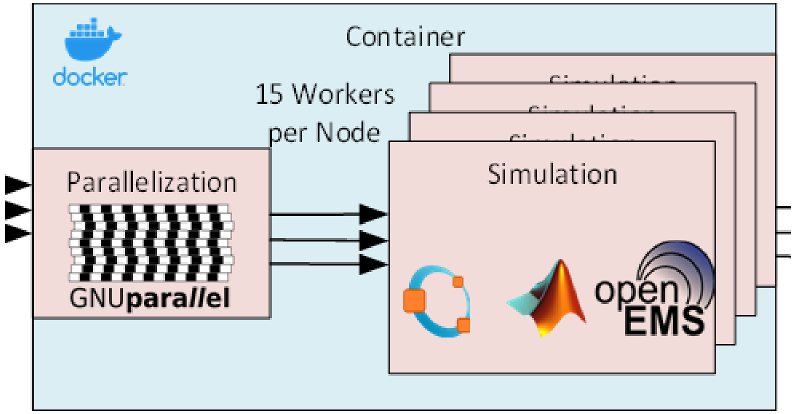

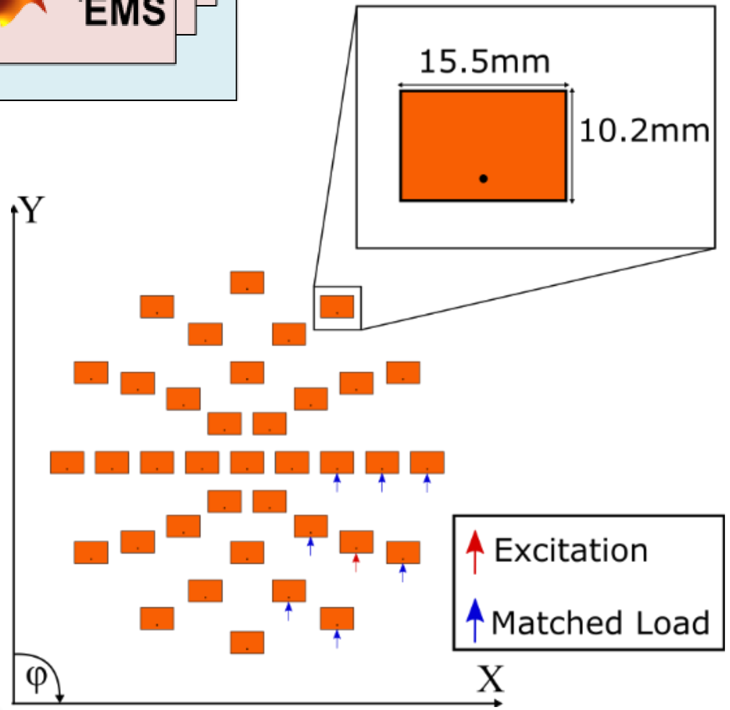

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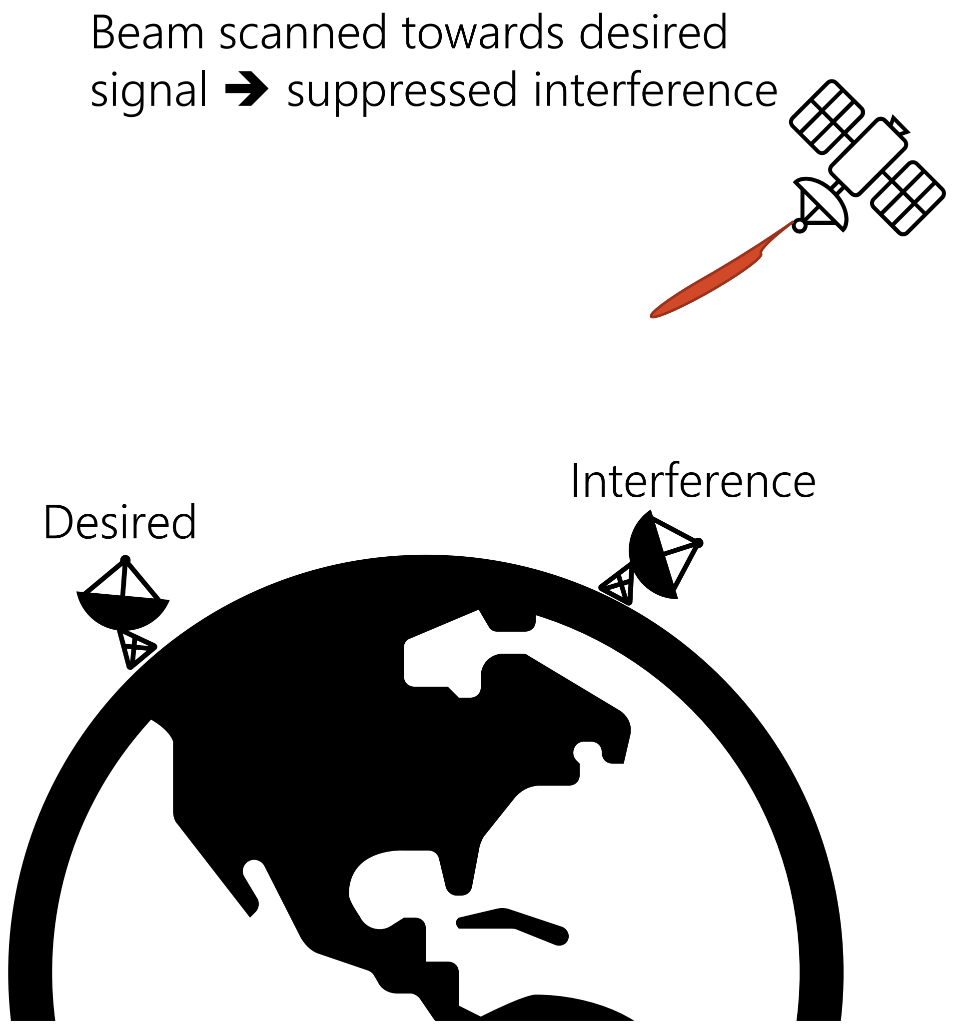
Outline

1. Introduction
2. Background Information
3. Methodology
4. Results and Conclusions

Introduction

- Frequency Independent Array Applications:
  - Multi-band or wideband communications
    - Cellular
    - Satcom
  - Radar
    - Synthetic Aperture
    - Threat Detection
- Antenna array provides higher gain and beam scanning which increase signal strength and reduce noise/interference



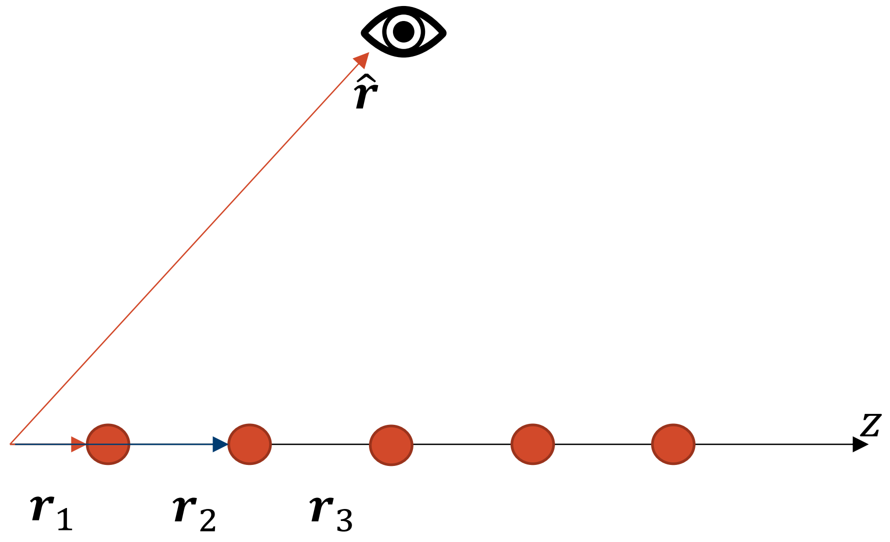
Introduction: Wideband Array Design Challenges

- Wideband radiating elements – Extensive research in this area
  - Vivaldi [1]
  - Tightly Coupled Arrays [2]
  - Spiral Antennas [3]
  - Many more…
- Periodic array problems: grating lobes limit scan range, sidelobes reduce spatial filtering capability
  - Array thinning [4]
  - Aperiodic arrays [5]
- Current contributions:
  - Dense aperiodic arrays
  - Varying element sizes to maximize aperture efficiency

[1] E. Gazit, "Improved design of the Vivaldi antenna," IEE Proceedings H (Microwaves, Antennas and Propagation), vol. 135, no. 2, pp. 89–92, Apr. 1988, doi: 10.1049/ip-h-2.1988.0020.
[2] H. Wheeler, "Simple relations derived from a phased-array antenna made of an infinite current sheet," IEEE Transactions on Antennas and Propagation, vol. 13, no. 4, pp. 506–514, Jul. 1965, doi: 10.1109/TAP.1965.1138456.
[3] J. Dyson, "The equiangular spiral antenna," IRE Transactions on Antennas and Propagation, vol. 7, no. 2, pp. 181–187, Apr. 1959, doi: 10.1109/TAP.1959.1144653.
[4] M. A. Elmansouri, G. R. Friedrichs, L. B. Boskovic, and D. S. Filipovic, "An X-Band Through Ka-Band Thinned All-Metal Vivaldi Phased Array," IEEE Transactions on Antennas and Propagation, vol. 69, no. 11, pp. 7613–7623, Nov. 2021, doi: 10.1109/TAP.2021.3076680.
[5] M. D. Gregory and D. H. Werner, "Ultrawideband Aperiodic Antenna Arrays Based on Optimized Raised Power Series Representations," IEEE Transactions on Antennas and Propagation, vol. 58, no. 3, pp. 756–764, Mar. 2010, doi: 10.1109/TAP.2009.2039315.
[6] P. M. Ruiz, I. Hinostroza, R. Guivarc'h, and R. Haupt, "Concentric ring array of connecting spirals with interleaved WAVES," in 2018 United States National Committee of URSI National Radio Science Meeting (USNC-URSI NRSM), Jan. 2018, pp. 1–2.

Background: Total Array Pattern Calculations

- $P_{tot}(\theta, \varphi, k) = \sum_{n=1}^{N} \boldsymbol{f}_n(\theta, \varphi, \mathrm{k}) e^{-jk\boldsymbol{r}_n \cdot \hat{\boldsymbol{r}}(\theta,\varphi)}$
  - (θ, φ) Observation Angle
  - $k = \frac{2\pi}{\lambda}$ Wave number
  - $\boldsymbol{f}_n(\theta, \varphi, k)$ Radiation pattern of the nth element
  - $\boldsymbol{r}_n$ Position vector to the nth element
  - $\hat{\boldsymbol{r}}(\theta, \varphi)$ Unit vector towards observation angle
- **Traditional way of using $\boldsymbol{f}_n(\theta, \varphi, k)$:**
  - Array processing research often treats as isotropic and ignores coupling
  - Phased array research utilize periodic boundary condition to simulate the embedded element pattern
- **This work assumes $\boldsymbol{f}_n(\theta, \varphi, k)$ is different for each *n***



Background: Uniform Array Limitations

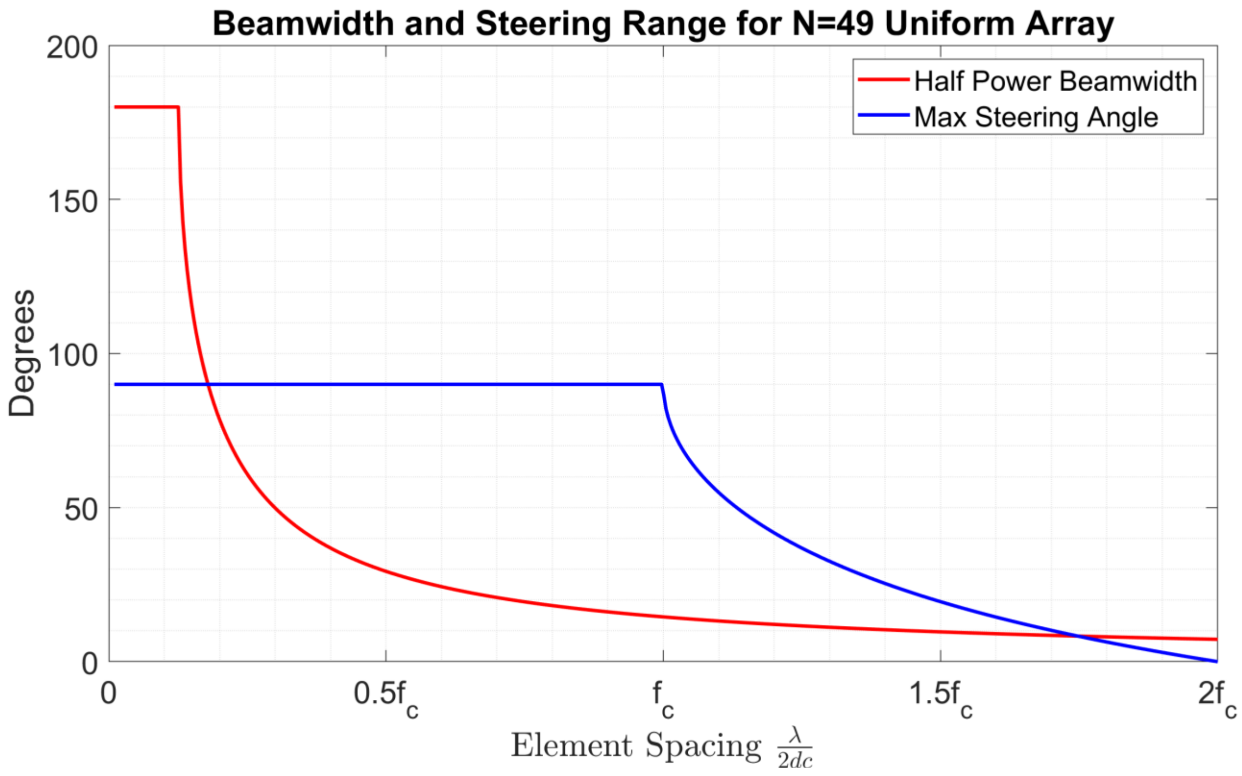
- From the analytical solution to AF of a uniform array, we can derive:
  - Half power beam width (HPBW):

    $\Theta = 2\left[\frac{\pi}{2} - \cos^{-1}\frac{1.391\lambda}{\pi N d}\right]$

  - Maximum scan angle before first grating lobe:

    $\theta_{max} = \sin^{-1}\left(\frac{m\lambda}{d}\right)$

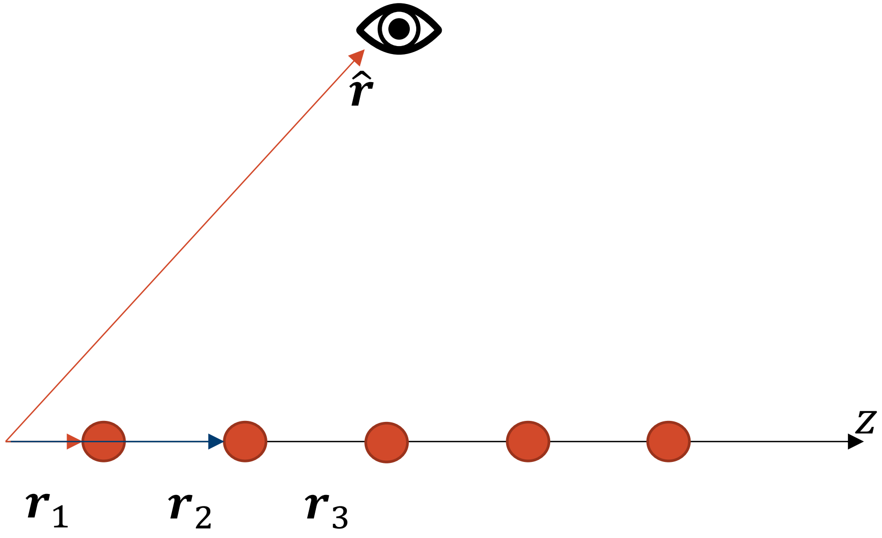
- Both figures of merit are functions of *frequency* and *spacing (d)*
- HPBW also a function of number of elements N
- If we have spatial filtering requirements in N=49 array:
  - 60° steering: max freq. is $1.05f_c$
  - 30° HPBW: min freq. is $0.5f_c$
- Typically, an element designed for $0.5f_c$ radiation won't fit in $\frac{\lambda_c}{2}$ lattice
- **Uniform Array useful bandwidth is 2:1**

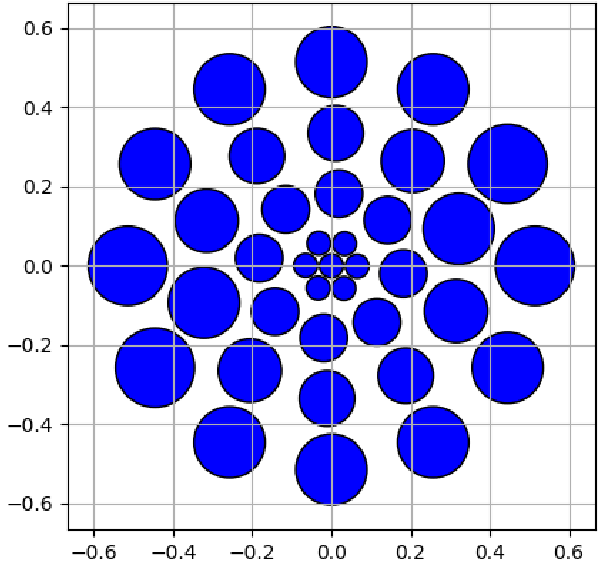


Background: Aperiodic Array Advantages

- Use same element type, but with different size:
  - Reduce the minimum spacing to improve high frequency grating lobe performance
  - Increase the maximum element size to improve low frequency radiation efficiency
- Use pseudo-random element positions to reduce sidelobe level (non-uniform)

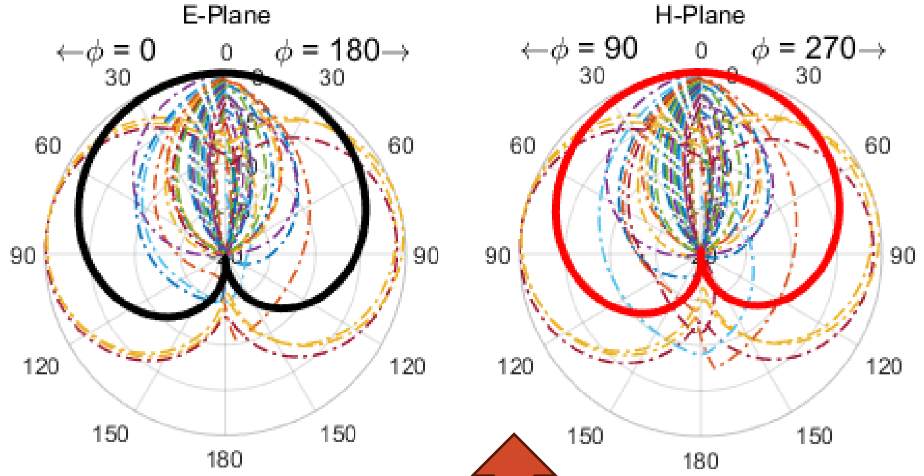
- Advantages:
  - Maximize the wideband radiation efficiency for a specific aperture area
  - Reduced sidelobe levels





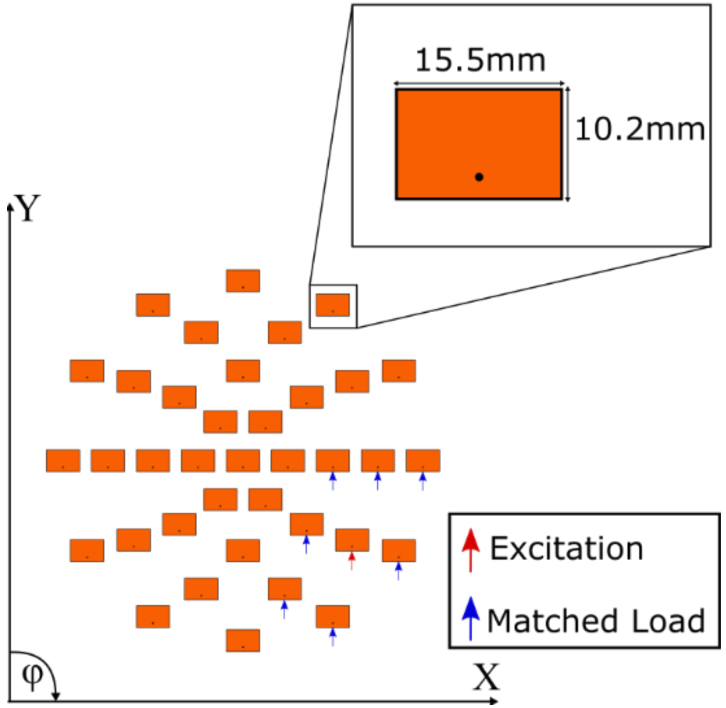
Methodology: Microstrip Patch Antenna Test Case

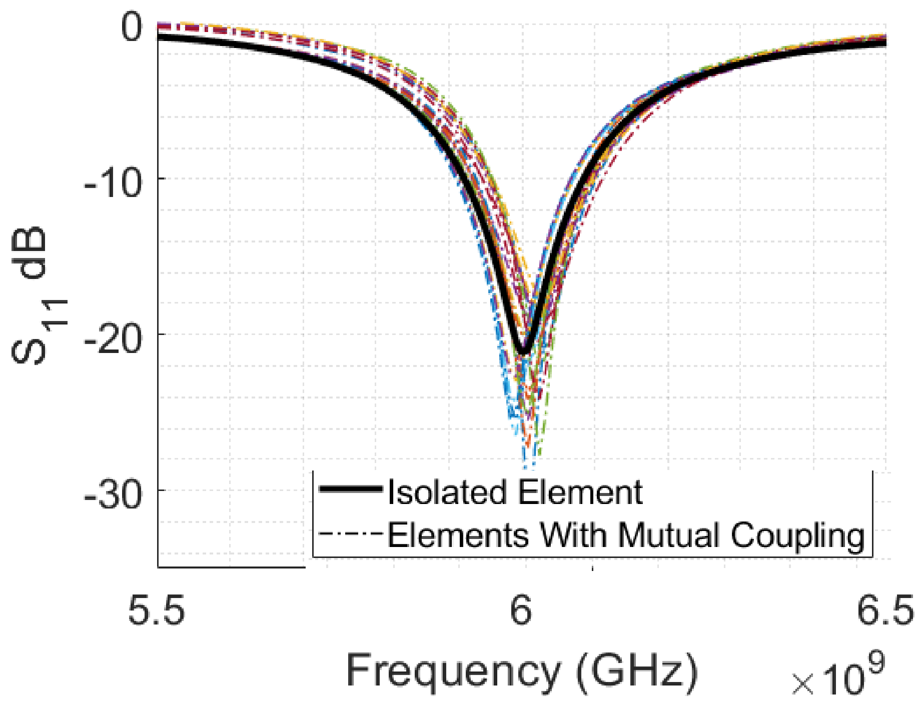
- Aperiodic array of same size microstrip patch simulated at 6GHz
- Concentric ring spacing = 25mm = $\frac{\lambda}{2}$



Isolated Element

Element pattern with mutual coupling





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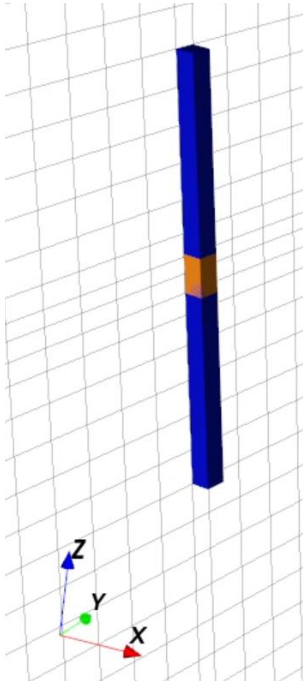
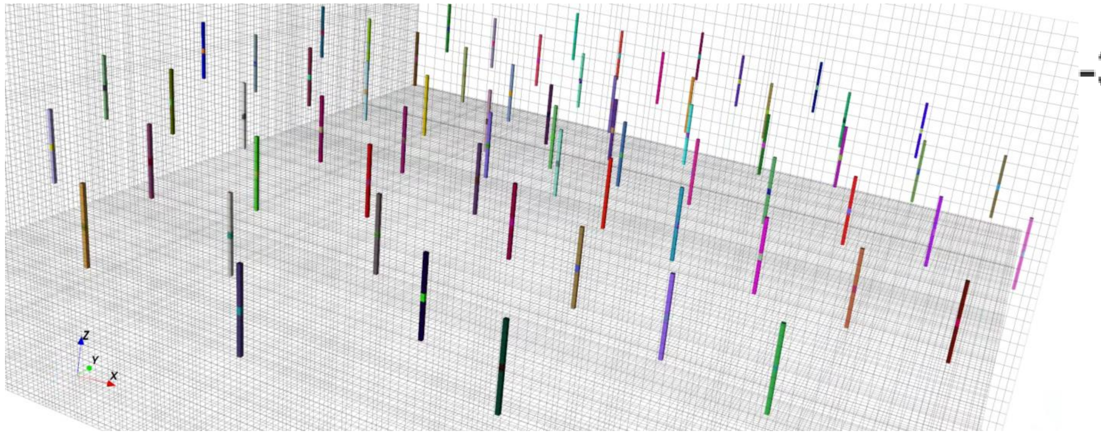
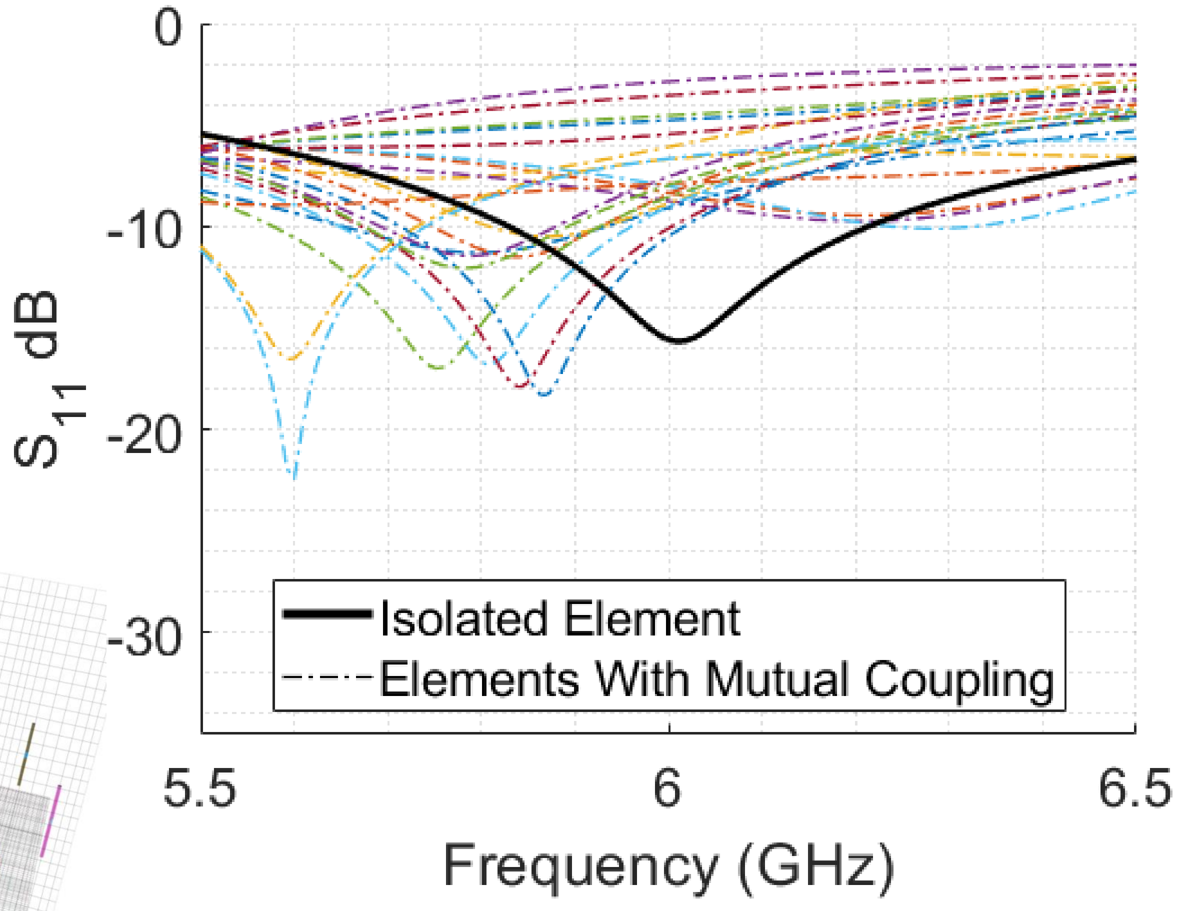
Methodology: Dipole Antenna Test Case

- Z-axis aligned dipole in the same array as patch
- Dashed lines show different S11 for different element locations
- Dipole length is 0.48λ at 6GHz

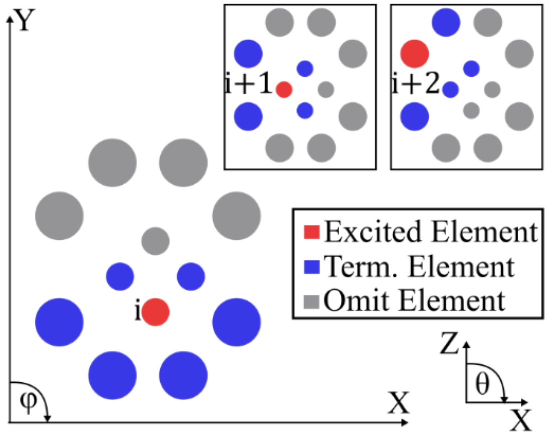


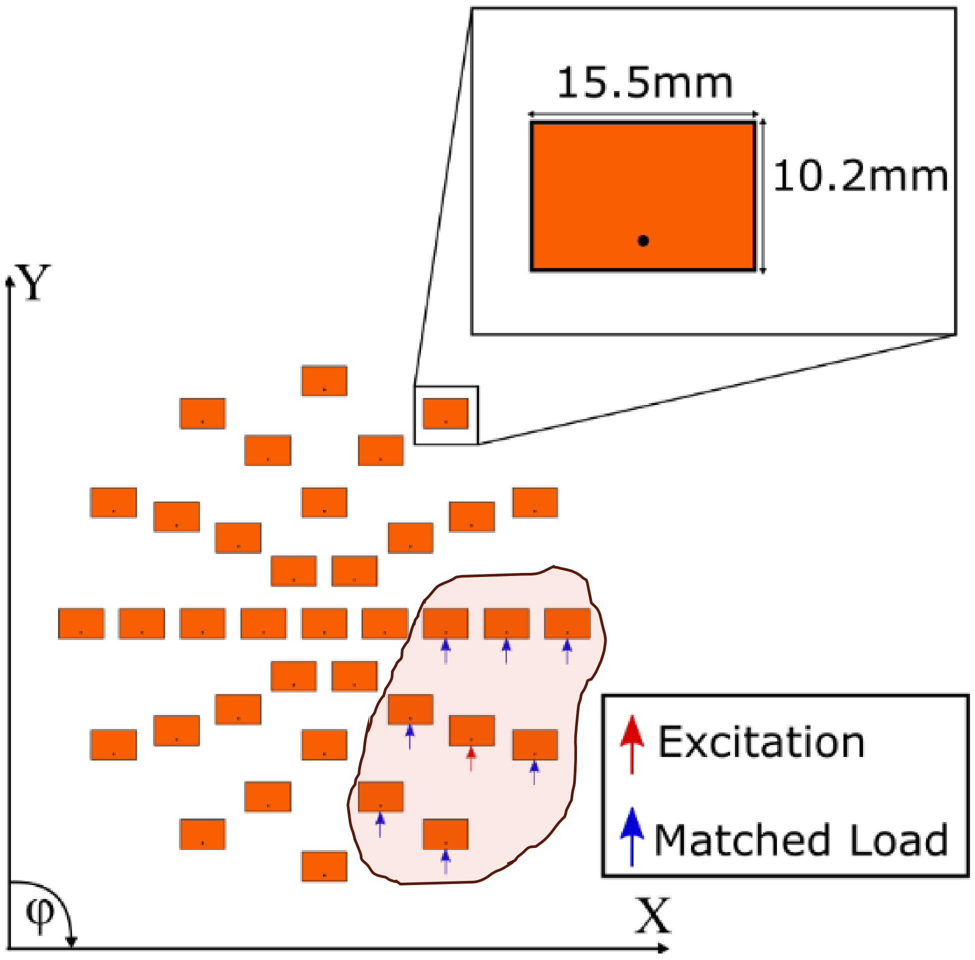




Methodology: Subarray Tessellation Technique

- Use nearest neighbors to construct subarrays for full wave simulation
- Finite difference time domain used for wideband simulation of unique elements for each array site.
- Methodology demonstrated with microstrip patch and dipole test cases

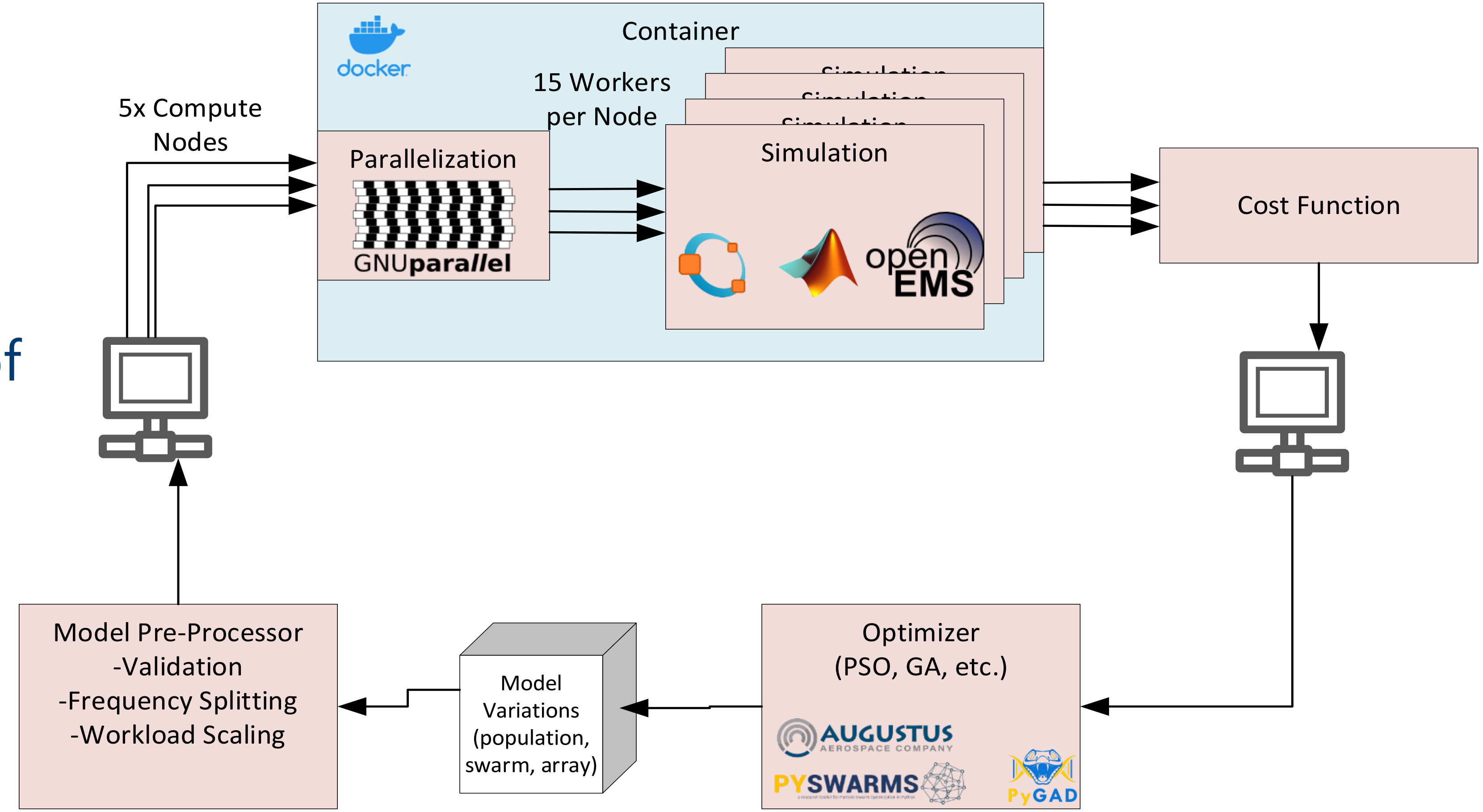




[1] E. de Lera Acedo, N. Razavi-Ghods, D. G. Ovejéro, R. Sarkis, and C. Craeye, “Compact representation of the effects of mutual coupling in non-regular arrays devoted to the SKA telescope,” in 2011 International Conference on Electromagnetics in Advanced Applications, Sep. 2011, pp. 390–393. doi: 10.1109/ICEAA.2011.6046372.

Methodology: Computation Framework

- Subarray tessellation is conducive to scaling the simulation to compute cluster
- Increase the throughput of optimizing aperiodic, pseudorandom, sparse, etc. array with real elements and mutual coupling



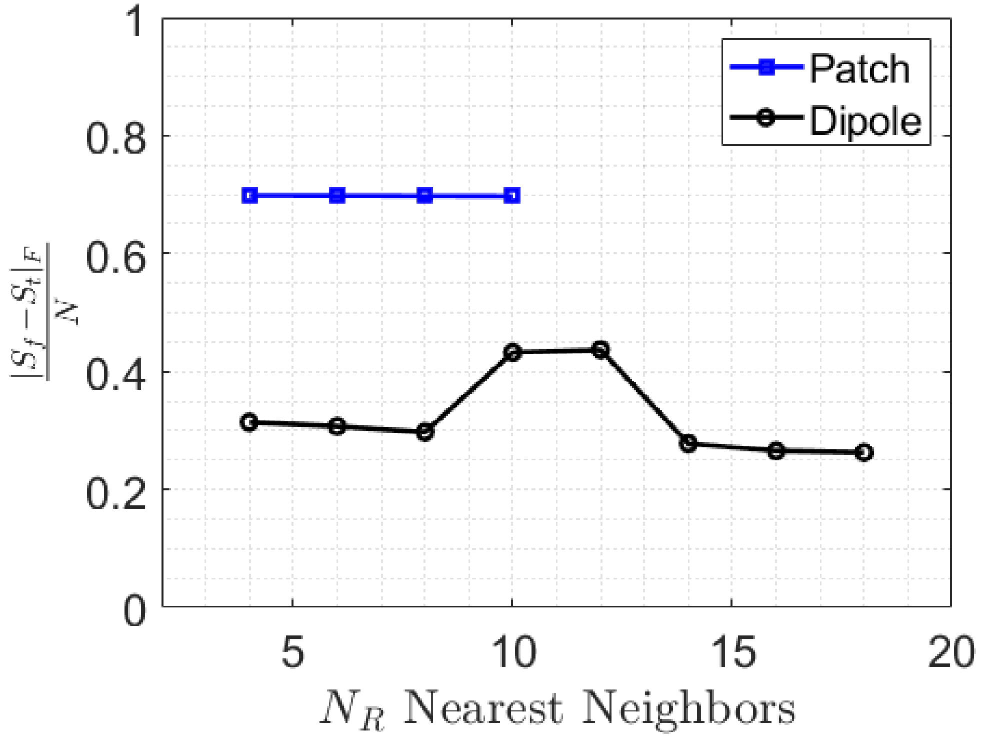
[1] O. Tange (2018): GNU Parallel 2018, March 2018, https://doi.org/10.5281/zenodo.1146014.
[2] T. Liebig, A. Rennings, S. Held, and D. Erni, "openEMS – a free and open source equivalent-circuit (EC) FDTD simulation platform supporting cylindrical coordinates suitable for the analysis of traveling wave MRI applications," International Journal of Numerical Modelling: Electronic Networks, Devices and Fields, vol. 26, no. 6, pp. 680–696, 2013, doi: 10.1002/jnm.1875.

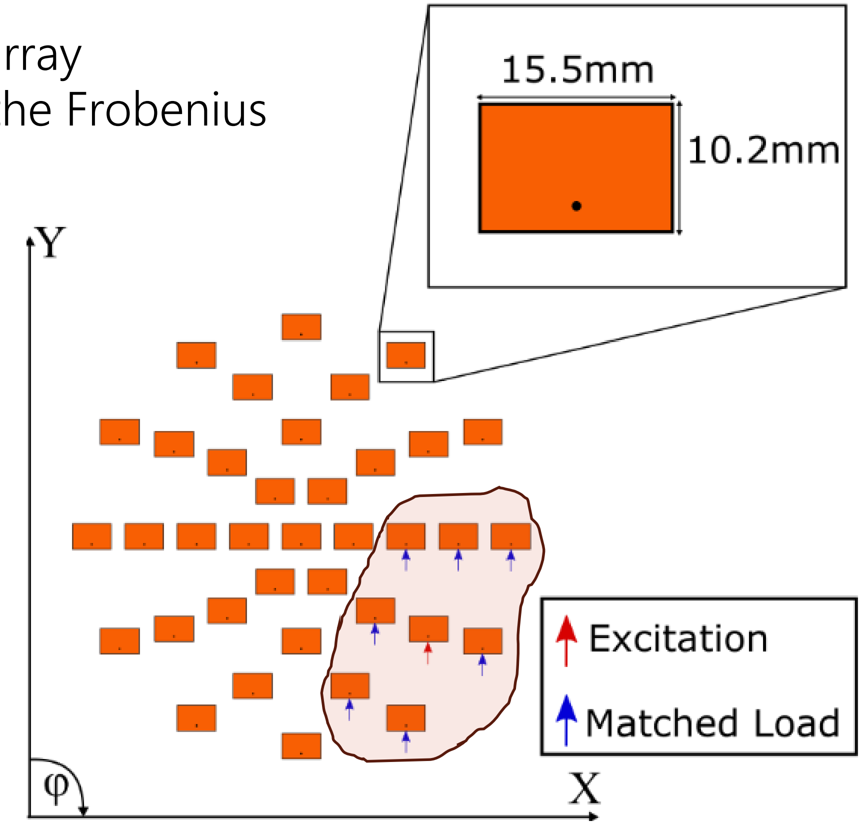
Results: Nearest Neighbors Convergence 37 Element Array

- Convergence of the subarray tessellation to the full array simulation is observed by measuring:

$$|S_f - S_t|_F$$

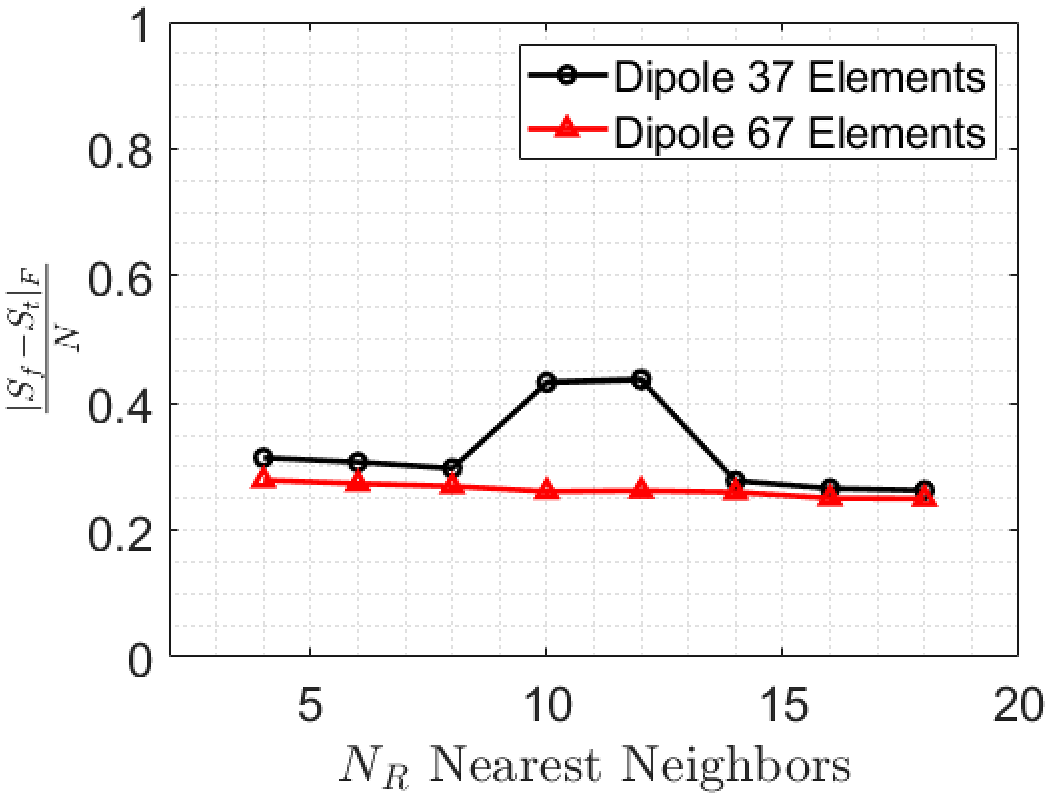
Where S_f is the 37x37 S parameter matrix for one frequency of the full array simulation, S_t is the same matrix for tessellation simulation, and $|\cdot|_F$ is the Frobenius norm.

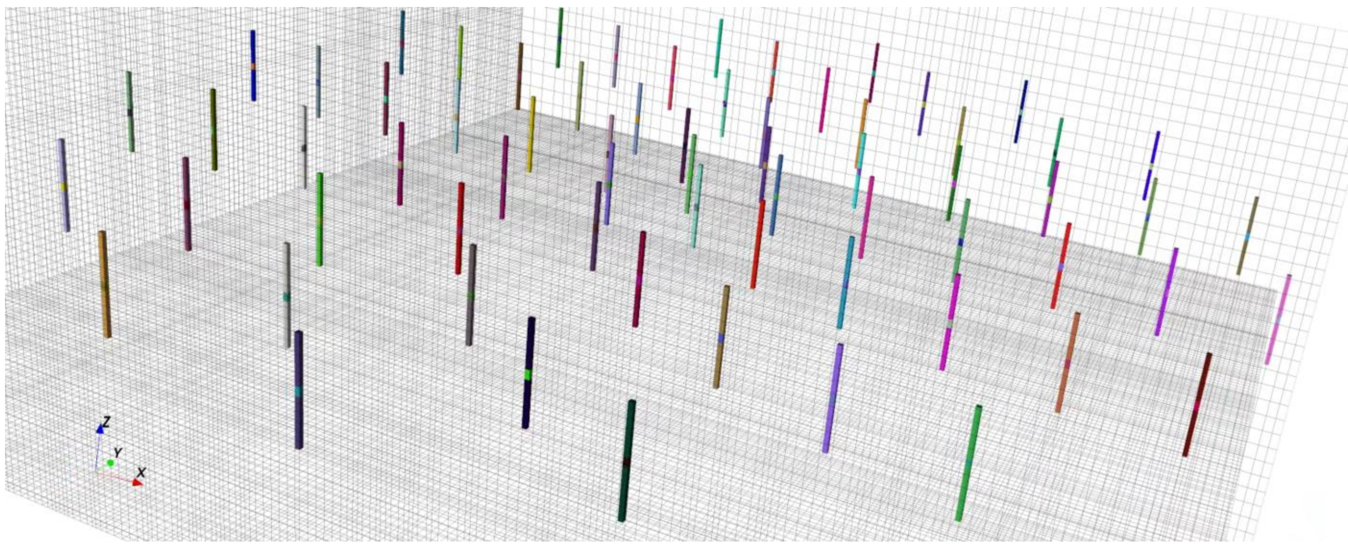




Results: Nearest Neighbors Convergence 67 Element Array

- Concentric rings increased from 4 to 6, element count increased from 37 to 67



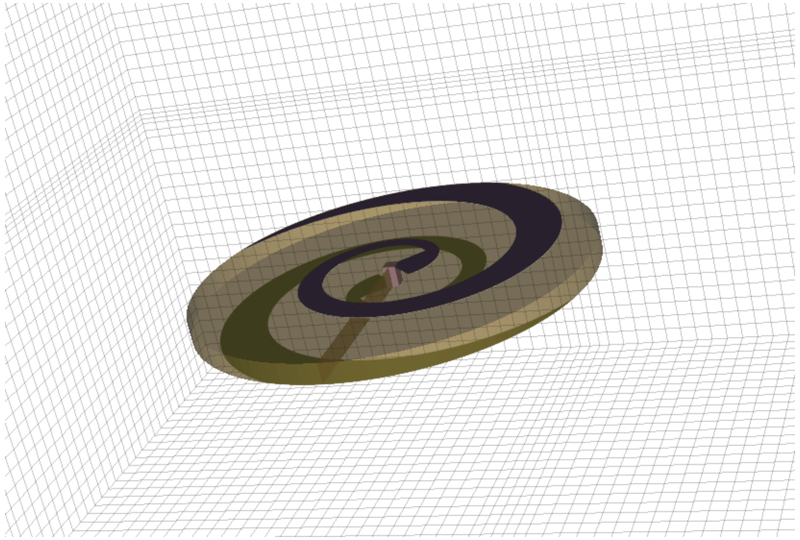


Conclusions

- Subarray Tessellation shows potential to approximate coupling in a full-wave simulation of an aperiodic array.
- Radius of influence shows strong dependence on antenna element type.
- Need larger test problems to determine convergence criteria.

Future Work

- Test convergence with larger array
- Test other types of antenna elements
- Apply to wideband statistical array design



Questions?

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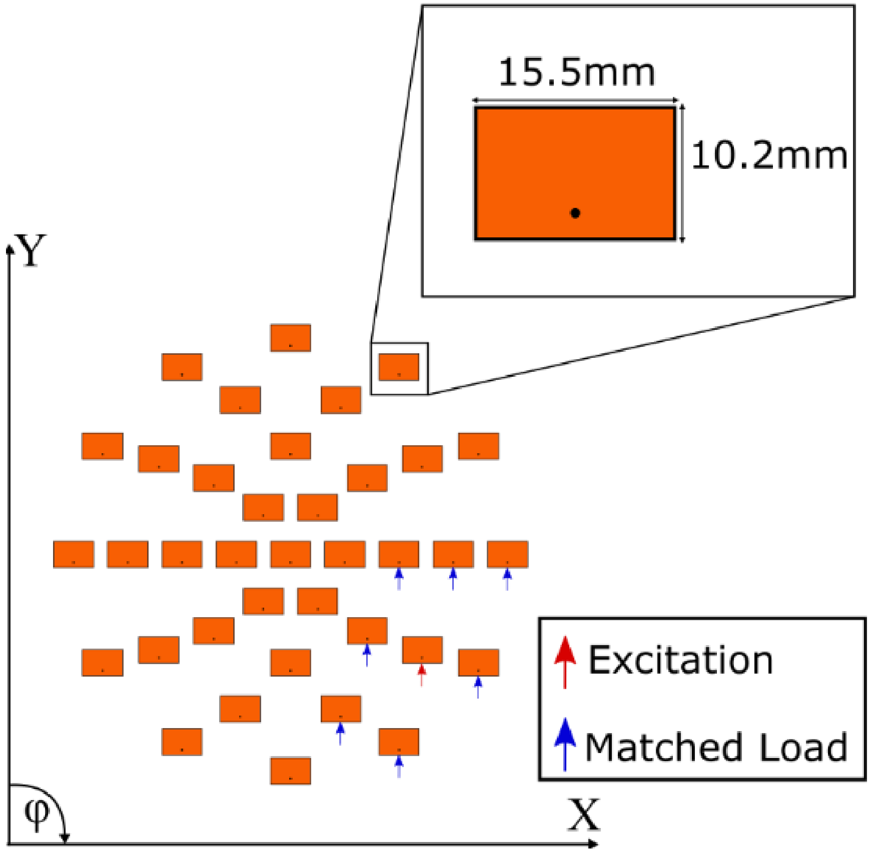

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