SCHOOL of ENGINEERING

Department of Electrical & Computer Engineering

SAND2013-5198C

An Approach for In-Situ Scan Impedance Characterization of Phased Antenna Arrays

8th July 2013

IEEE APS 2013, Paper #2873

Thomas E. Christian, Jr.

Hung Loui

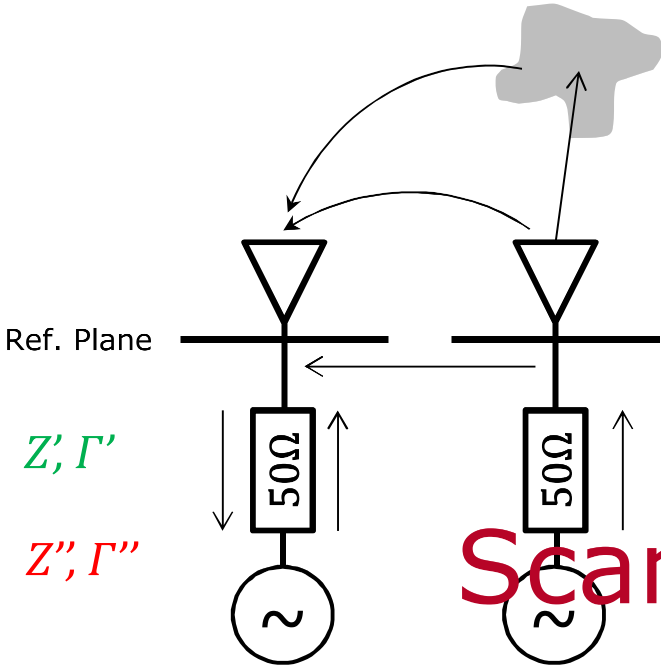
C. G. Christodoulou

Dale Dubbert

Objectives of this Study

- **Understand** mutual coupling and its effects on scan/active impedance, and subsequent array excitation
- **Develop** an automated in-situ instrumentation system to measure mutual coupling between four planar array elements, but adaptable to an arbitrary number, or non-planar elements
- **Formulate** a mathematical algorithm to predict active scan impedance variations via measured mutual coupling

Scan Impedance

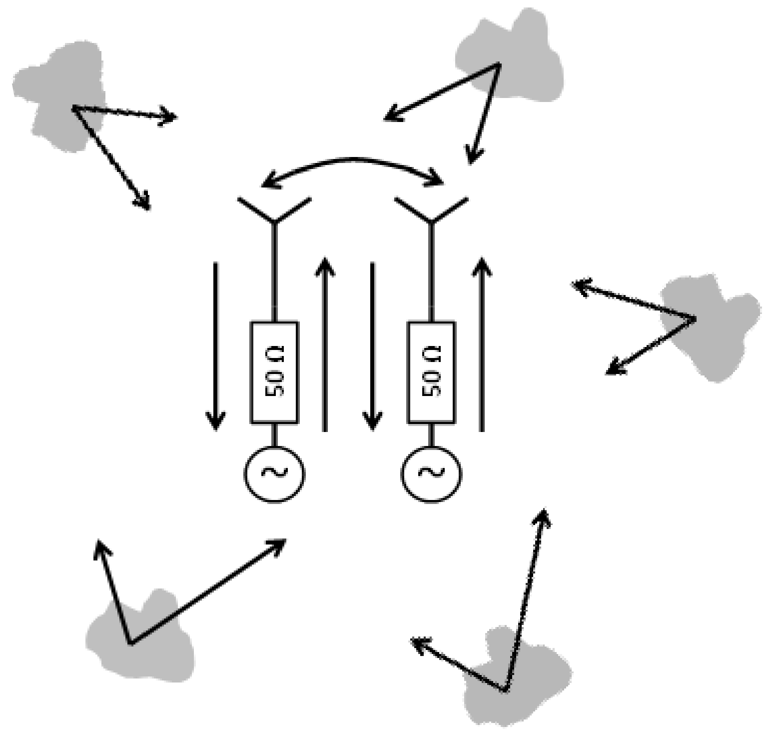


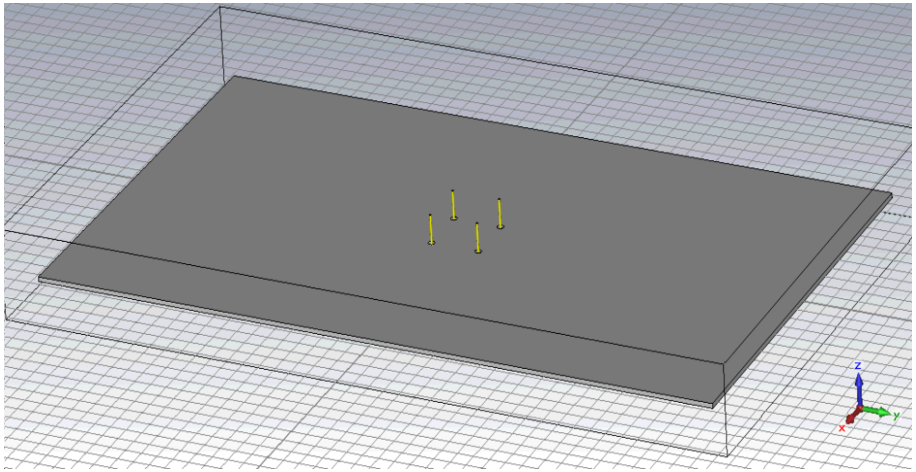
$$Z' = Z_o \frac{1+\Gamma'}{1-\Gamma'}$$

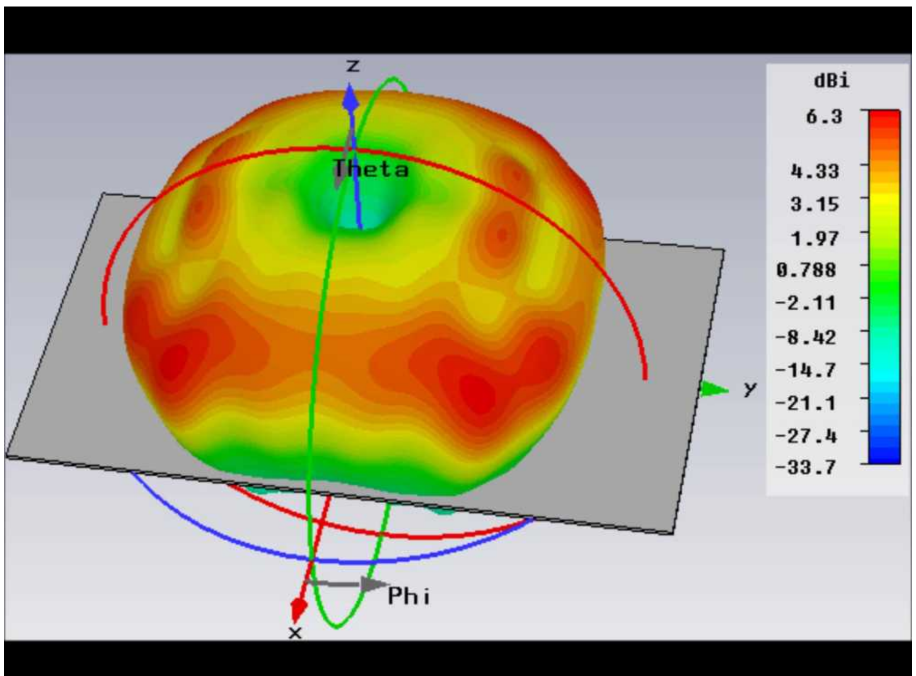
$$Z'' = Z_o \frac{1+\Gamma''}{1-\Gamma''}$$

Primary Mechanisms of Mutual Coupling

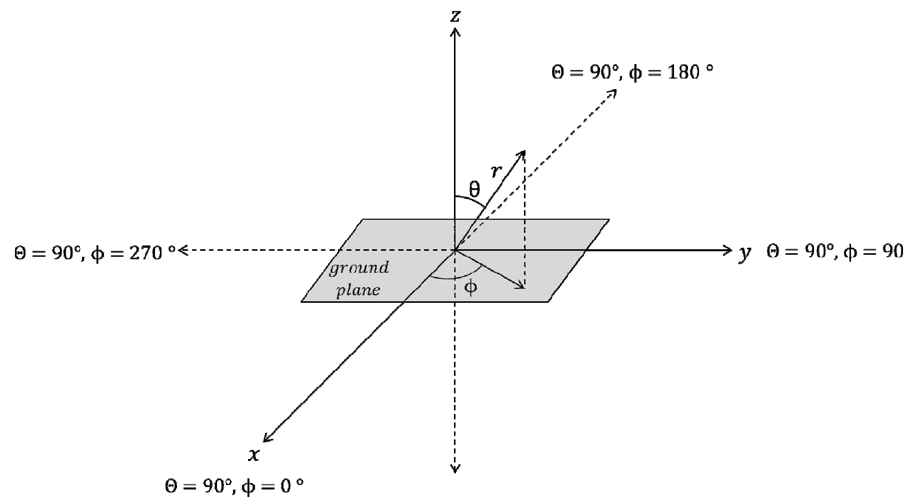
- Coupling between elements
- Coupling from within the array
- Scattering from nearby objects


50 Ω
50 Ω





Spherical Coordinate System



$$E_\theta \simeq j\eta \frac{kI_o l e^{-jkr}}{4\pi r} \sin\theta [2\cos(kh\cos\theta)], \qquad z \geq 0$$

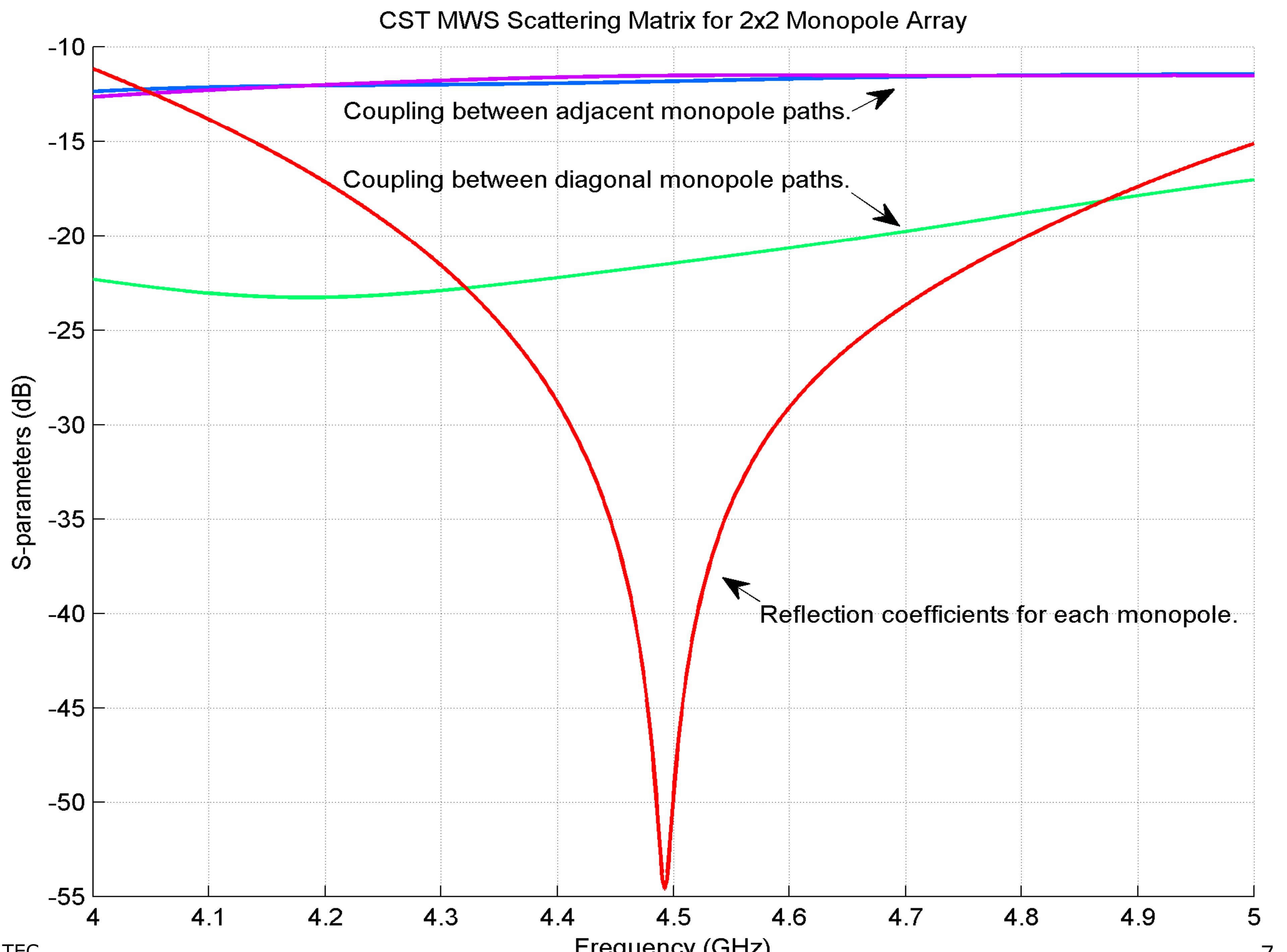
$$E_\theta = 0, \qquad z < 0$$

Scattering Parameters

- Represent transmission and reflections of an N-port network. Perfect for representing mutual coupling of an antenna array.
- Can easily be measured with a network analyzer

$$\begin{bmatrix} b_1 \\ \vdots \\ b_N \end{bmatrix} = \begin{bmatrix} S_{11} & \cdots & S_{1N} \\ \vdots & \ddots & \vdots \\ S_{N1} & \cdots & S_{NN} \end{bmatrix} \begin{bmatrix} a_1 \\ \vdots \\ a_N \end{bmatrix}$$

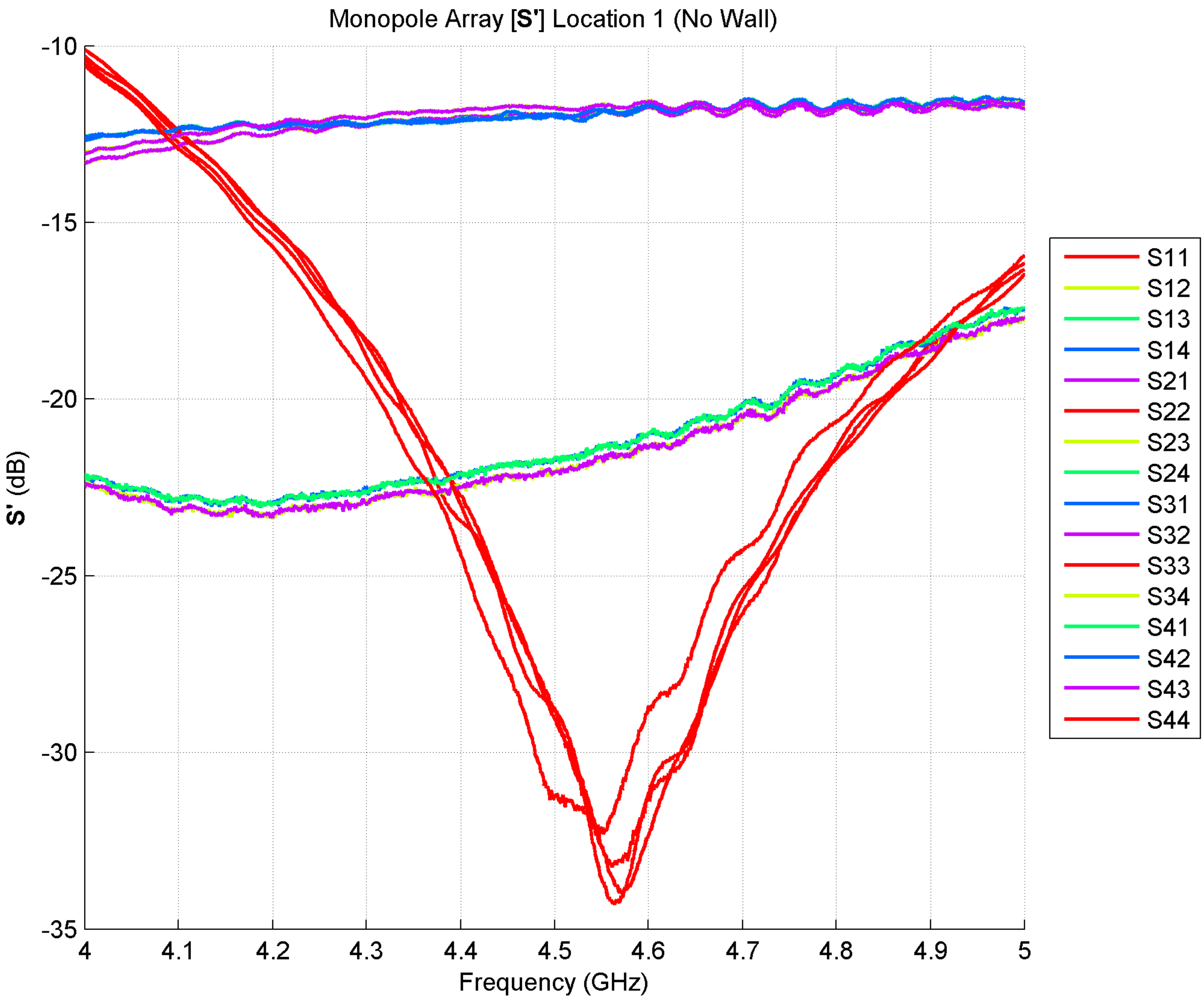
$$a_n = \frac{V_n^+}{\sqrt{Z_{0n}}} \qquad b_n = \frac{V_n^-}{\sqrt{Z_{0n}}} \qquad S_{ij} = \left.\frac{b_i}{a_j}\right|_{a_k=0, for\ k\neq j}$$

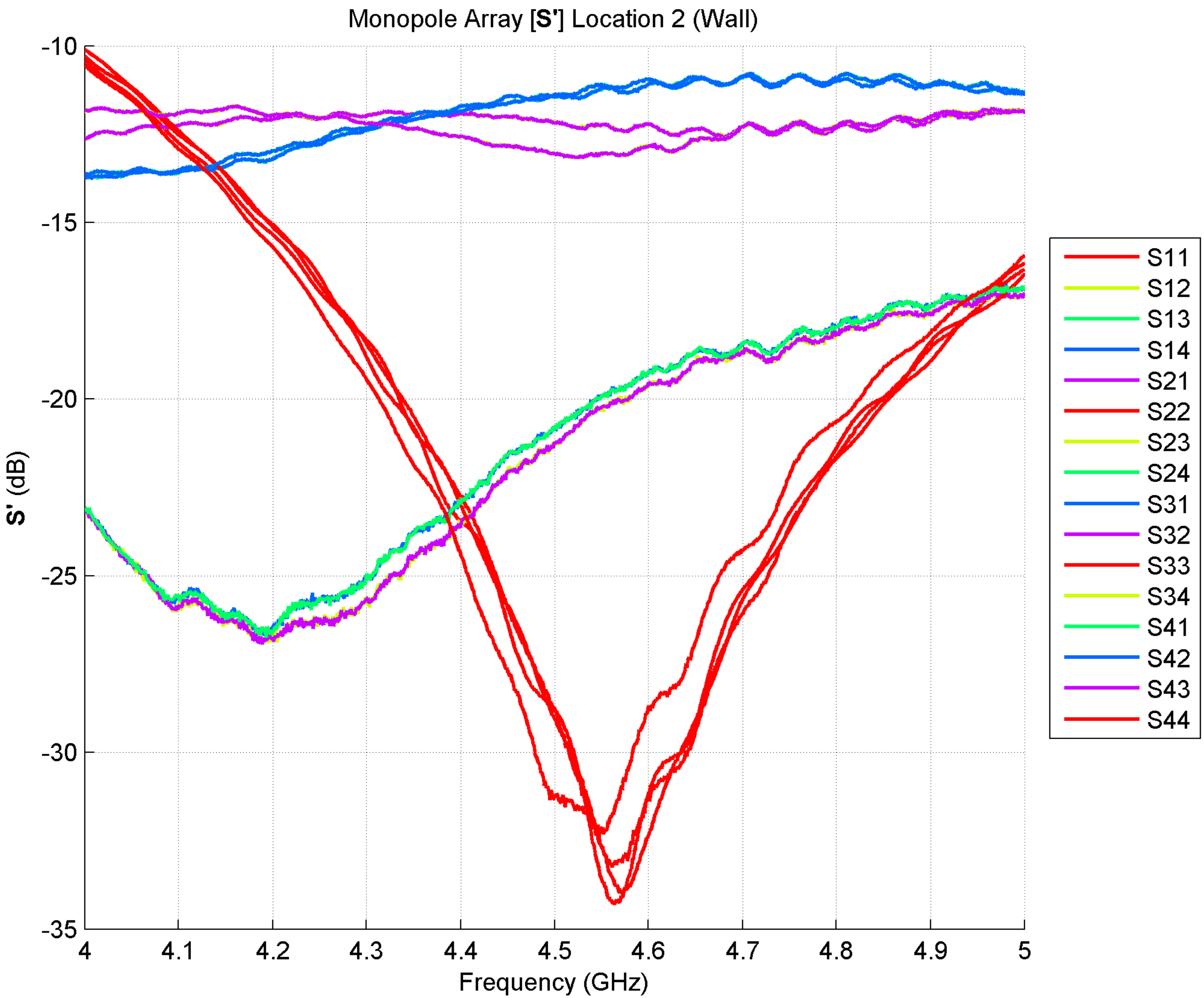


CST MWS Scattering Matrix for 2x2 Monopole Array
S-parameters (dB)
Frequency (GHz)
-10
-15
-20
-25
-30
-35
-40
-45
-50
-55
4
4.1
4.2
4.3
4.4
4.5
4.6
4.7
4.8
4.9
5
Coupling between adjacent monopole paths.
Coupling between diagonal monopole paths.
Reflection coefficients for each monopole.


Sandia
National
Laboratories
THE UNIVERSITY OF
NEW MEXICO

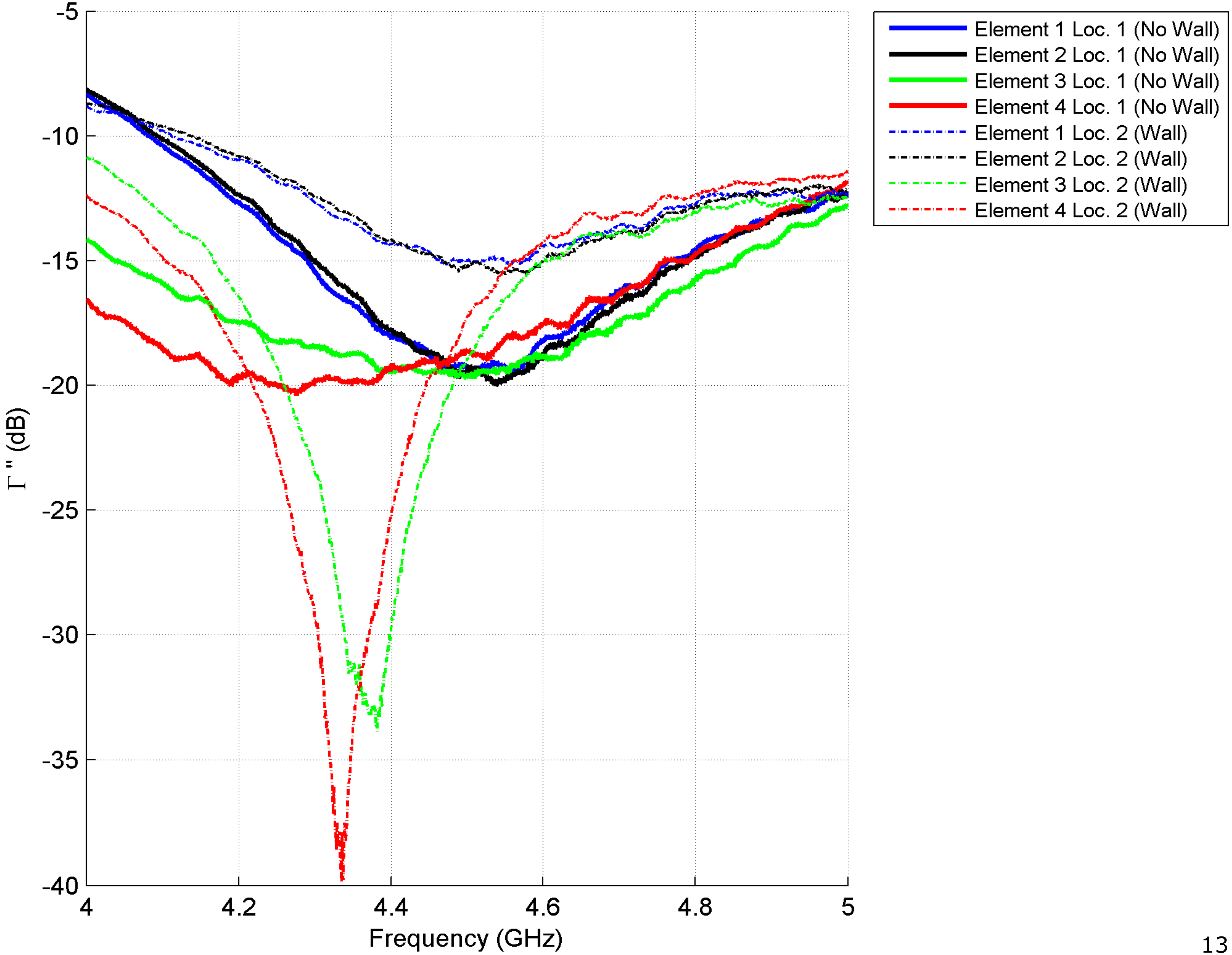

Sandia
National
Laboratories
THE UNIVERSITY OF
NEW MEXICO


Monopole Array [S'] Location 1 (No Wall)
-10
-15
-20
-25
-30
-35
S' (dB)
4
4.1
4.2
4.3
4.4
4.5
4.6
4.7
4.8
4.9
5
Frequency (GHz)
S11
S12
S13
S14
S21
S22
S23
S24
S31
S32
S33
S34
S41
S42
S43
S44

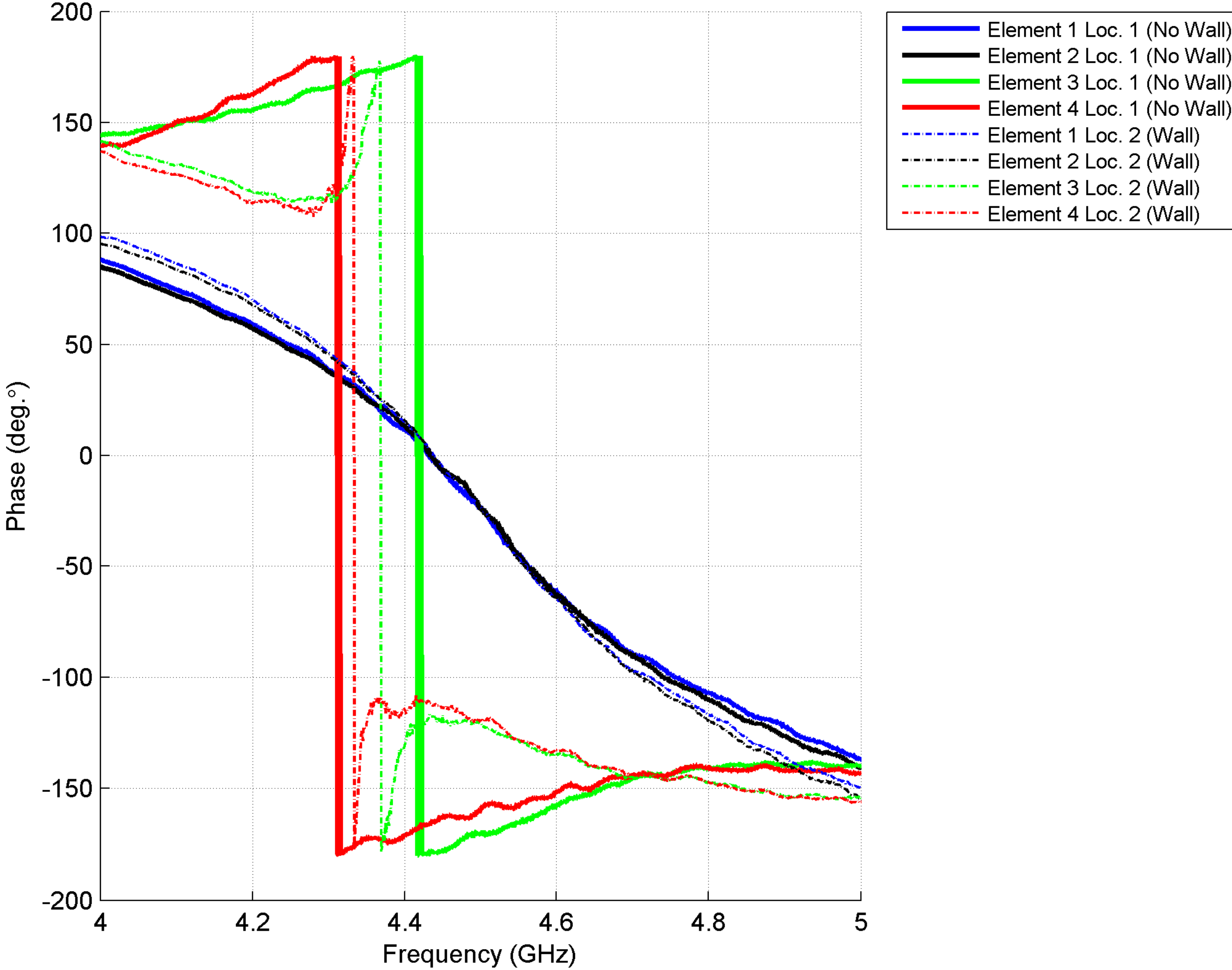


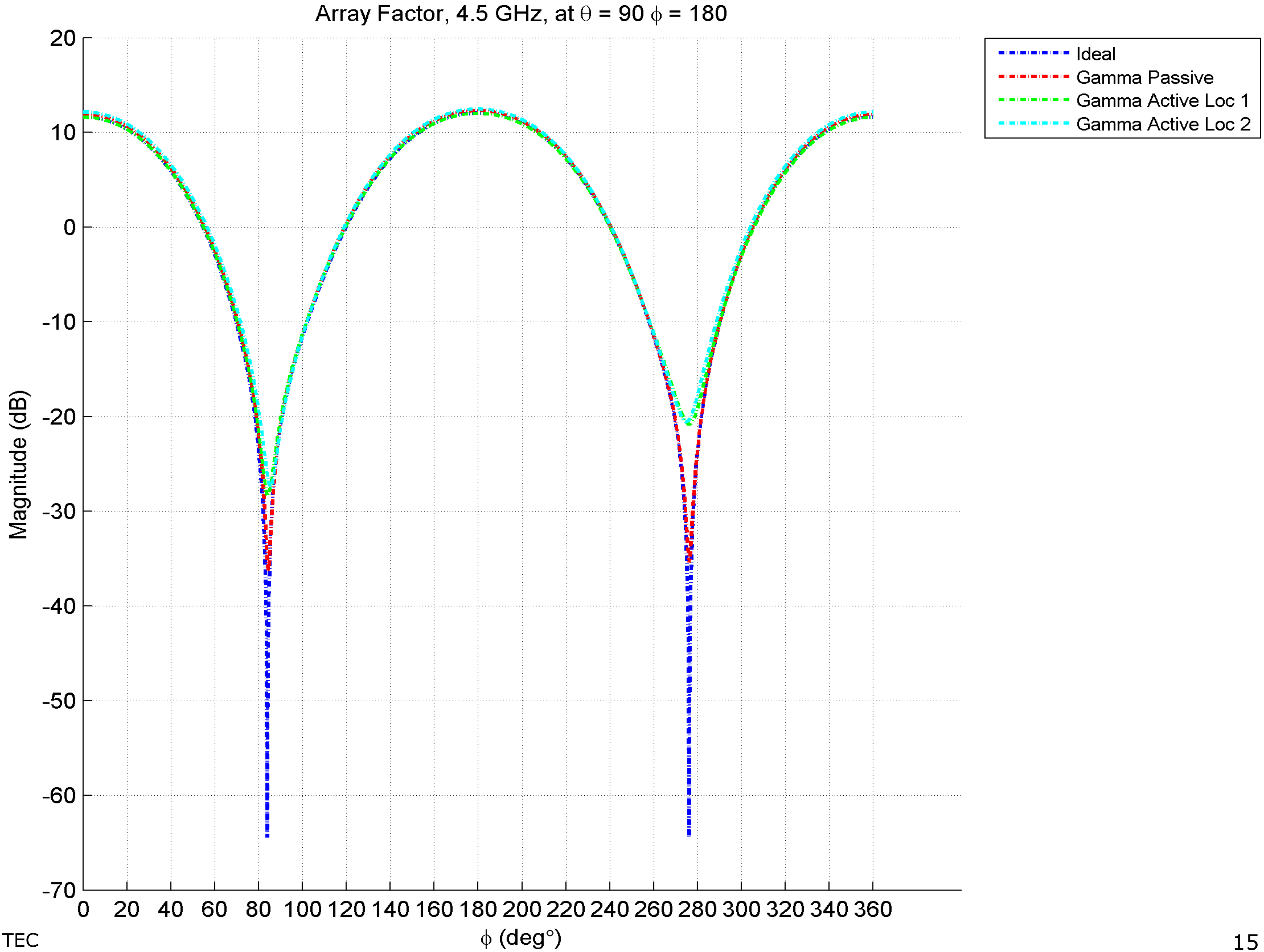
Monopole Array [S'] Location 2 (Wall)
-10
-15
-20
-25
-30
-35
S' (dB)
4
4.1
4.2
4.3
4.4
4.5
4.6
4.7
4.8
4.9
5
Frequency (GHz)
S11
S12
S13
S14
S21
S22
S23
S24
S31
S32
S33
S34
S41
S42
S43
S44

Mutual Coupling Environment 1 vs. Mutual Coupling Environment 2, Γ '' at θ = 90°. and ϕ = 180°

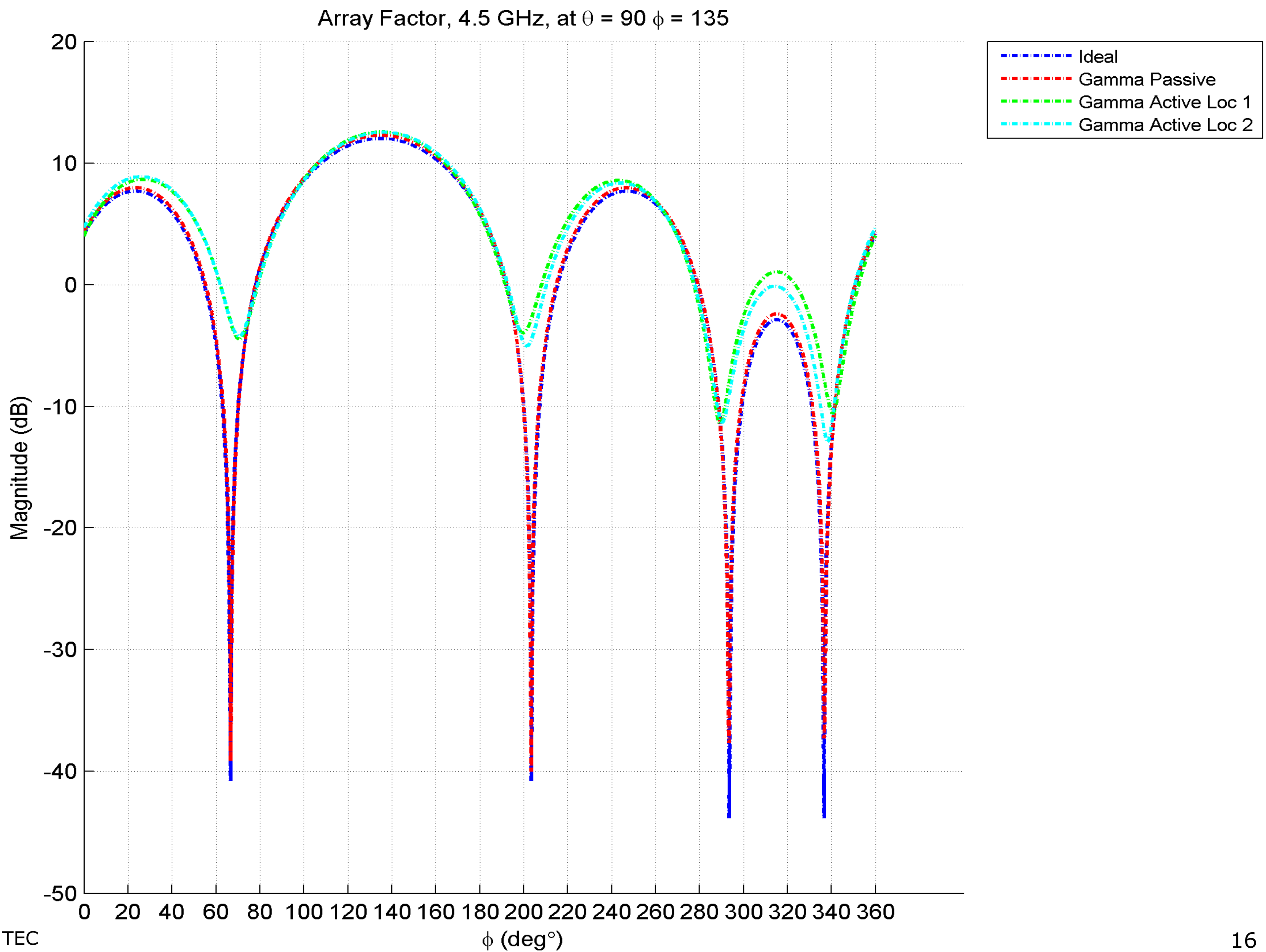


Mutual Coupling Environment 1 vs. Mutual Coupling Environment 2, Γ " at θ = 90°. and φ = 180°





Array Factor, 4.5 GHz, at θ = 90 ϕ = 180
Ideal
Gamma Passive
Gamma Active Loc 1
Gamma Active Loc 2
Magnitude (dB)
20
10
0
-10
-20
-30
-40
-50
-60
-70
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
ϕ (deg°)



Array Factor, 4.5 GHz, at θ = 90 ϕ = 135
Ideal
Gamma Passive
Gamma Active Loc 1
Gamma Active Loc 2
Magnitude (dB)
20
10
0
-10
-20
-30
-40
-50
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360
ϕ (deg°)

Scan Impedance Theory

$$Z_{mn}(\theta,\phi) = Z(0,0)\frac{1+\Gamma_{mn}(\theta,\phi)}{1-\Gamma_{mn}(\theta,\phi)}$$

$$\Gamma_m = \frac{b_m}{a_m}$$

$$\begin{bmatrix} b_1 \\ \vdots \\ b_N \end{bmatrix} = \begin{bmatrix} S_{11} & \cdots & S_{1N} \\ \vdots & \ddots & \vdots \\ S_{N1} & \cdots & S_{NN} \end{bmatrix} \begin{bmatrix} a_1 \\ \vdots \\ a_N \end{bmatrix}$$

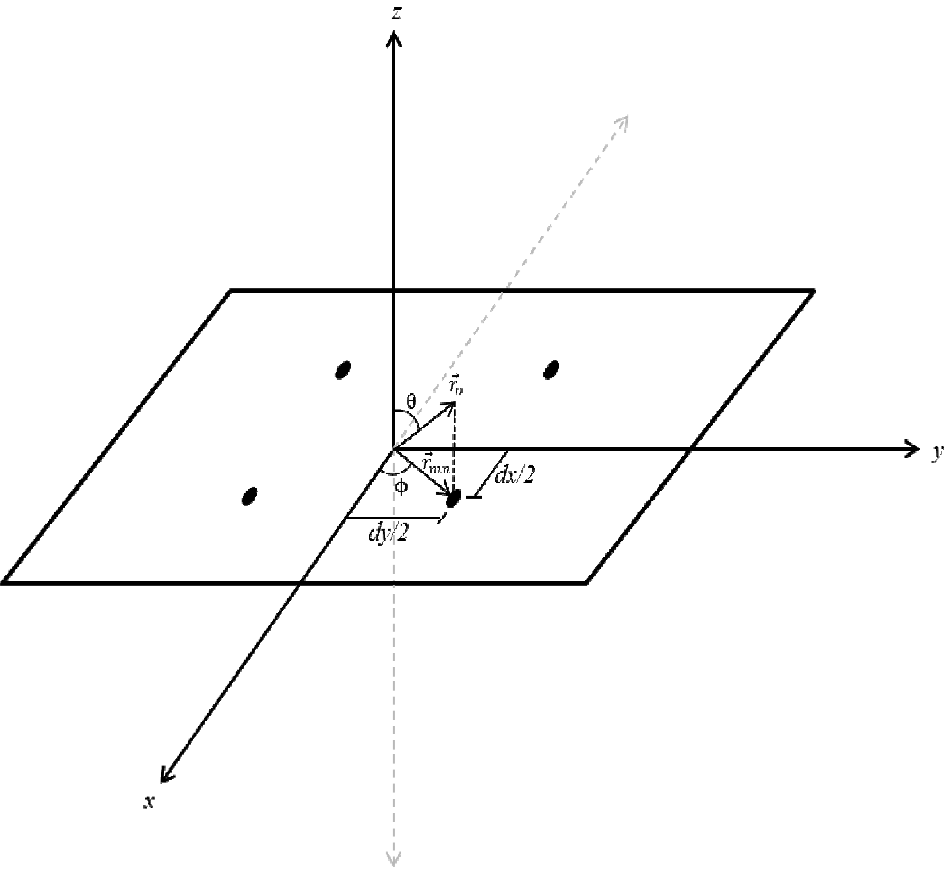
Each element is active during scanning according to an excitation defined by the array factor which forms [a]

$$\begin{aligned} b_1 &= S_{11}a_1 + S_{12}a_2 + S_{13}a_3 + S_{14}a_4 \\ b_2 &= S_{21}a_1 + S_{22}a_2 + S_{23}a_3 + S_{24}a_4 \\ b_3 &= S_{31}a_1 + S_{32}a_2 + S_{33}a_3 + S_{34}a_4 \\ b_4 &= S_{41}a_1 + S_{42}a_2 + S_{43}a_3 + S_{44}a_4 \end{aligned}$$

scan reflection coeff. for port N:

$$\Gamma_N'' = \frac{b_N}{a_N} = \frac{S_{N1}a_1 + S_{N2}a_2 + \cdots + S_{NN}a_N}{a_N}$$

How is column vector [a] determined?



$$AF(\theta,\phi) = \sum_{1}^{M}\sum_{1}^{N} A_{mn} e^{-j\beta\hat{r}\cdot\vec{r}_{mn}} \underbrace{e^{j\alpha_{mn}}}$$

Excitation for Scanning

$$\hat{r} = \sin\theta\cos\phi\,\hat{x} + \sin\theta\sin\phi\,\hat{y} + \cos\theta\hat{z}$$

$$\vec{r}_{mn} = x_{mn}\hat{x} + y_{mn}\hat{y} + z_{mn}\hat{z}$$

$$\alpha_{mn} = \beta\hat{r}_o\cdot\vec{r}_{mn}$$

$$\alpha_{mn} = \omega\sqrt{\mu_o\varepsilon_o}\,\hat{r}_o\cdot\vec{r}_{mn}$$

$$\alpha_{mn} = \omega\frac{\hat{r}_o\cdot\vec{r}_{mn}}{c} \qquad \tau_{mn} = \frac{\hat{r}_o\cdot\vec{r}_{mn}}{c}$$

$$a_N = A_N e^{-j\alpha_N} \qquad [a] = \begin{bmatrix} a_1 \\ \vdots \\ a_N \end{bmatrix}$$

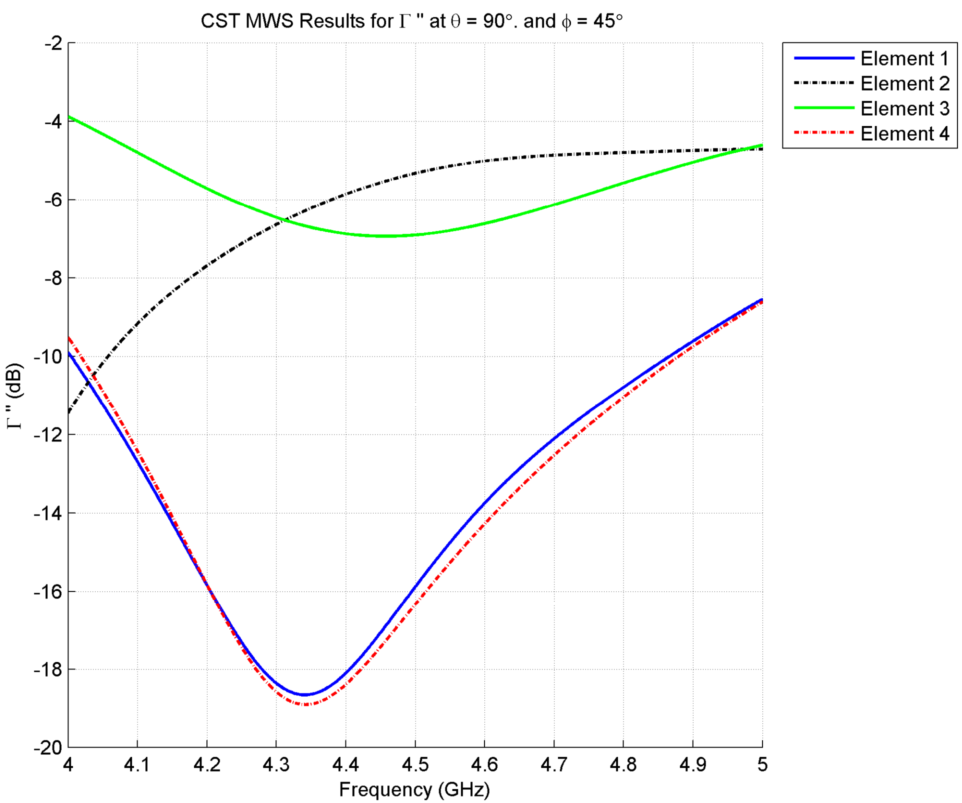
Scan Reflection Coefficient Solution

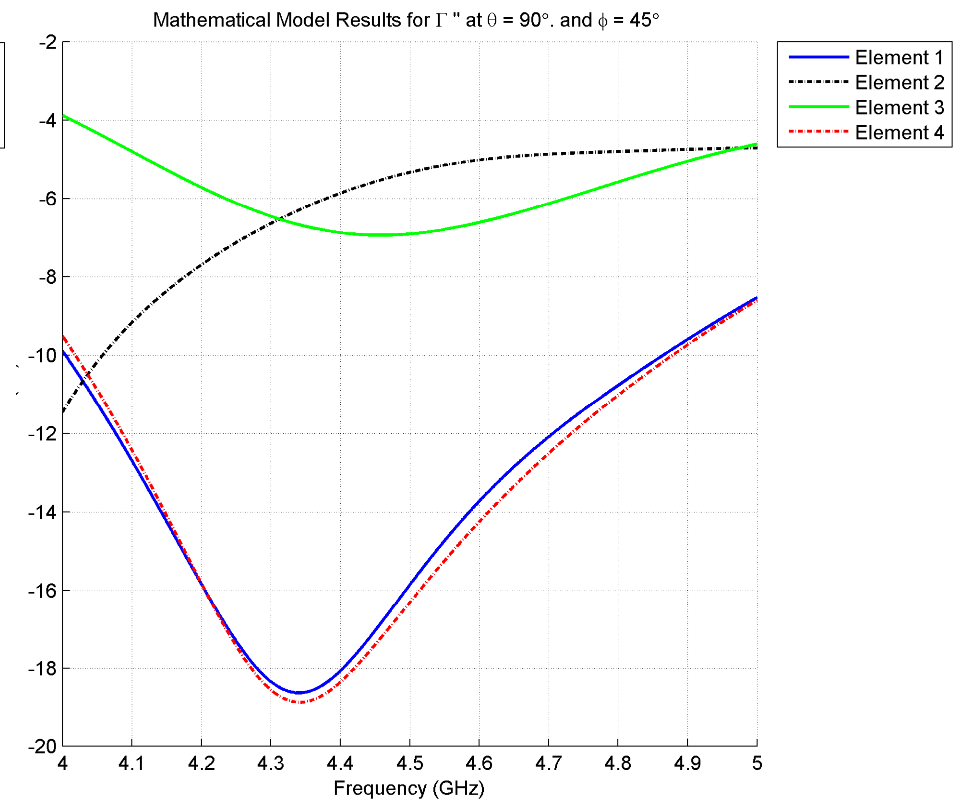
$$\begin{bmatrix} b_1'' \\ \vdots \\ b_N'' \end{bmatrix} = \begin{bmatrix} S_{11}' & \cdots & S_{1n}' \\ \vdots & \ddots & \vdots \\ S_{N1}' & \cdots & S_{NN}' \end{bmatrix} \begin{bmatrix} a_1'' \\ \vdots \\ a_N'' \end{bmatrix}$$

$$\begin{bmatrix} \Gamma_1'' \\ \vdots \\ \Gamma_N'' \end{bmatrix} = \begin{bmatrix} b_1'' \\ \vdots \\ b_N'' \end{bmatrix} ./ \begin{bmatrix} a_1'' \\ \vdots \\ a_N'' \end{bmatrix}$$

Element Wise Division

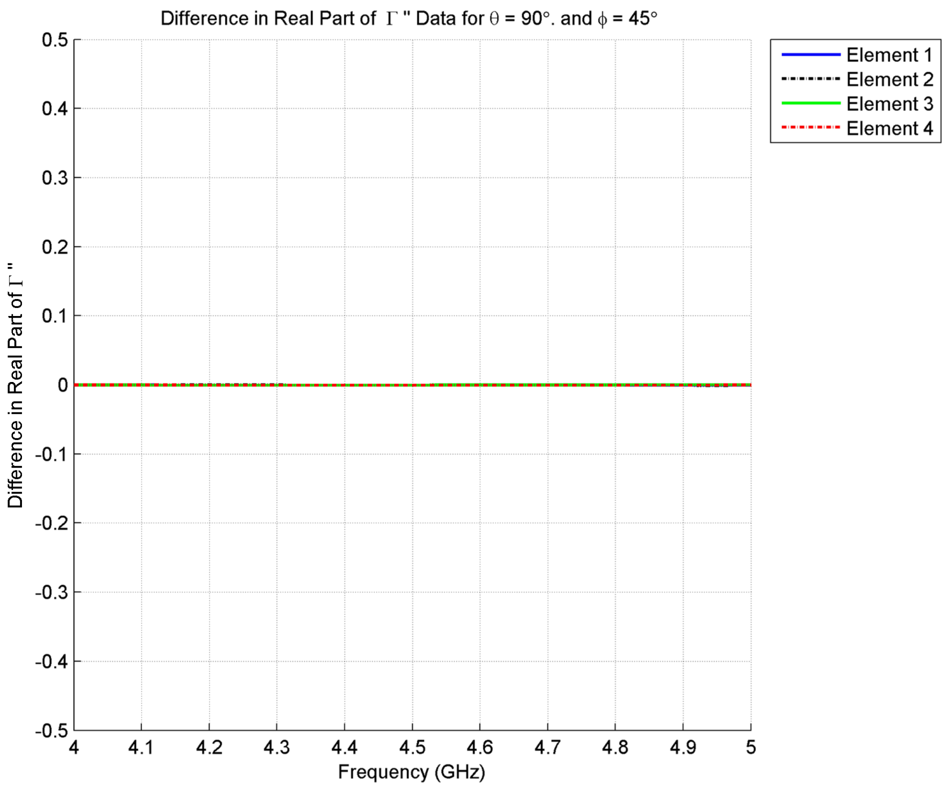
Validation of Scan Impedance Theory

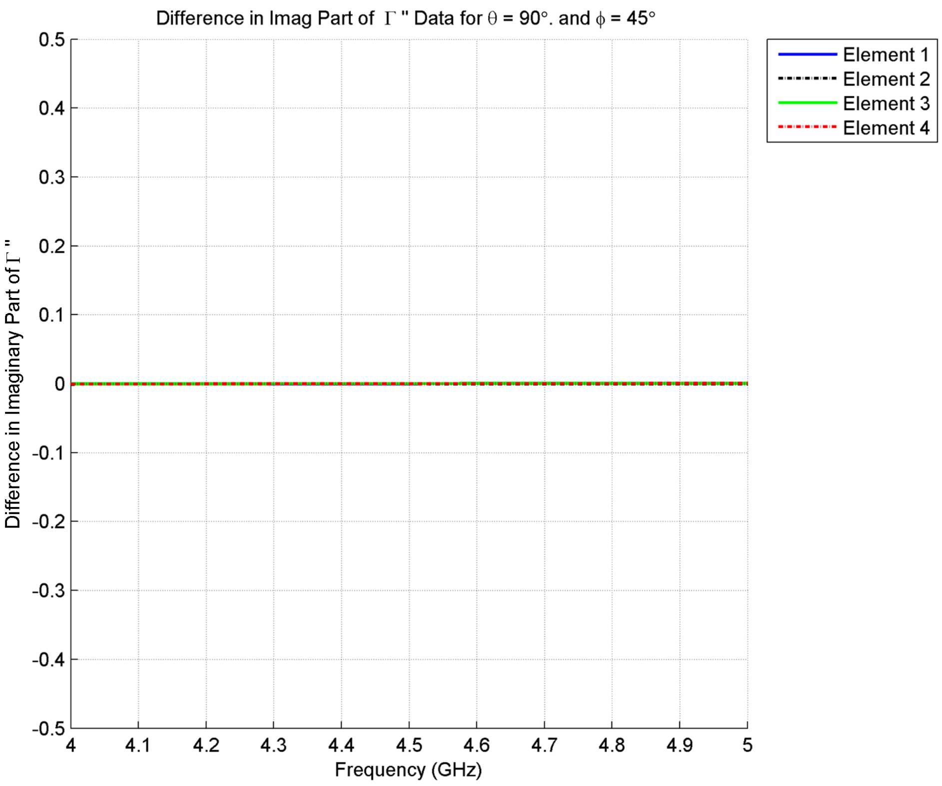




- 8 Comparisons completed in increments of 45° around phi

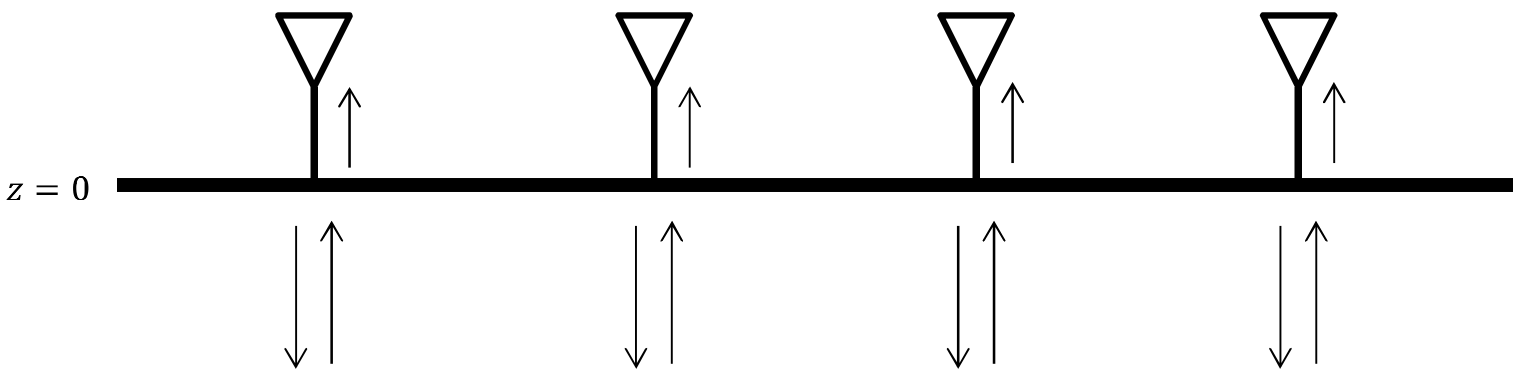
Validation Continued…





Change In the Array Factor

$(1+\Gamma_1''(\theta,\phi))a_1 e^{-j\phi_1}$ $(1+\Gamma_2''(\theta,\phi))a_2 e^{-j\phi_2}$ $(1+\Gamma_3''(\theta,\phi))a_3 e^{-j\phi_3}$ $(1+\Gamma_4''(\theta,\phi))a_4 e^{-j\phi_4}$



Applied Excitations → $a_1 e^{j\phi_1}$ $a_2 e^{j\phi_2}$ $a_3 e^{j\phi_3}$ $a_4 e^{j\phi_4}$

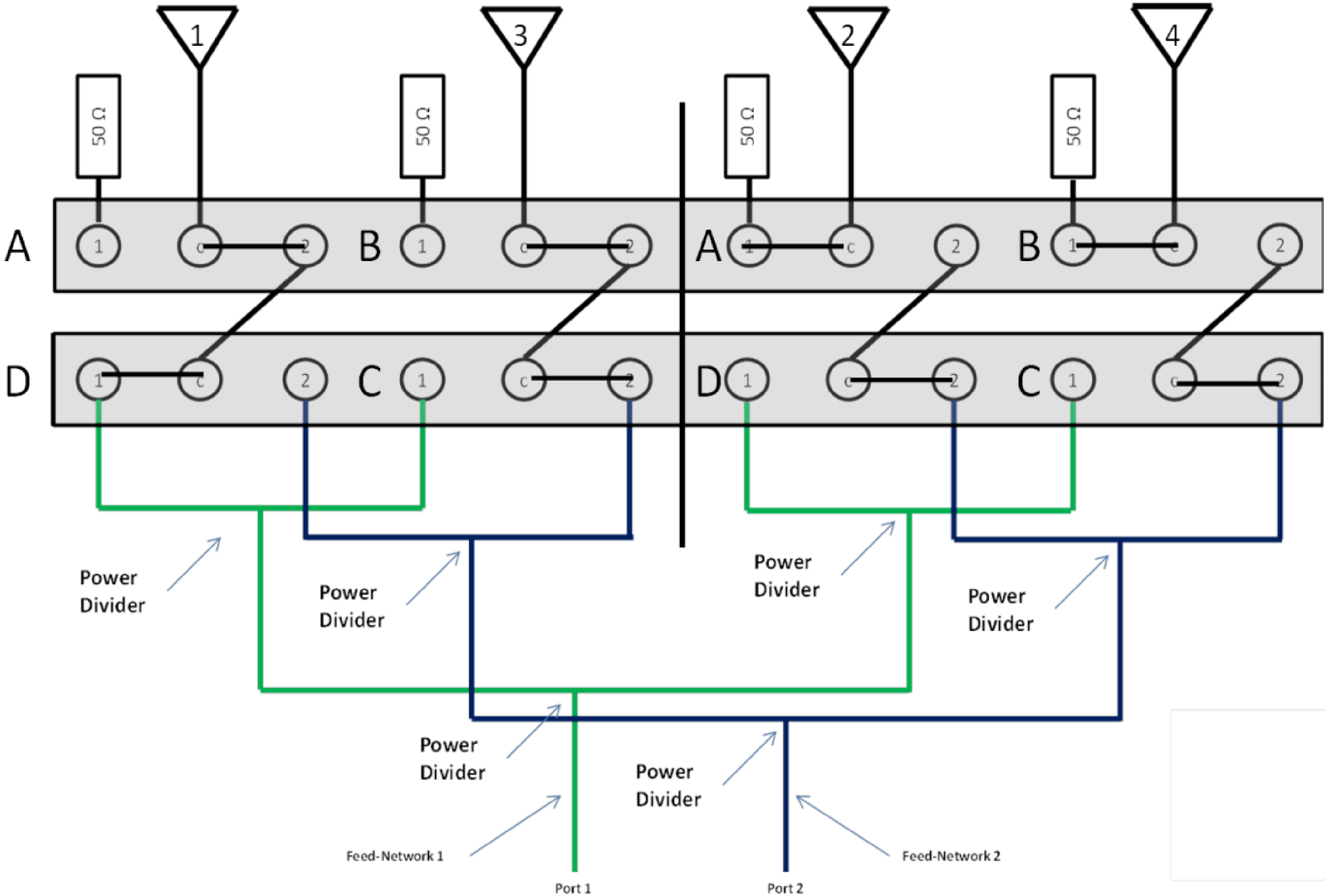
$$a_1 = a_2 = a_3 = a_4$$

$$V(z) = V_o^+(e^{-j\beta z} + \Gamma e^{+j\beta z}),\quad z<0 \qquad T = 1+\Gamma$$

$$V(z) = V_o^+ T e^{-j\beta z},\quad z>0 \qquad \boxed{V(z) = V_o^+(1+\Gamma)e^{-j\beta z}}$$

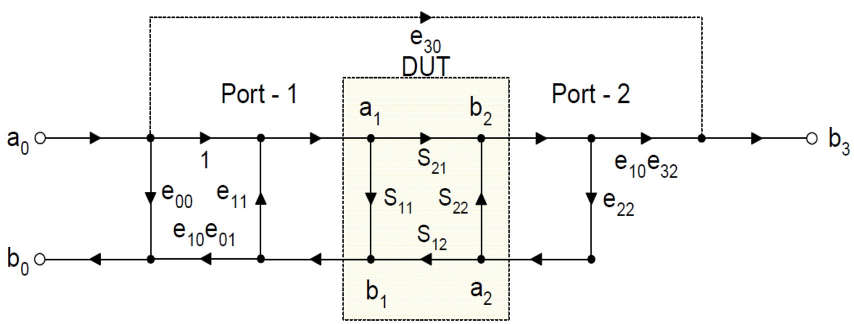
In-Situ System Design

- Two ports required to measure mutual coupling between two elements
- For N elements, N ports are needed or two ports can be used to measure all permutations, however this requires access to all elements; doing this manually is impractical, and buying an N port PNA is expensive
- But we have a solution…

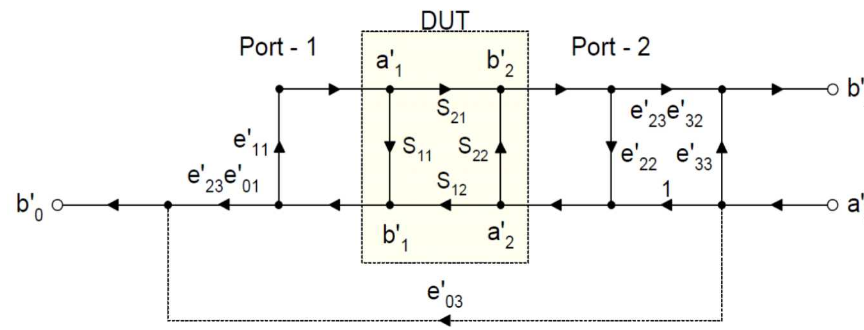

1
3
2
4
50 Ω
50 Ω
50 Ω
50 Ω
A
B
A
B
D
C
D
C
Power Divider
Power Divider
Power Divider
Power Divider
Power Divider
Power Divider
Feed-Network 1
Feed-Network 2
Port 1
Port 2

Error Correction

FORWARD MODEL



REVERSE MODEL



$$S_{11M} = \frac{b_0}{a_0} = e_{00} + \frac{e_{10}e_{01}(S_{11} - e_{22}\Delta s)}{1 - e_{11}S_{11} - e_{22}S_{22} + e_{11}e_{22}\Delta s}$$

$$S_{21M} = \frac{b_3}{a_0} = e_{30} + \frac{e_{10}e_{32}S_{21}}{1 - e_{11}S_{11} - e_{22}S_{22} + e_{11}e_{22}\Delta s}$$

$$S_{22M} = \frac{b_3'}{a_3'} = e_{33}' + \frac{e_{23}'e_{32}'(S_{22} - e_{11}'\Delta s)}{1 - e_{11}'S_{11} - e_{22}'S_{22} + e_{11}'e_{22}'\Delta s}$$

$$S_{12M} = \frac{b_0'}{a_3'} = e_{03}' + \frac{e_{23}'e_{01}'(S_{12})}{1 - e_{11}'S_{11} - e_{22}'S_{22} + e_{11}'e_{22}'\Delta s}$$

S-Parameter Actuals

$$S_{11} = \frac{\left(\frac{S_{11M} - e_{00}}{e_{10}e_{01}}\right)\left[1 + \left(\frac{S_{22M} - e'_{33}}{e'_{23}e'_{32}}\right)e'_{22}\right] - e_{22}\left(\frac{S_{21M} - e_{30}}{e_{10}e_{32}}\right)\left(\frac{S_{12M} - e'_{03}}{e'_{23}e'_{01}}\right)}{D}$$

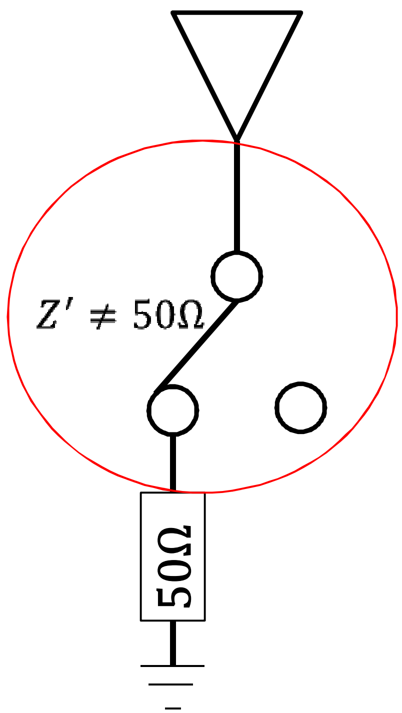
$$S_{21} = \frac{\left(\frac{S_{21M} - e_{30}}{e_{10}e_{32}}\right)\left[1 + \left(\frac{S_{22M} - e'_{33}}{e'_{23}e'_{32}}\right)(e'_{22} - e_{22})\right]}{D}$$

$$S_{22} = \frac{\left(\frac{S_{22M} - e'_{33}}{e'_{23}e'_{32}}\right)\left[1 + \left(\frac{S_{11M} - e_{00}}{e_{10}e_{01}}\right)e_{11}\right] - e'_{11}\left(\frac{S_{21M} - e_{30}}{e_{10}e_{32}}\right)\left(\frac{S_{12M} - e'_{03}}{e'_{23}e'_{01}}\right)}{D}$$

$$S_{12} = \frac{\left(\frac{S_{12M} - e'_{03}}{e'_{23}e'_{01}}\right)\left[1 + \left(\frac{S_{11M} - e_{00}}{e_{10}e_{01}}\right)(e_{11} - e'_{11})\right]}{D}$$

$$D = \left[\left[1 + \left(\frac{S_{11M} - e_{00}}{e_{10}e_{01}}\right)e_{11}\right]\left[1 + \left(\frac{S_{22M} - e'_{33}}{e'_{23}e'_{32}}\right)e'_{22}\right] - \left(\frac{S_{21M} - e_{30}}{e_{10}e_{32}}\right)\left(\frac{S_{12M} - e'_{03}}{e'_{23}e'_{01}}\right)e_{22}e'_{11}\right].$$

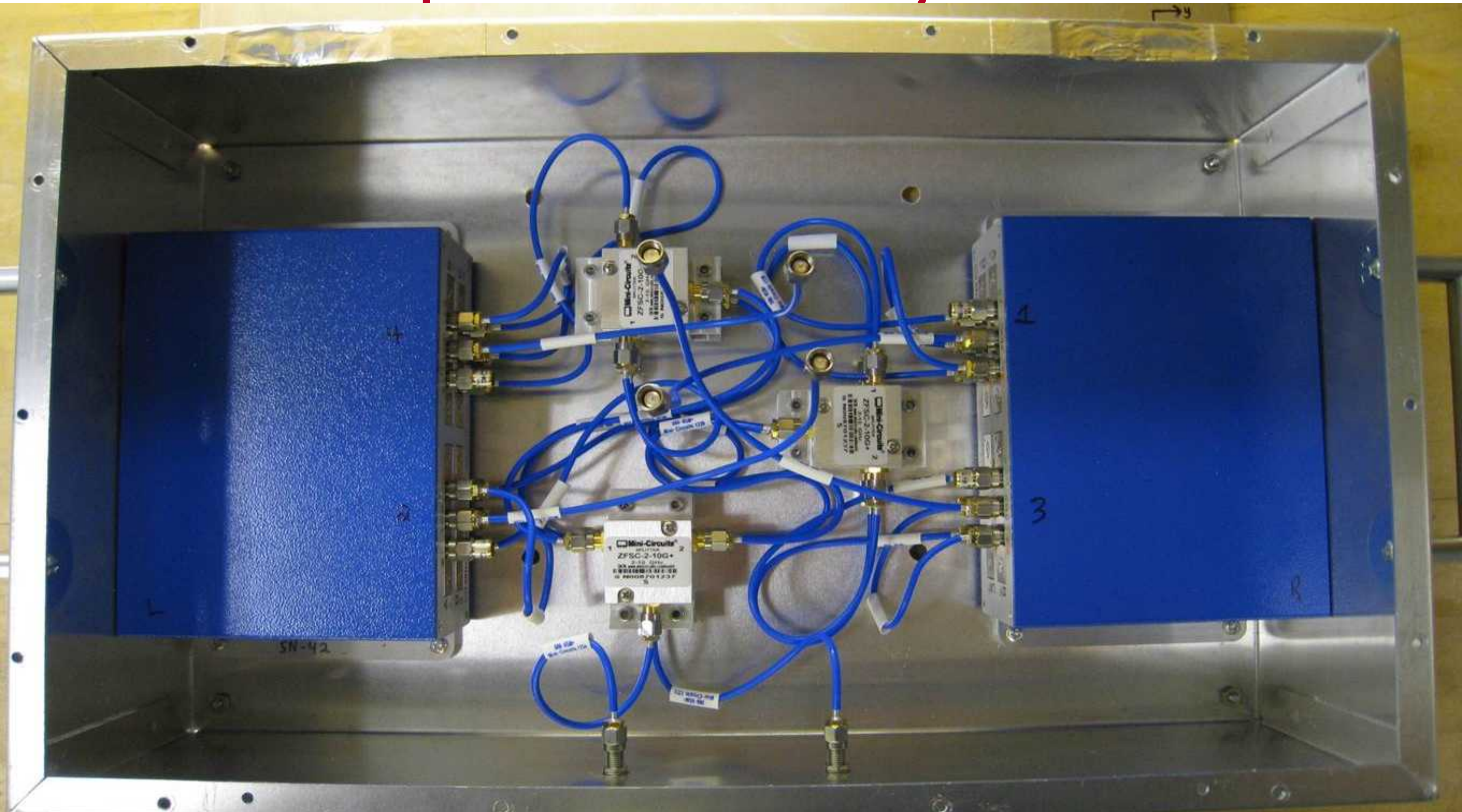
Impedance Renormalization



- During S-parameter measurements, unused ports should be terminated with ideal matched loads
- The unused antenna ports in the in-situ measurement system are not ideal, and thus add unwanted reflection back into the measurement
- This can be accounted for by using the impedance renormalization transform to put measurement reference back to a 50 ohm system.

$$S' = (I - S)^{-1}(S - \Gamma)(I - S \cdot \Gamma)^{-1}(I - S)$$

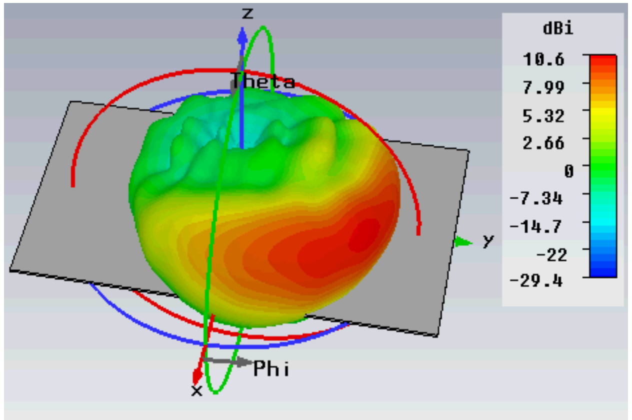
Implemented System

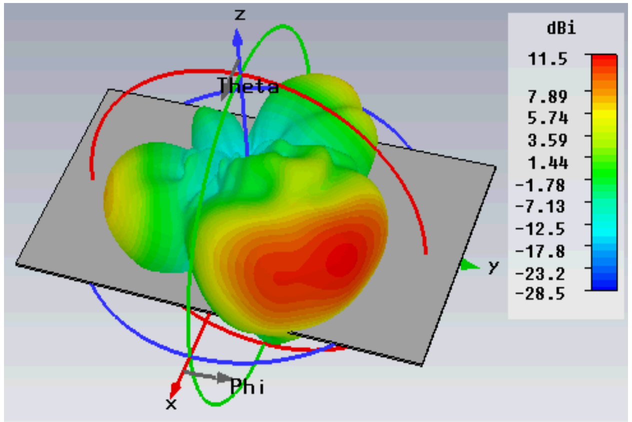


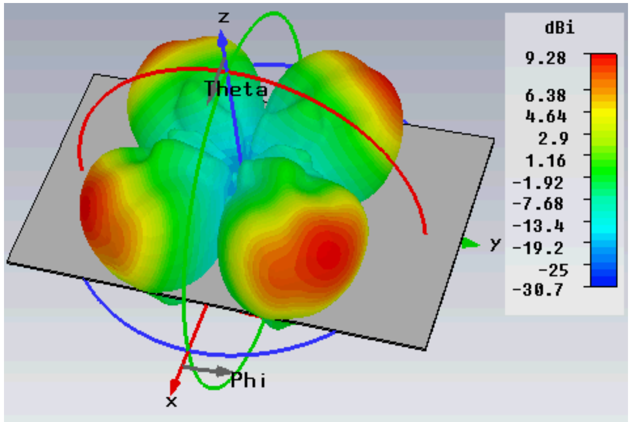
Element Spacing Study

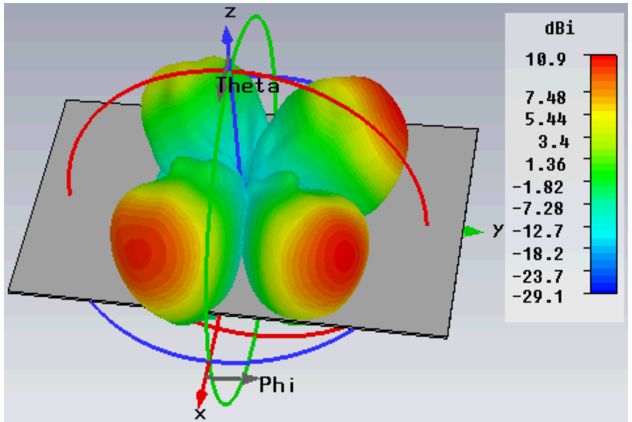
Element Spacings				
Wavelength Spacing	**0.25λ**	**0.50λ**	**0.75λ**	**1.00λ**

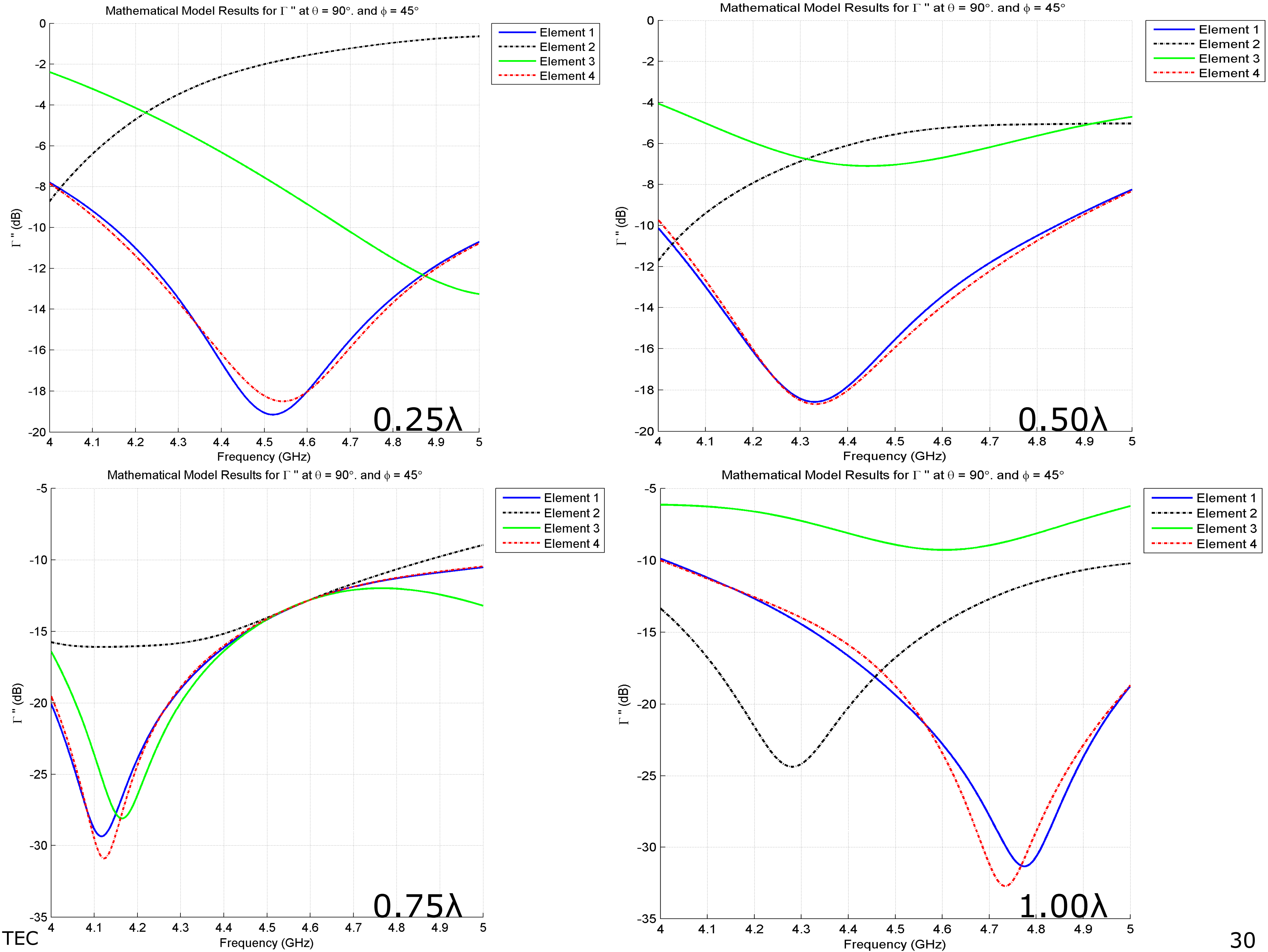
$\Theta = 90°, \phi = 45°$











Mathematical Model Results for Γ " at θ = 90°. and ϕ = 45°
Element 1
Element 2
Element 3
Element 4
Γ " (dB)
Frequency (GHz)
0.25λ
Mathematical Model Results for Γ " at θ = 90°. and ϕ = 45°
Element 1
Element 2
Element 3
Element 4
Γ " (dB)
Frequency (GHz)
0.50λ
Mathematical Model Results for Γ " at θ = 90°. and ϕ = 45°
Element 1
Element 2
Element 3
Element 4
Γ " (dB)
Frequency (GHz)
0.75λ
Mathematical Model Results for Γ " at θ = 90°. and ϕ = 45°
Element 1
Element 2
Element 3
Element 4
Γ " (dB)
Frequency (GHz)
1.00λ

Conclusions

- In-Situ scan impedance characterization is needed for phased antenna arrays that can be placed in diverse locations in the field.
- If mutual coupling changes, so does scan impedance.
- An approach and implementation for in-situ mutual coupling measurements has been given and implemented in hardware.
- The mathematics that exists for scan impedance/reflection calculation has been expanded upon and formulated into two elegant matrix equations.

Future Work

- Expansion of this system into a compact microstrip array utilizing IC packages or dye packaging to accomplish rf switching. Also incorporation of true time delay units or phase shifters as well as attenuators.

- This study has set up the fundamental theory necessary to begin research into mitigation techniques to account for the effects of scan impedance.
  - Perhaps a tuning system could be implemented
  - Direct mitigation technique in the array fabrication to eliminate or dampen out the effect of mutual coupling
  - Potentially a new form of array synthesis could be developed to account for this issue

Questions?

Backup Slides

References

[1] T. C. Cheston and J. Frank, "Phased Array RADAR Antennas," in RADAR Handbook, Massachusetts, McGraw-Hill, 1990, pp. 7.23-7.26.

[2] W. L. Stutzman and G. A. Thiele, Antenna Theory and Design, 2nd Edition, Danvers: John Wiley & Sons, Inc., 1998.

[3] D. M. Pozar, "Scan Blindness in Infinite Phased Arrays of Printed Dipoles," IEEE Transactions on Antennas and Propagation, Vols. AP-32, no. 6, pp. 602-610, 1984.

[4] D. M. Pozar, "The Active Element Pattern," IEEE Transactions on Antennas and Propagation, vol. 42, no. 8, pp. 1776-1778, 1994.

[5] A. J. Fenn, "Theoretical and Experimental Study of Monopole Phased Array Antennas," IEEE Transactions on Antennas and Propagation, Vols. AP-33, no. 10, pp. 118-1126, 1985.

[6] J.-w. Yu, D.-C. Park, I.-H. Han, D.-S. Kim and C.-H. Kim, "Scan Reflection Coefficient of Open-Ended Waveguide Array," in Proceedings of ISAP2007, Niigata, Japan, 2007.

[7] D. T. McGrath, "Calculation of Coupling Coefficients for Arrays With Skewed Lattices From Infinite Array Scan Reflection Data," IEEE Transaction on Antennas and Propagation, vol. 55, no. No.7, pp. 2116-2119, 2007.

[8] D. T. McGrath, Requirements for Calculation of Coupling Coefficients for Generic Arrays from Infinite Array Scan Reflection Data, IEEE, 2006.

[9] S. CHEN and R. IWATA, Mutual Coupling Effects in Microstrip Patch Phased Array Antenna, IEEE, 1998.

[10] H. M. Aumann, A. J. Fenn and F. G. Willwerth, "Phased Array Antenna Calibration and Pattern Prediction Using Mutual Coupling Measurements," IEEE Transactions on Antennas and Propagation, vol. 33, no. 7, pp. 844 - 850, 1989.

References Cont…

[11] D. Rytting, Network Analyzer Error Models and Calibration Methods.

[12] J. C. Tippet and R. A. Speciale, "A Rigorous Technique for Measuring the Scattering Matrix of a Multiport Device with a 2-Port Network Analyzer," IEEE Transactions on Microwave Theory and Techniques, Vols. MTT-30, no. 5, pp. 661-666, May 1982.

[13] H. Dropkin, "Comments on "A Rigorous Technique for Measuring the Scattering Matrix of a Multiport Device with a Two-Port Network Analyzer"," IEEE Transactions on Microwave Theory and Techniques, vol. 31, no. 1, pp. 79 - 81, 1983.

[14] E. V. Lil, "Comments on "A Rigorous Technique for Measuring the Scattering Matrix of a Multiport Device with a Two-Port Network Analyzer"," IEEE Transactions on Microwave Theory and Techniques, Vols. MTT-33, no. 3, pp. 286 - 287, 1985.

[15] C. Craeye, B. A. Garcia, E. G. Munoz and R. Sarkis, "An Open-Source Code for the Calculation of the Effects of Mutual Coupling in Arrays of Wires and for the ASM-MBF Method," International Journal of Antennas and Propagation, Vols. 2010, Article ID 137903, 10 pages, 2010.

[16] R. L. Haupt, "Mutual Coupling, Ch. 6," in Antenna Arrays: A Computational Approach, Danvers, John Wiley & Sons, Inc, 2010, pp. 339 - 399.

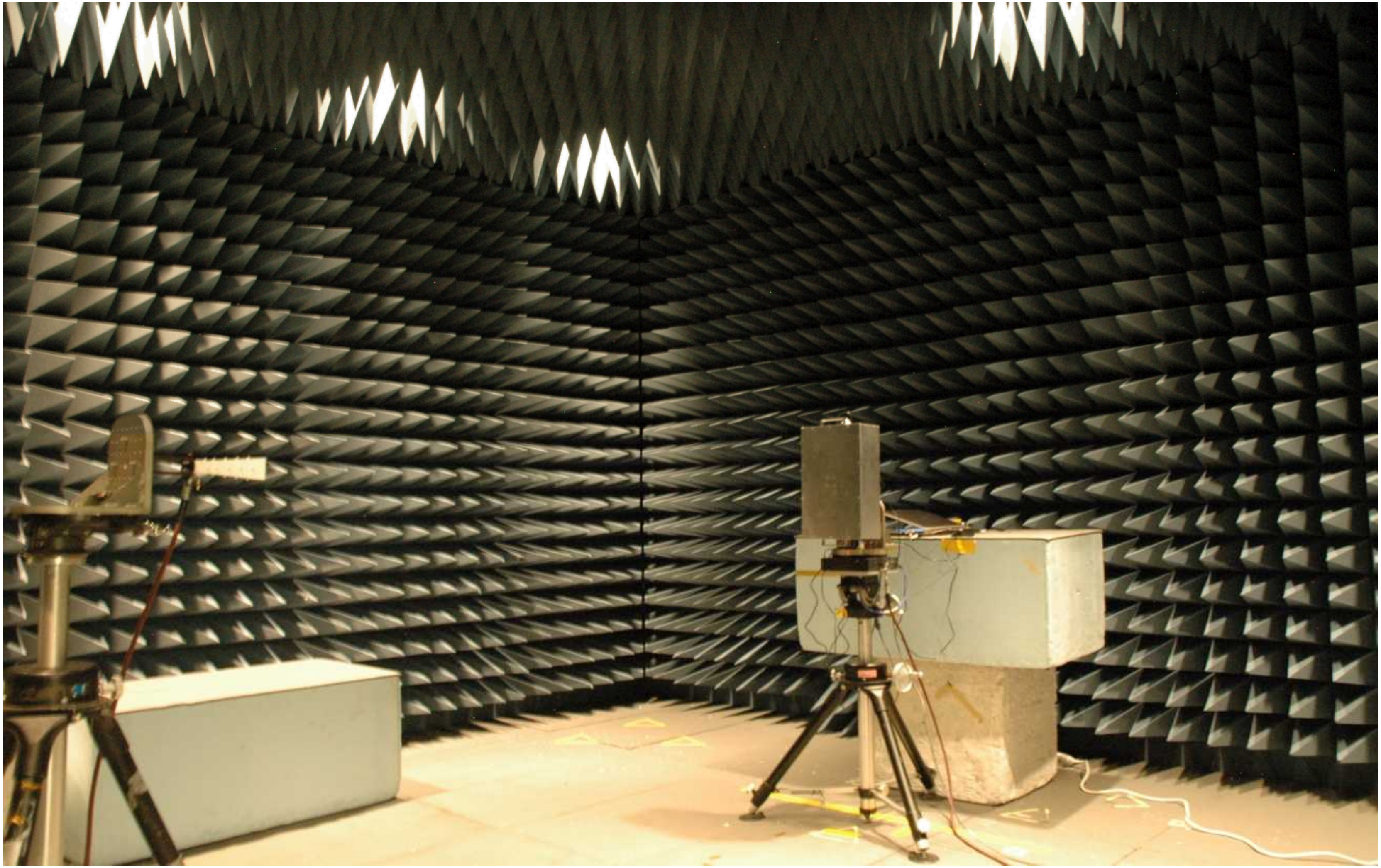
[17] D. M. Pozar, Microwave Engineering, 3rd Edition, Danvers: John Wiley & Sons, Inc., 2005.

[18] C. A. Balanis, Antenna Theory Analysis and Design, 3rd Edition, Danvers: John Wiley & Sons, Inc., 2005.

[19] C. A. Balanis, Advanced Engineering Electromagnetics, Danvers: John Wiley & Sons, Inc., 1989.

[20] D. M. Pozar, Microwave Engineering, Hoboken: John Wiley & Sons, Inc., 2005.

Radiation Pattern Measurement



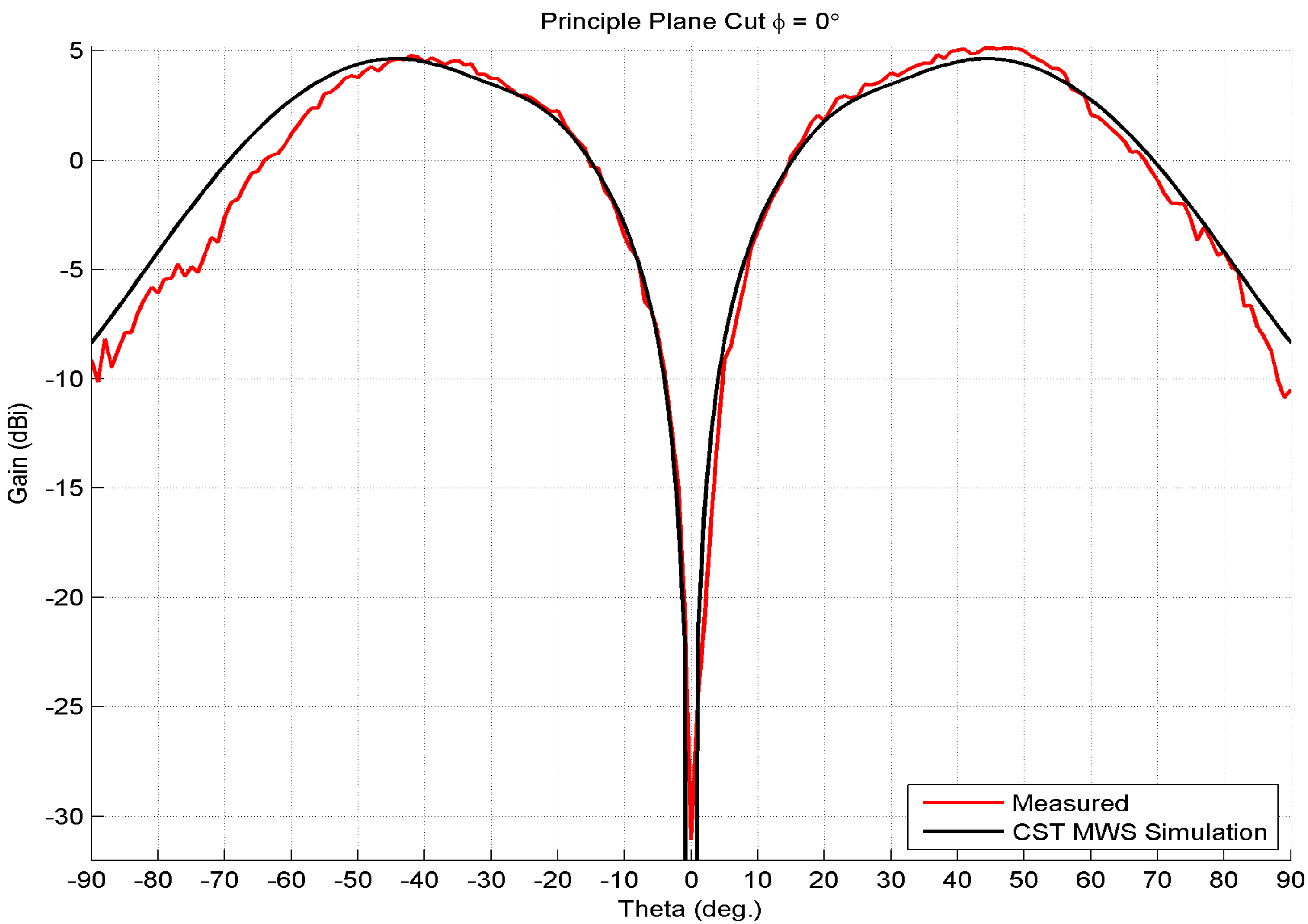
Principle Plane Cut for $\phi = 0°$

UNM SCHOOL of ENGINEERING

Sandia National Laboratories

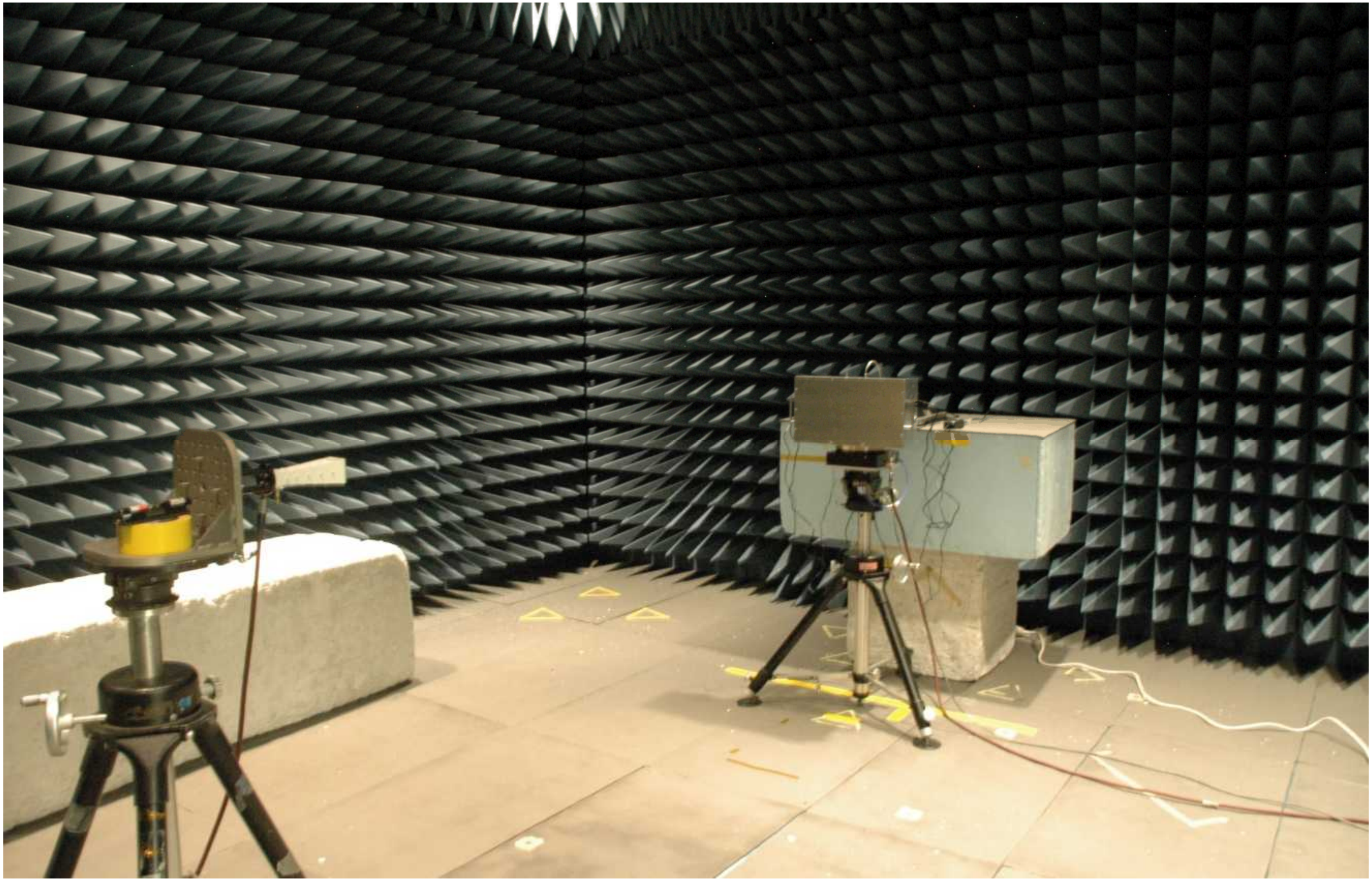
Department of Electrical & Computer Engineering

Radiation Pattern Measurement



Principle Plane Cut for $\phi = 0°$

Radiation Pattern Measurement



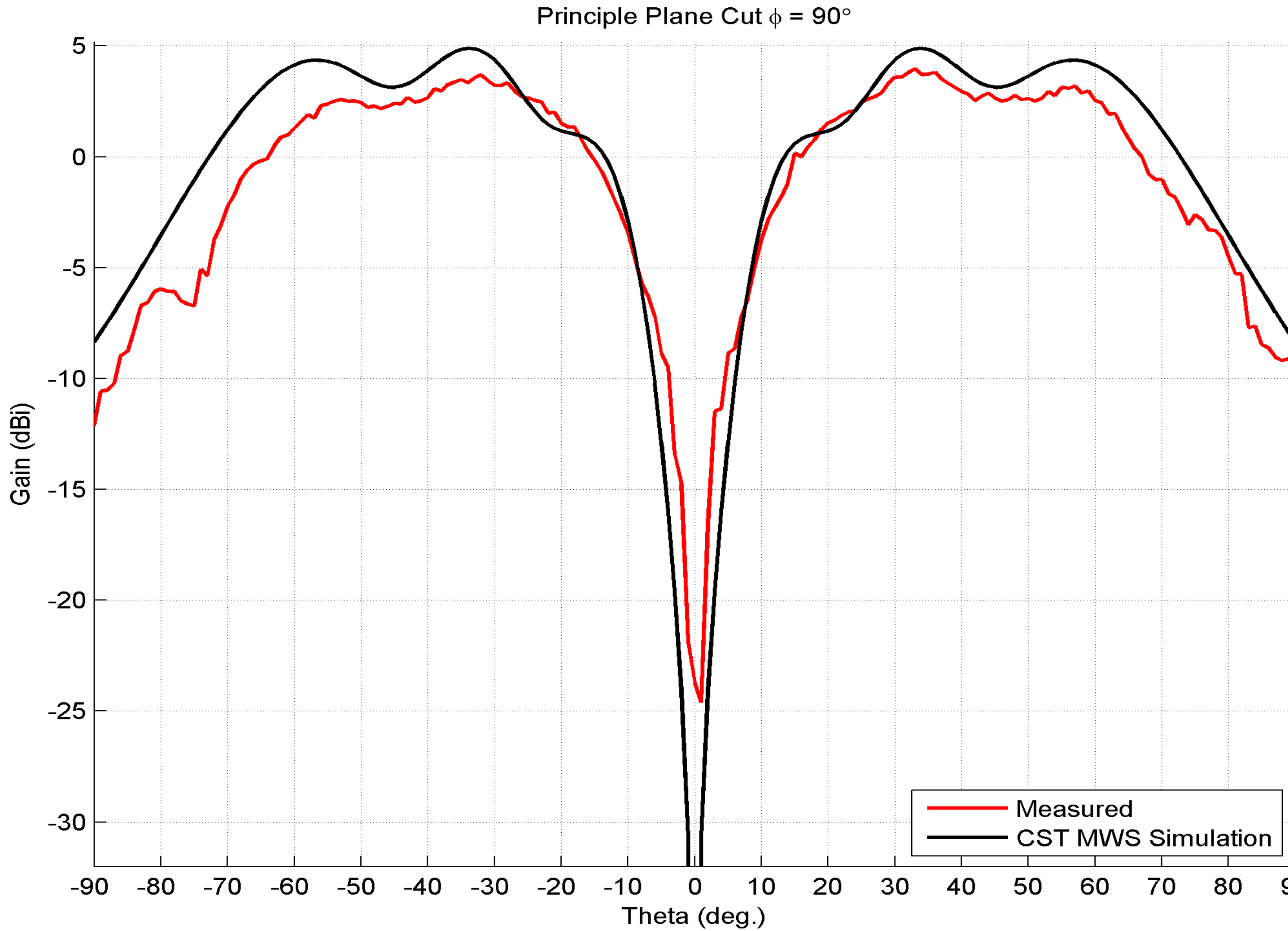
Principle Plane Cut for $\phi = 90°$

UNM SCHOOL of ENGINEERING

Sandia National Laboratories

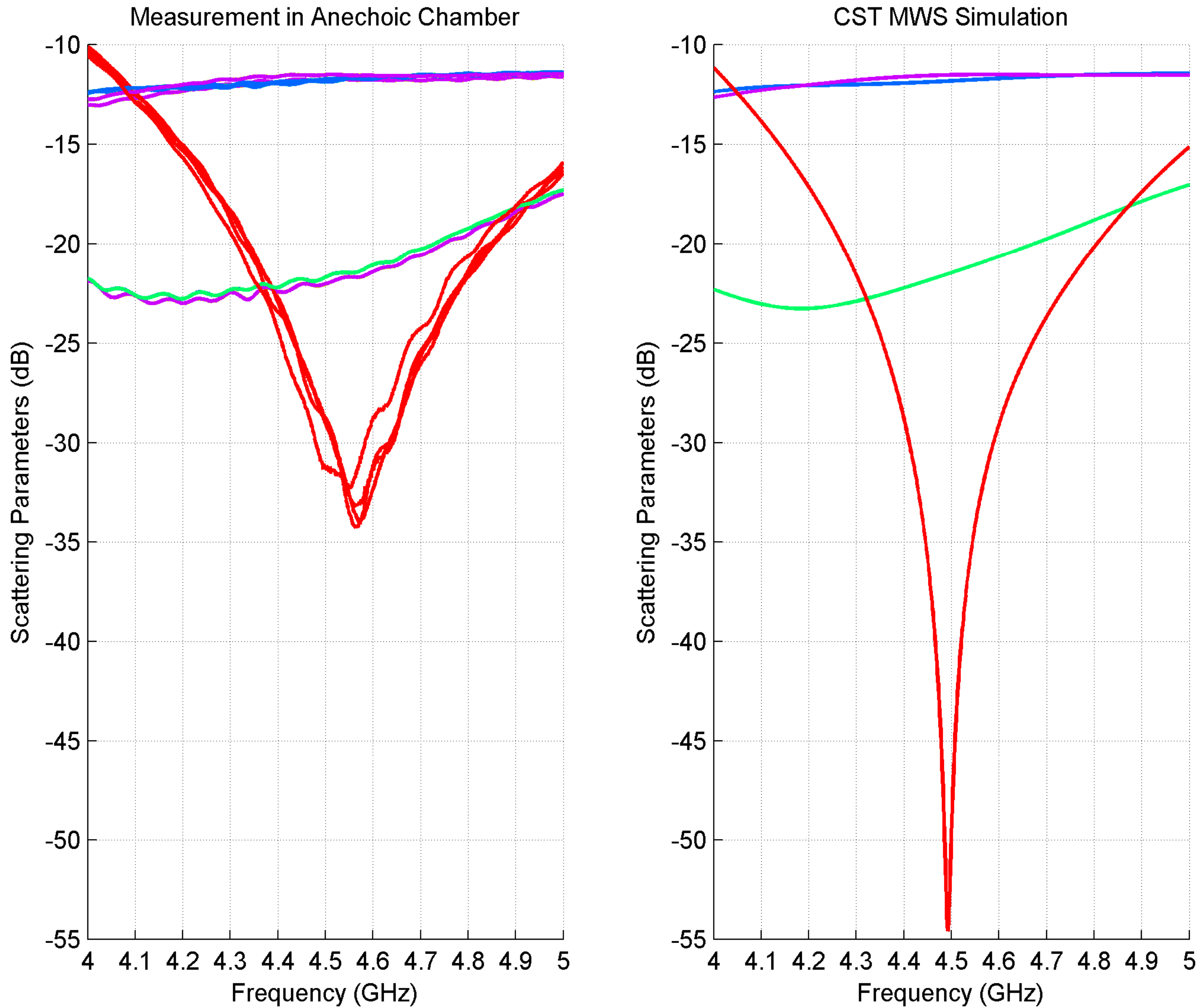
Department of Electrical & Computer Engineering

Radiation Pattern Measurement



Principle Plane Cut for $\phi = 90°$

Side by Side Comparison



Scan Reflection Matrix Expanded

$$\Gamma_1'' = \frac{S_{11}|a_1|e^{j\xi_1} + S_{12}|a_2|e^{j\xi_2} + S_{13}|a_3|e^{j\xi_3} + \cdots + S_{1n}|a_m|e^{j\xi_m}}{|a_1|e^{j\xi_1}}$$

$$\Gamma_2'' = \frac{S_{21}|a_1|e^{j\xi_1} + S_{22}|a_2|e^{j\xi_2} + S_{23}|a_3|e^{j\xi_3} + \cdots + S_{2n}|a_m|e^{j\xi_m}}{|a_2|e^{j\xi_2}}$$

$$\vdots$$

$$\Gamma_m'' = \frac{S_{m1}|a_1|e^{j\xi_1} + S_{m2}|a_2|e^{j\xi_2} + S_{m3}|a_3|e^{j\xi_3} + \cdots + S_{mn}|a_m|e^{j\xi_m}}{|a_m|e^{j\xi_m}}$$

$$a_m'' = |a_m|e^{j\xi_m}$$

Where ξ is the respective phasing at element m.

System Caveat

- Self-Reflection Coefficient measurements are currently not 100% accurate
- Currently, manual measured self-reflection coefficients are being used.
- All transmission coefficients are considered to be in good agreement with manual measured scattering parameters and account for 75% of the total scattering matrix and contain the effects of mutual coupling
- Extensive debugging has occurred and some simple simulations of the automatic system have been completed and shown to be in agreement with the error correction theory
- Potential reason could be an unaccounted for hardware issue