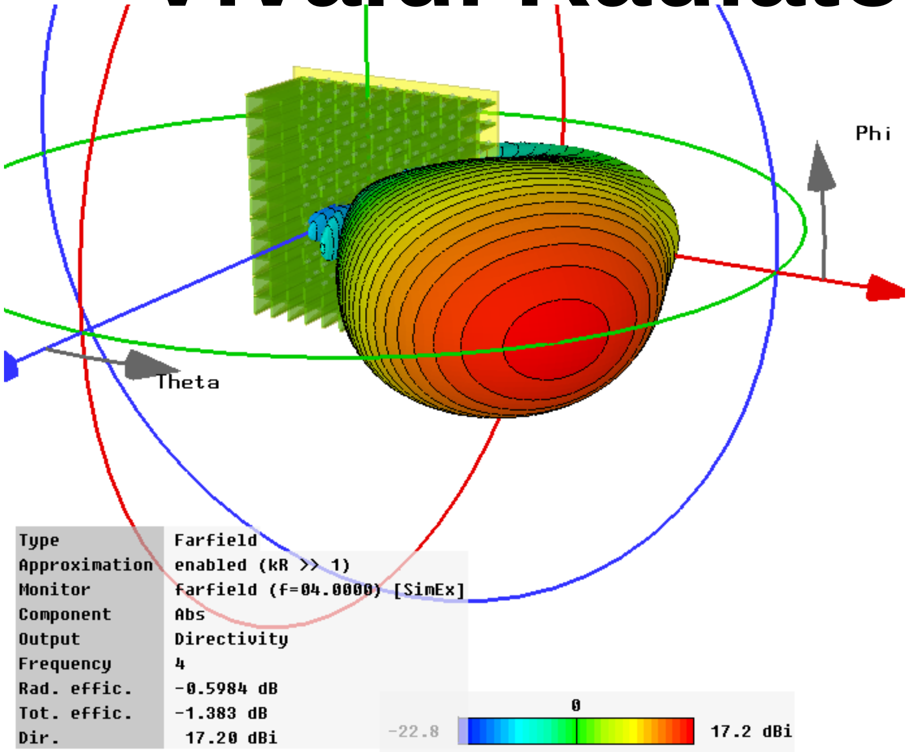
Beam Steering & Shaping in a Finite Array of Coupled Vivaldi Radiators



Type	Farfield
Approximation	enabled (kR >> 1)
Monitor	farfield (f=04.0000) [SimEx]
Component	Abs
Output	Directivity
Frequency	4
Rad. effic.	-0.5984 dB
Tot. effic.	-1.383 dB
Dir.	17.20 dBi

Simulation Using CST Studio Suite 2011™ Microwave Studio® at Sonnet Software, Inc.

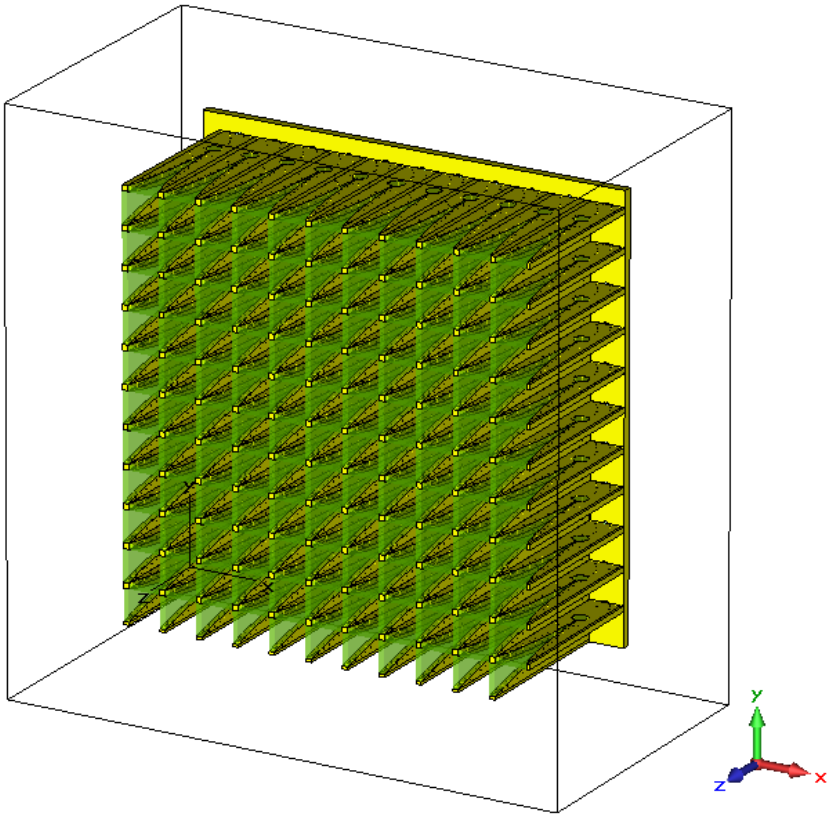
Dr. James R Willhite

11x11 Dual Polarized Vivaldi Array

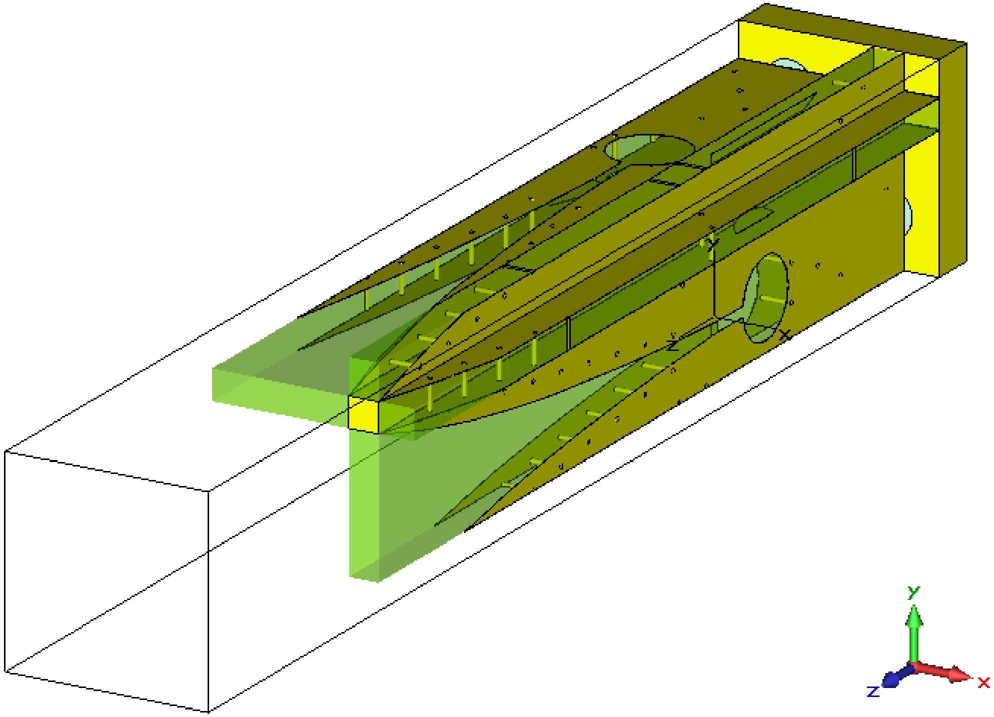
Antenna arrays are often modeled using an infinite array approximation; results from unit cells modeled with periodic boundaries. However if there is coupling between the elements in the array, the actual performance of a finite array will differ from this type of result because of changes in the local environment, edge effects.

A unit cell of dual polarized Vivaldi radiators was designed to cover the band 1– 8 GHz. This unit cell was then used in an Array Wizard (macro) to build a 11x11 array with $\lambda/2$ centers at 7GHz as shown here. This array is modeled as if in air; open add boundaries to all sides. This array is therefore modeled as a finite array on a finite ground.

We will study the coupling between the elements and the array pattern when the beam is directed off normal.

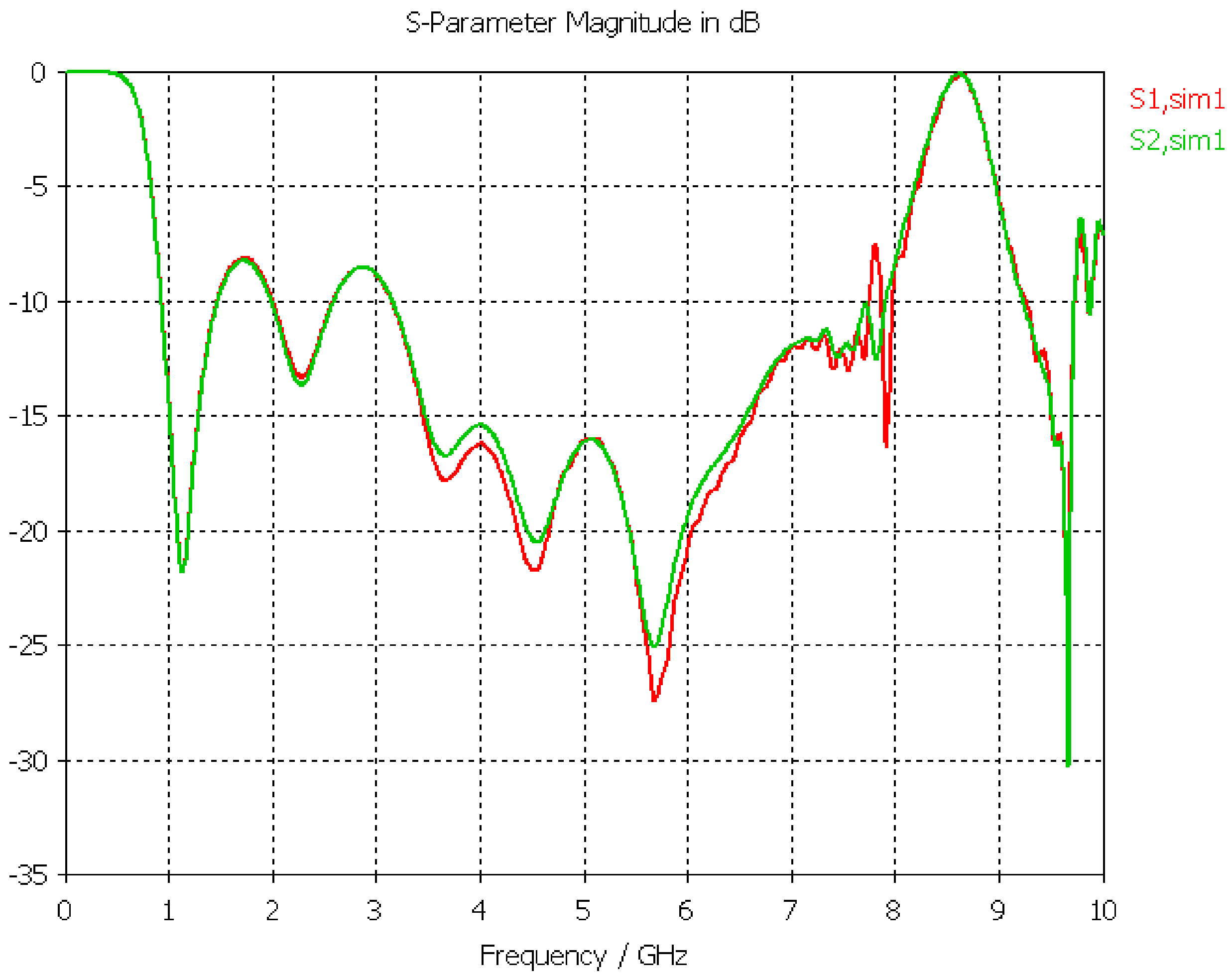


Unit Cell



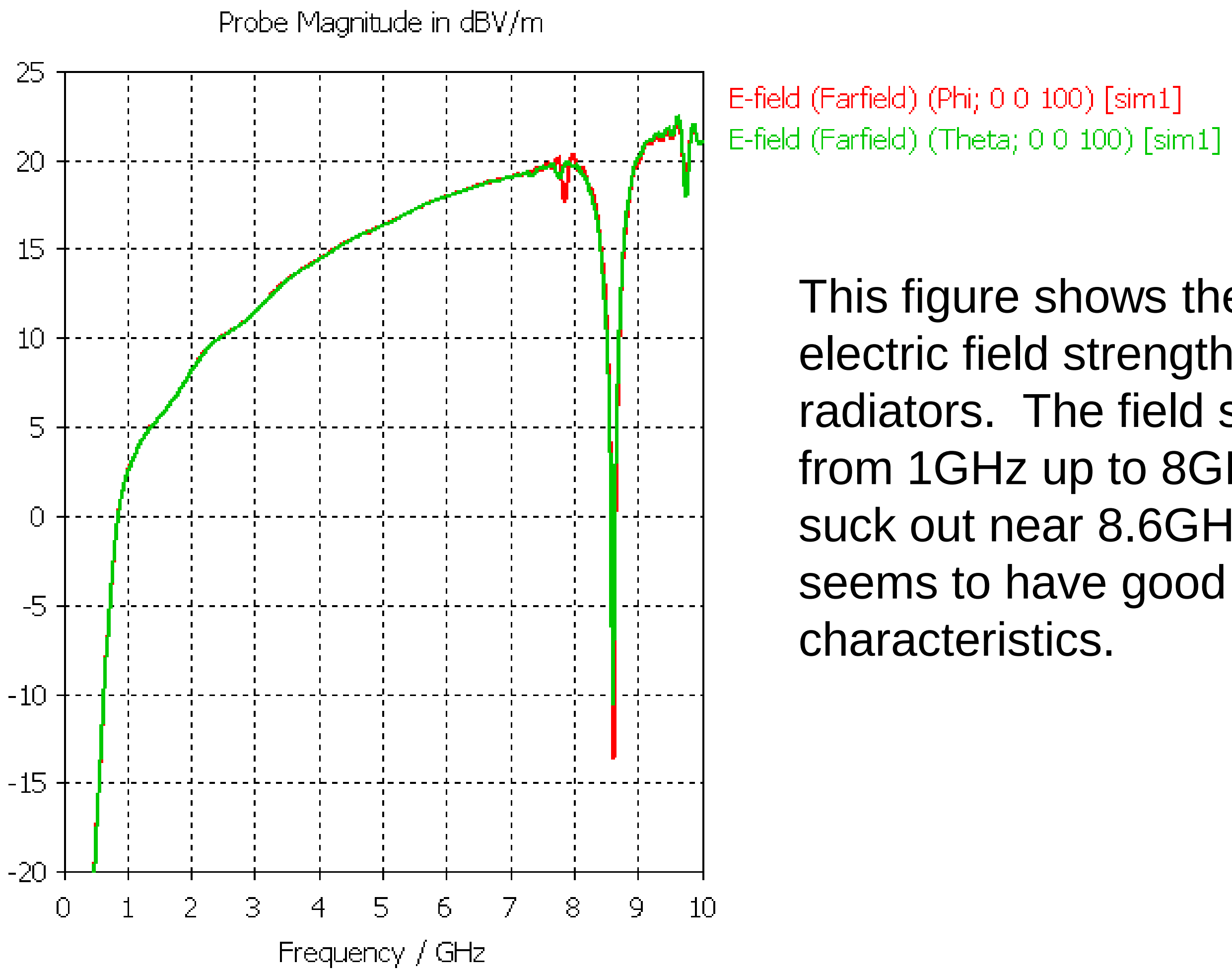
The first step in the array simulation is the design of the unit cell. Since the array has dual polarization, the unit cell has 2 radiators. Because the array is on a tight pitch ($\lambda/2$ @ 7GHz) the unit cell seems to slice the radiators into pieces but the boundaries are periodic and the pieces fit together giving the expected geometry. This is an infinite array simulation (approximation.) The element simulations required 7 minutes using an older FX5600 GPU on an Intel desktop.

Unit Cell Active Returns



The radiators in the unit cell are cross polarized and do not couple strongly. This figure shown the active or driven returns when the radiators are excited simultaneously. The operating band is 1-8 GHz.

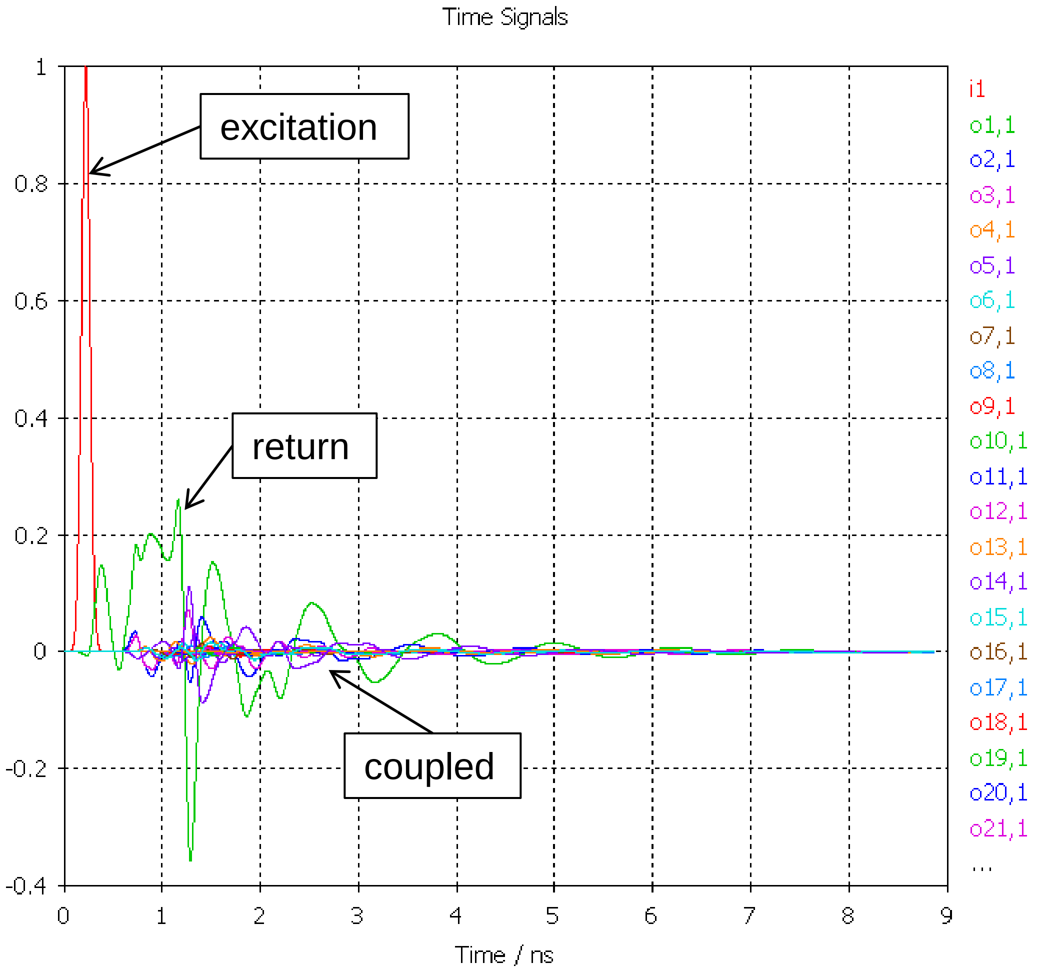
Broadside Radiation from Unit Cell



This figure shows the peak radiated electric field strength 1m from the radiators. The field strength increases from 1GHz up to 8GHz followed by a suck out near 8.6GHz. The band 1-8GHz seems to have good radiation characteristics.

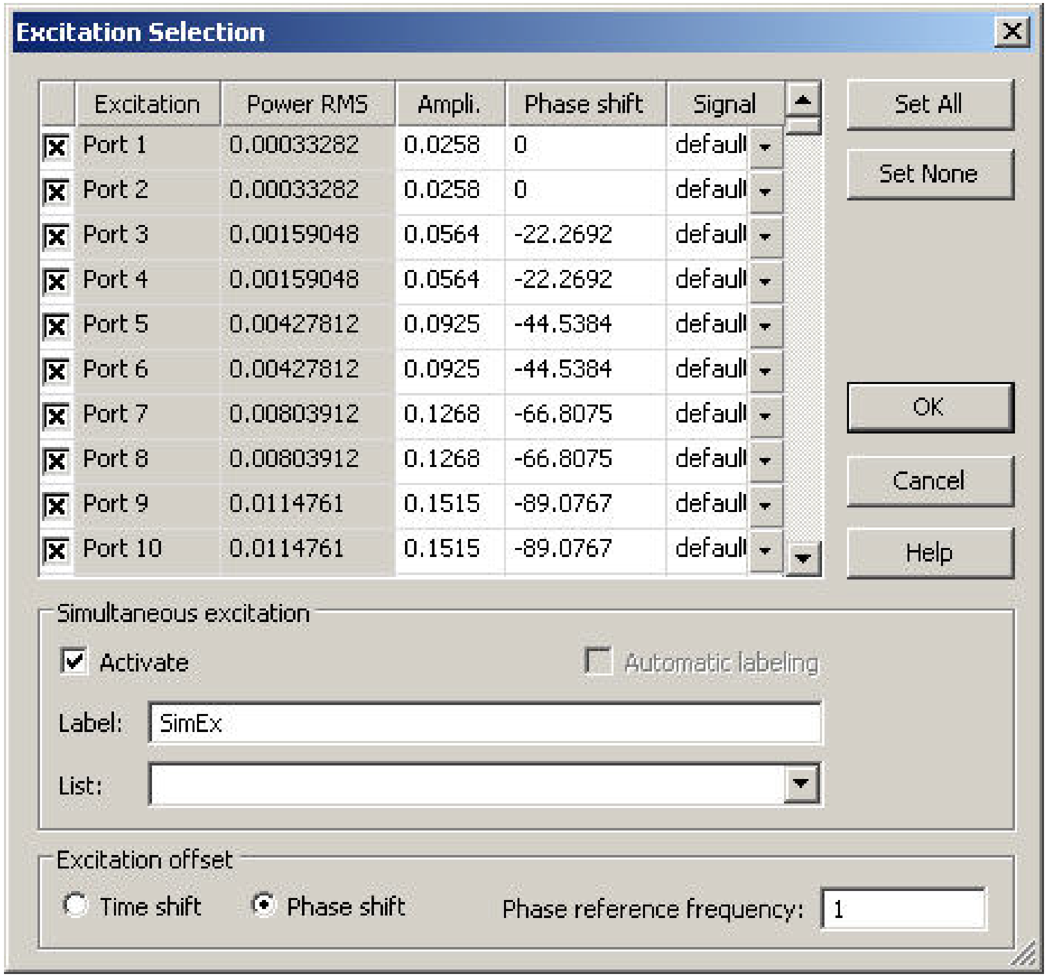
Port Signal for Element Pattern

An 11x11 array was built using the unit cell previously designed and an Array Wizard macro. This macro copies the unit cell into the (planar) array design and sets up the excitation for a beam; direction and weighting. Arrays were made nominally 0, 40, and 60° off axis with a 30dB Taylor weighting. Simulations could be run of these arrays exciting all elements (array beam) or exciting individual elements (element factors) with the others in as dummy loads. The models were simulated in the time domain. This figure shows some of the signals at the ports if Port 1 (lower left corner of array) were excited.



Excitations for Beam Steering

When an excitation is defining to direct an array beam in a particular direction, the excitation typically excites all the elements in the array simultaneously. The amplitudes of the excitations can be adjusted to reduce the side lobes. The beam direction is set by either defining a time shift between excitations or a phase shift between the elements. If a phase shift is chosen a reference frequency must be used. A time step will then be internally calculated to give the phase step at the reference frequency.



	Excitation	Power RMS	Ampli.	Phase shift	Signal
☒	Port 1	0.00033282	0.0258	0	default
☒	Port 2	0.00033282	0.0258	0	default
☒	Port 3	0.00159048	0.0564	-22.2692	default
☒	Port 4	0.00159048	0.0564	-22.2692	default
☒	Port 5	0.00427812	0.0925	-44.5384	default
☒	Port 6	0.00427812	0.0925	-44.5384	default
☒	Port 7	0.00803912	0.1268	-66.8075	default
☒	Port 8	0.00803912	0.1268	-66.8075	default
☒	Port 9	0.0114761	0.1515	-89.0767	default
☒	Port 10	0.0114761	0.1515	-89.0767	default

Simultaneous excitation

☑ Activate ☐ Automatic labeling

Label: SimEx

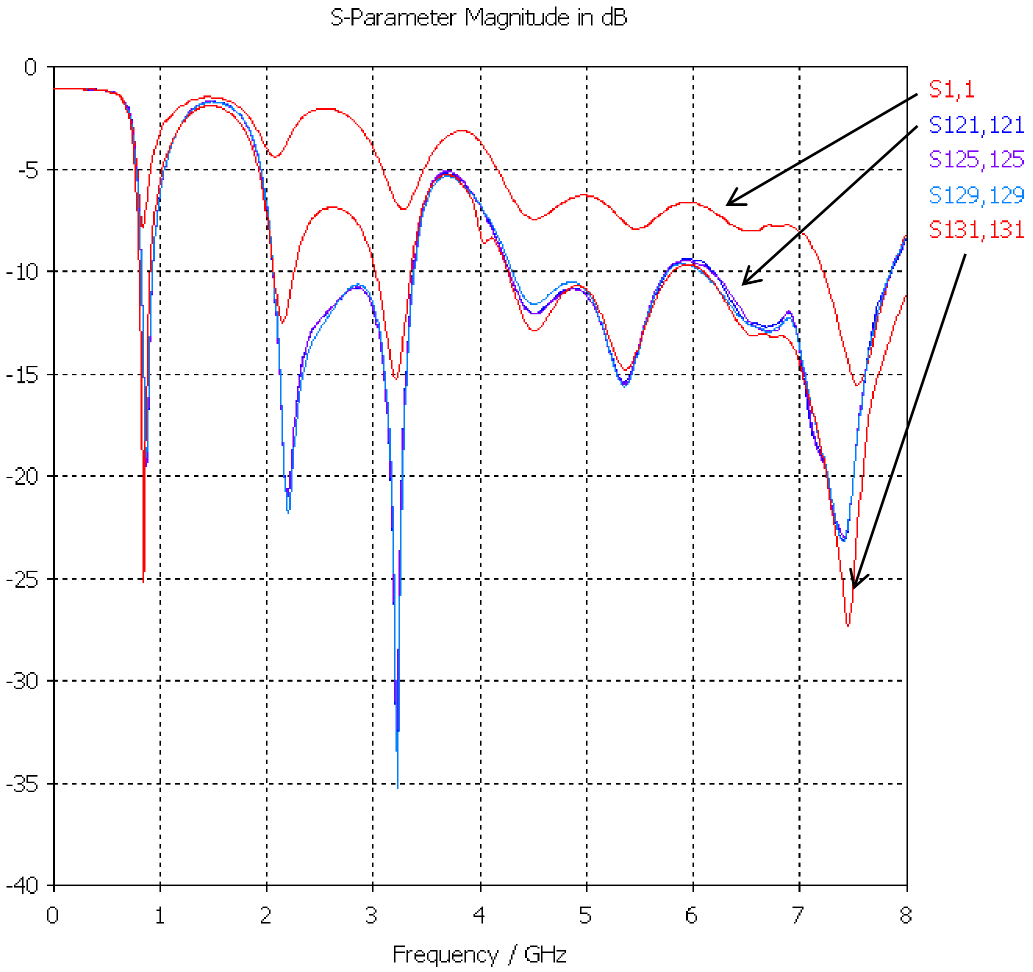
List:

Excitation offset

○ Time shift ● Phase shift Phase reference frequency: 1

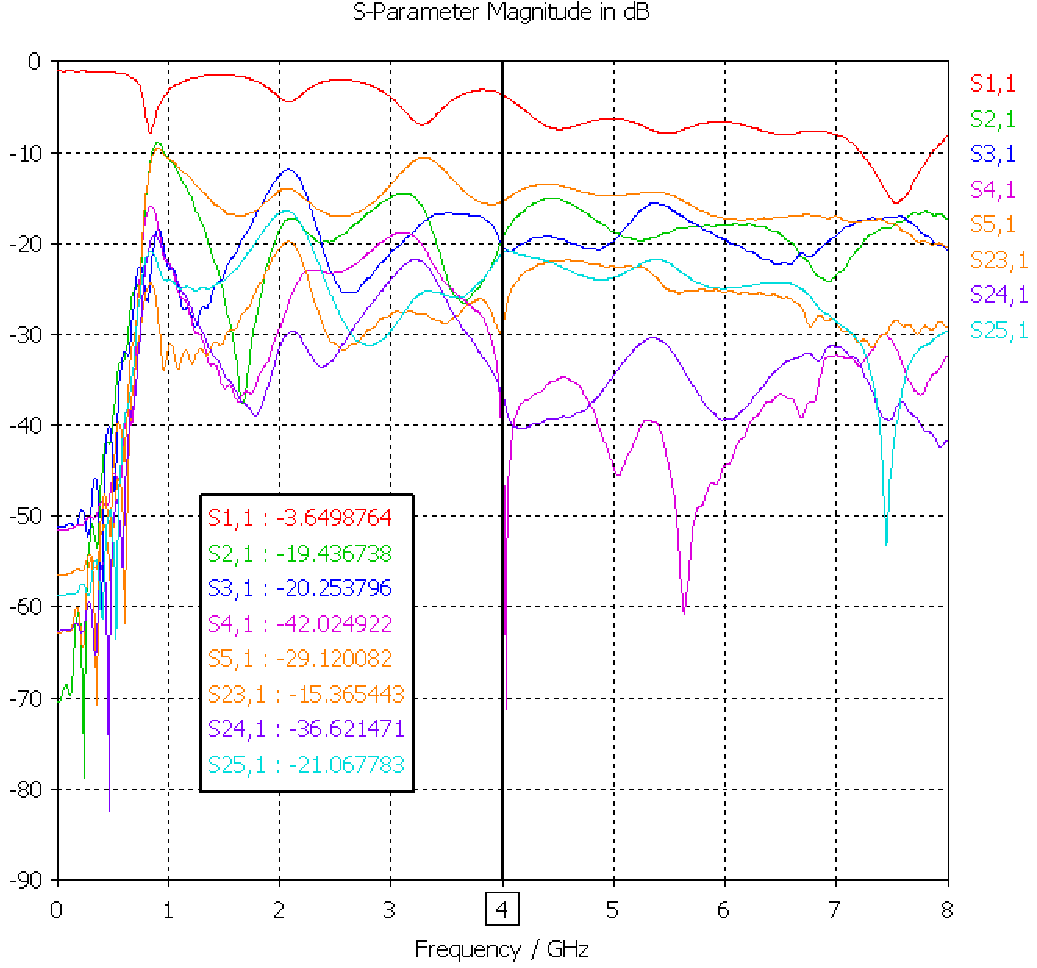
This is because in the time domain simulation the beam pointing is actually done with time delay. This means that the beam should be pointed in the same direction for all frequencies; no frequency squint. This figure shows the first 10 excitations for the Taylor weighted beam directed 60° off axis.

Returns



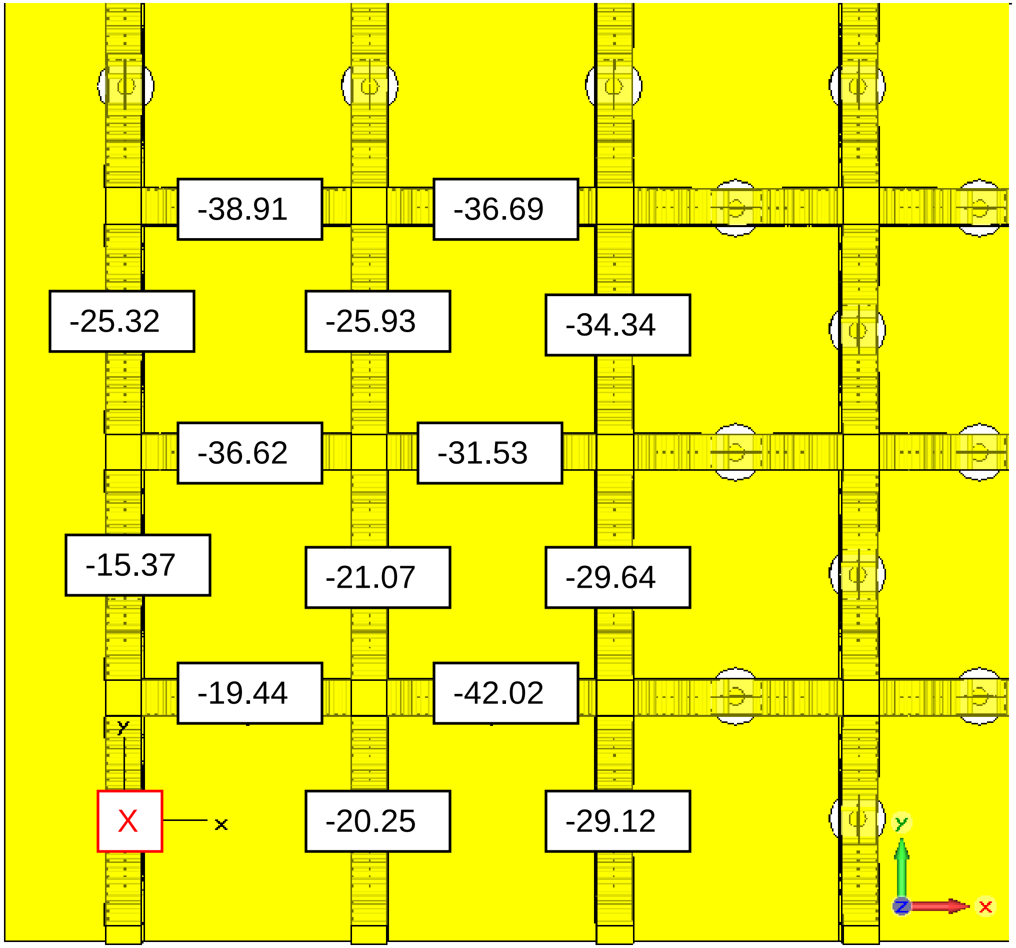
Simulations of individual elements in the lower left corner (Port 1) and at the array center (Port 121) moving to the center of the right edge (Ports 125 to 131). The returns from these elements vary with location and are different than the infinite array results shown previously.

Coupling to Corner Element



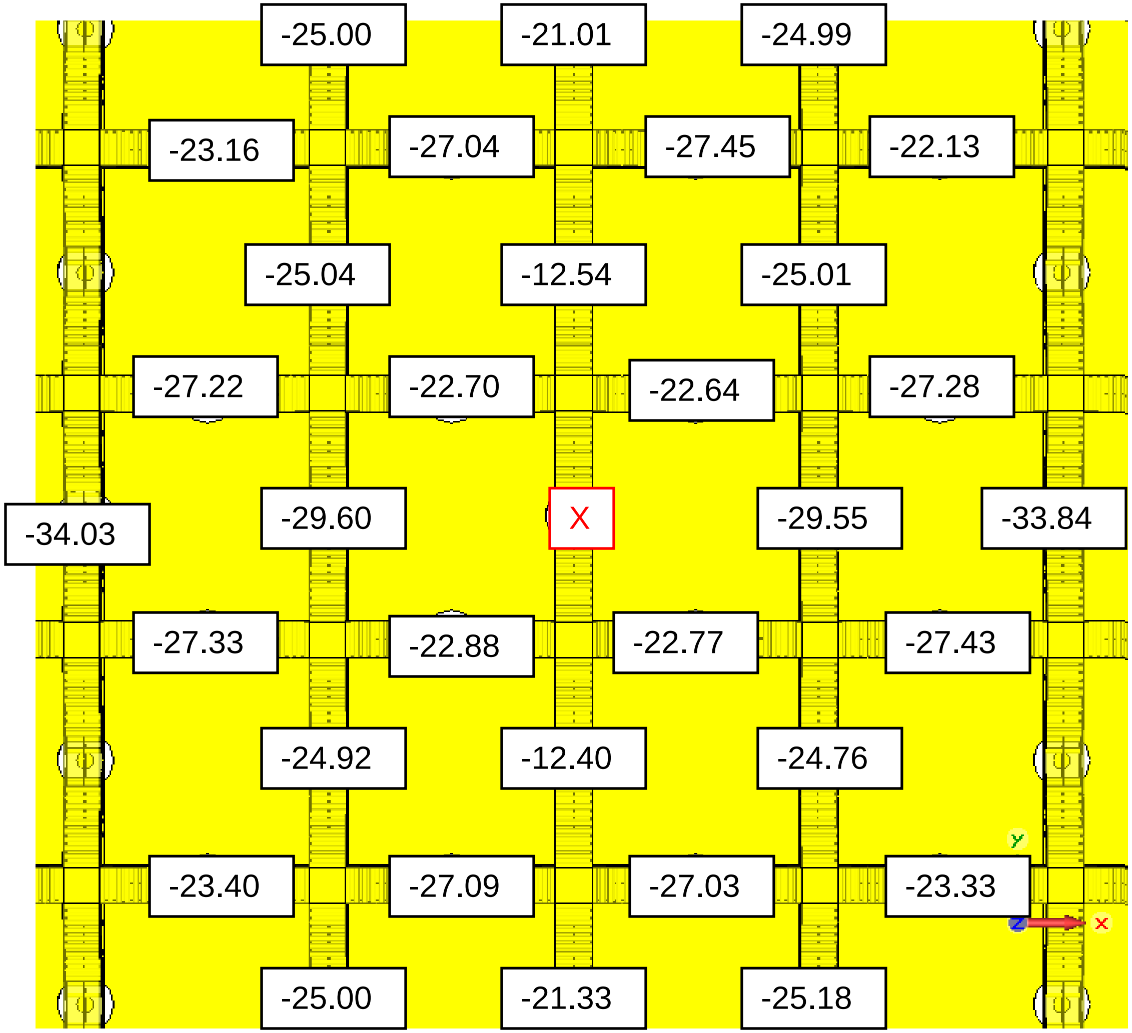
If only 1 element is excited, the coupling to all elements in the array is obtained. This figure shows the coupling from the corner element to other nearby elements. Note the rather high return.

Coupling From Corner Element at 4GHz



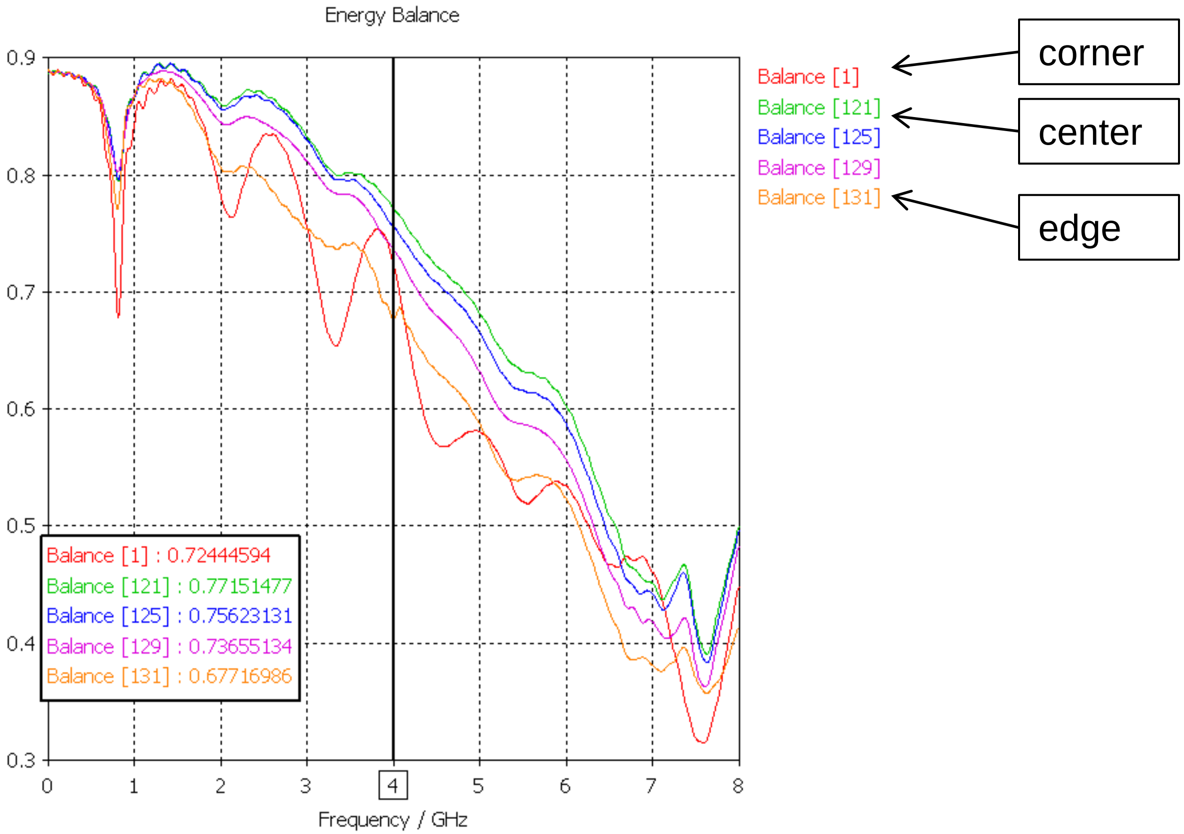
This figure shows a front view of the lower left portion of the array. Over laying the Vivaldi elements are the coupling values at 4GHz from the corner element, mark with X. The corner element is vertically oriented and couples stronger to elements above it.

Coupling From Central Element at 4GHz



The central element in the array (X) couples stronger to those in the same column than to others and the coupling to the first like neighbor is 2.8dB stronger than that of the corner element.

Balance Curves for Single Element Excitations



corner

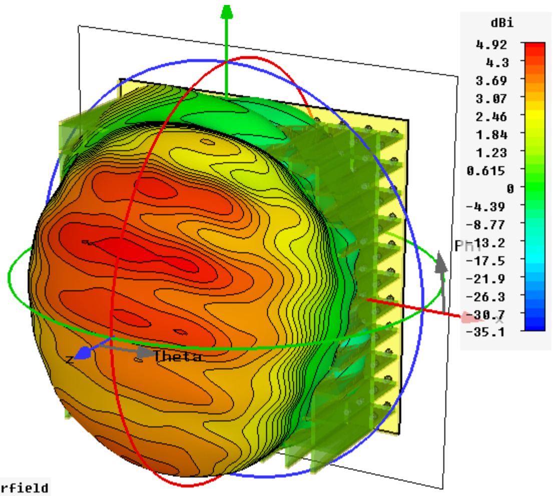
center

edge

The balance curves are the energy returning at the ports normalized to that applied at a port. If the balance is low there is either loss in materials or radiation. If the balance is near 1, most of the power returns to the array. Although the returns from the individual elements are low the balance is high, most of the power is coupled back into neighboring elements in the array.

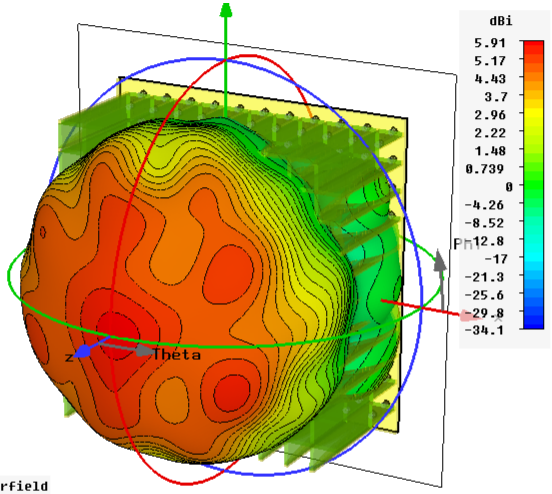
Element Factors at 4GHz

Lower left corner



Type	Farfield
Approximation	enabled (kR >> 1)
Monitor	farfield (f=04.0000) [1]
Component	Abs
Output	Directivity
Frequency	4
Rad. effic.	-1.161 dB
Tot. effic.	-4.392 dB
Dir.	4.919 dBi

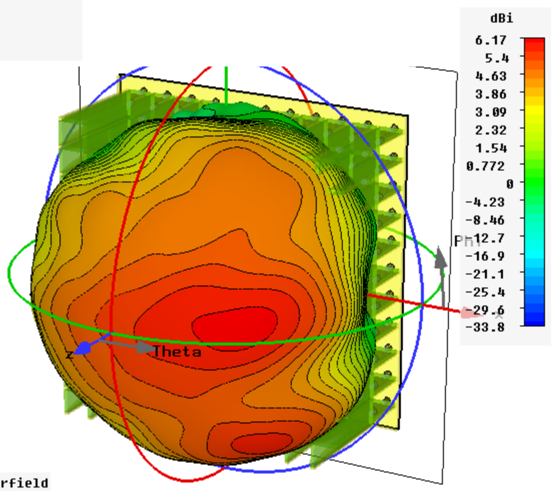
Array center



Type	Farfield
Approximation	enabled (kR >> 1)
Monitor	farfield (f=04.0000) [121]
Component	Abs
Output	Directivity
Frequency	4
Rad. effic.	-1.876 dB
Tot. effic.	-5.804 dB
Dir.	5.913 dBi

The radiation pattern for individual Vivaldi (element factors) change with location in the array. The peak directivity moves from 4.9dBi at the lower left corner to 6.1dBi in the middle of the right edge. The shape of the pattern also changes with location.

Center right edge



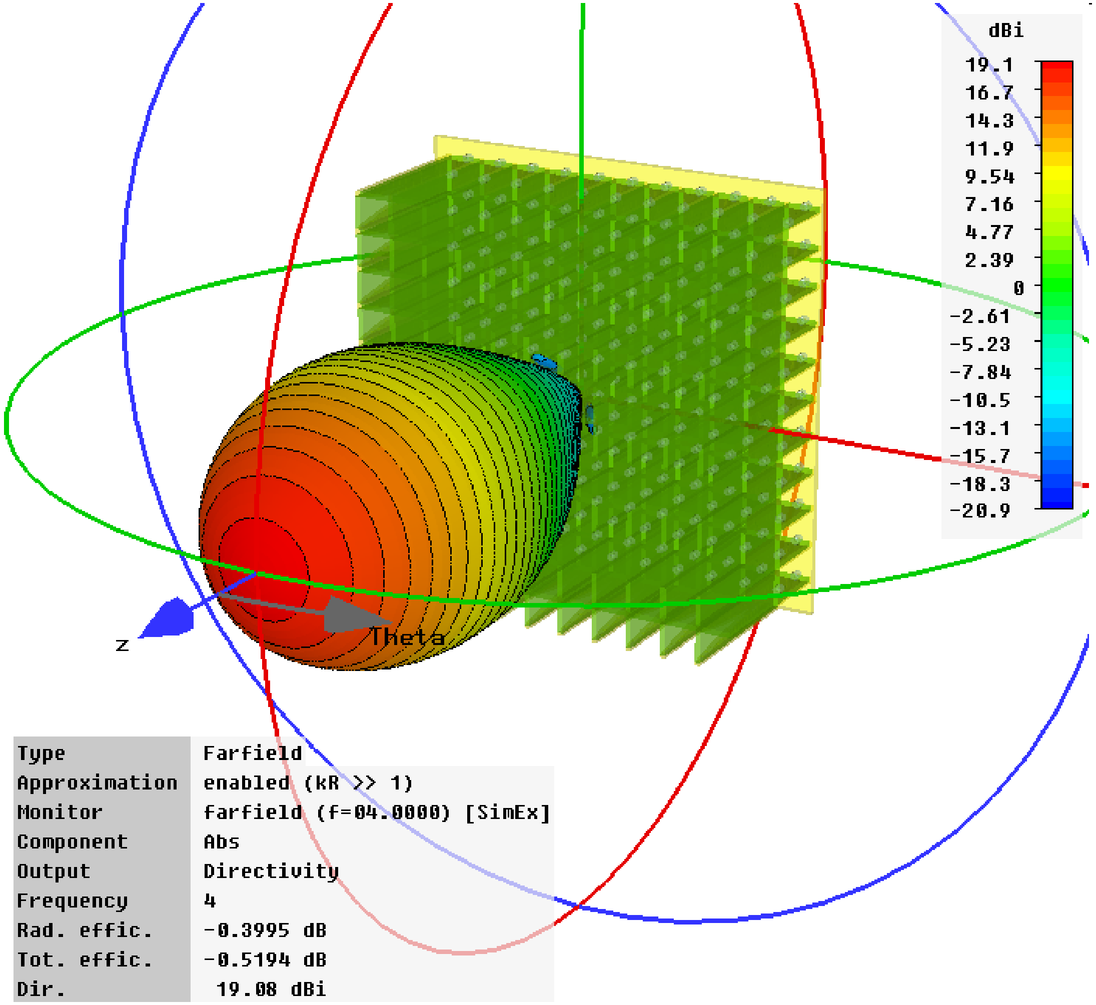
Type	Farfield
Approximation	enabled (kR >> 1)
Monitor	farfield (f=04.0000) [131]
Component	Abs
Output	Directivity
Frequency	4
Rad. effic.	-1.246 dB
Tot. effic.	-3.910 dB
Dir.	6.175 dBi

Array Directivity: Broadside Beam Taylor Weighted -30dB

The array was then simulated with all elements excited simultaneously. An amplitude weighting was given for a Taylor -30dB side lobe level.

Phasing (actually timing) was set to direct the array factor off axis. In this broadband study no attempt was made to obtain circular polarization; the radiators in each cell were excited with no phase difference.

This figure shows the directivity with the array factor pointed on axis; no phase shifts.



```
Type           Farfield
Approximation  enabled (kR >> 1)
Monitor        farfield (f=04.0000) [SimEx]
Component      Abs
Output         Directivity
Frequency      4
Rad. effic.    -0.3995 dB
Tot. effic.    -0.5194 dB
Dir.            19.08 dBi
```

Solver Log

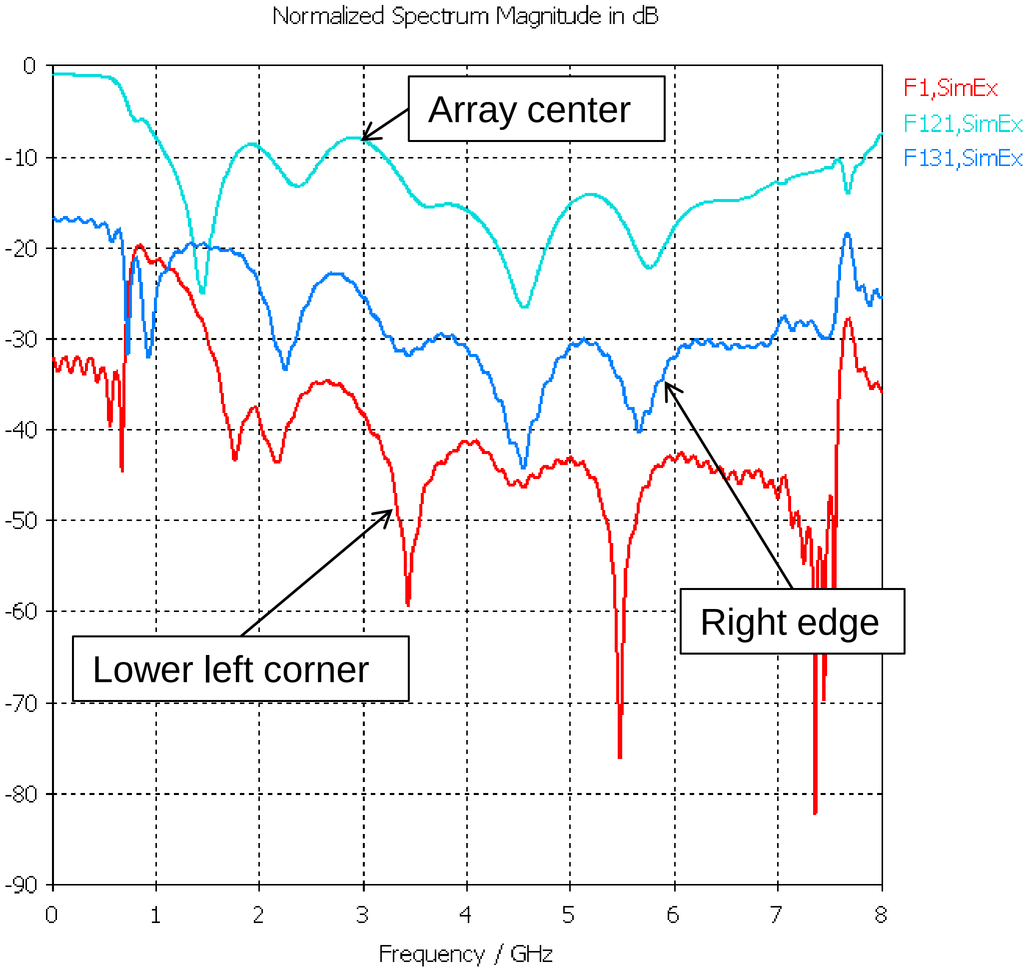
```
Peak memory used (kB)         Free physical memory (kB)
                      Physical     Virtual          At begin     Minimum
  ----------------------------------------------------------------------------
  Matrices calc.      6977756      8589448          29202444     21398864
  Solver run total    8611488      10492048         29229556     18298940
  ----------------------------------------------------------------------------

--------------------------------------------------------------------------------
Solver Statistics:

  Computer name:                        CORKY
       GPU info:                        GPU computing not activated
       Number of threads used:          4

  Number of mesh cells:                 27771939
  Excitation duration:                  4.443186e-001 ns
  Calculation time for excitation:      1781          s
  Number of calculated pulse widths:    19.9998
  Steady state accuracy limit:          -40           dB
  Simulated number of time steps:       14799
  Maximum number of time steps:         14799
  Time step width:
       without subcycles:               6.004637e-004 ns
       used:                            6.004637e-004 ns

  Matrix calculation time:              10640         s
  Solver setup time:                    1647          s
  Solver loop time:                     32831         s
  Solver post processing time:          1154          s
                                        ------------
  Total time:                           46272         s  ( = 12 h, 51 m, 12 s )

--------------------------------------------------------------------------------
  Total simulation time:                46275         s  ( = 12 h, 51 m, 15 s )
```

The array was simulated on a dual core, dual socket desktop computer: 3.00GHz Intel 5160. The simulation required 8.6G of RAM and 13 hours. Using a newer Tesla series 20 GPU is estimated to reduce the time to 2.5 hours. This is typical of all the array simulations shown here.

Array Results – Return Spectra for Taylor Weighted -30dB

With all elements excited but weighted, the return signals (active returns) change with location from the difference in coupling and also from the difference in excitation.

The return signal near dc is predominantly set by the excitation at that element. As the frequency increases and the elements begin to radiate, power can flow from one element to another. The return signal can become larger than the excitation, see in particular the result for the corner element.

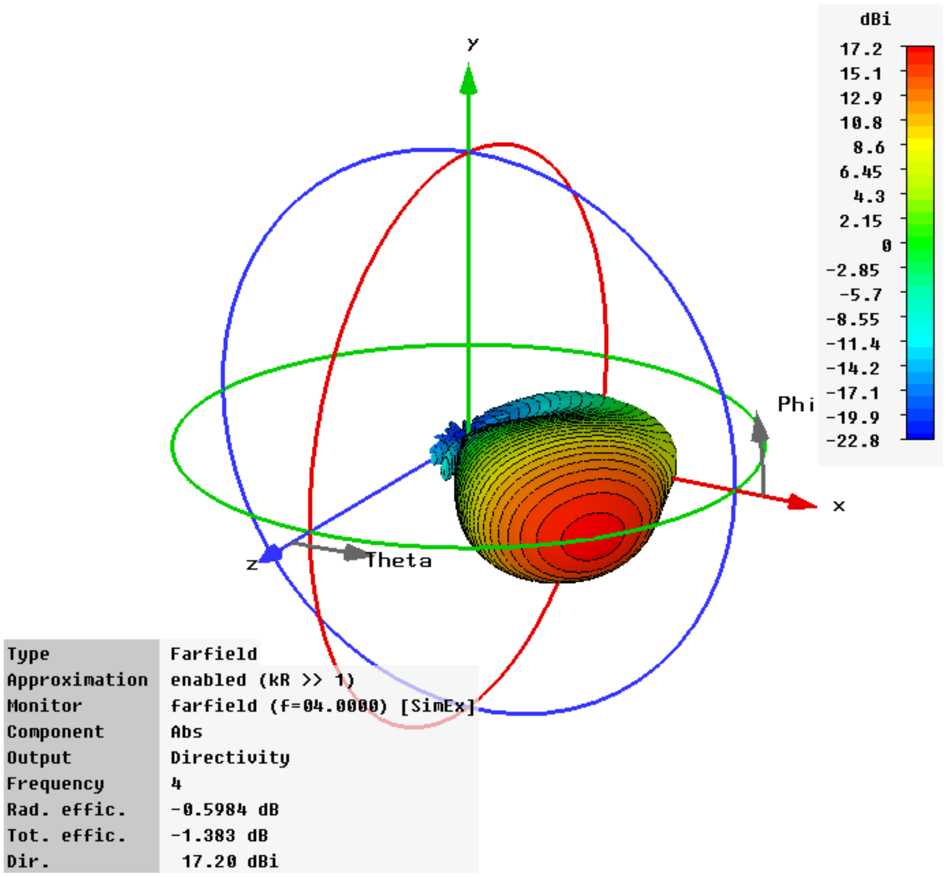


Array center

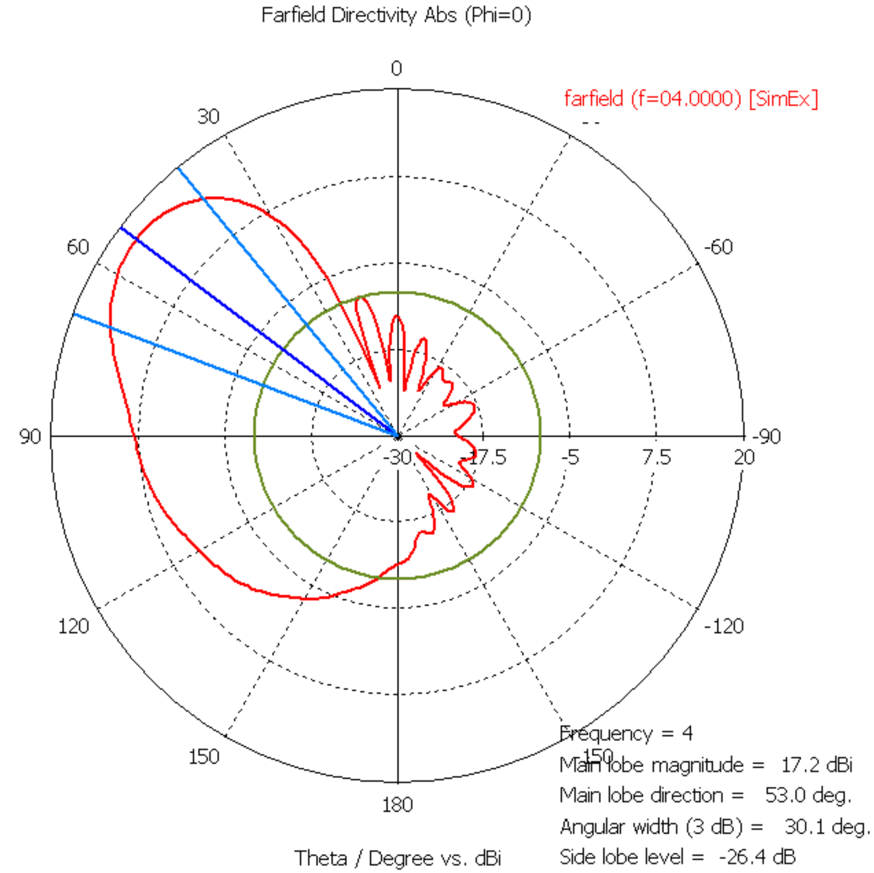
Lower left corner

Right edge

4GHz Beam for Array Factor 60 Off Normal



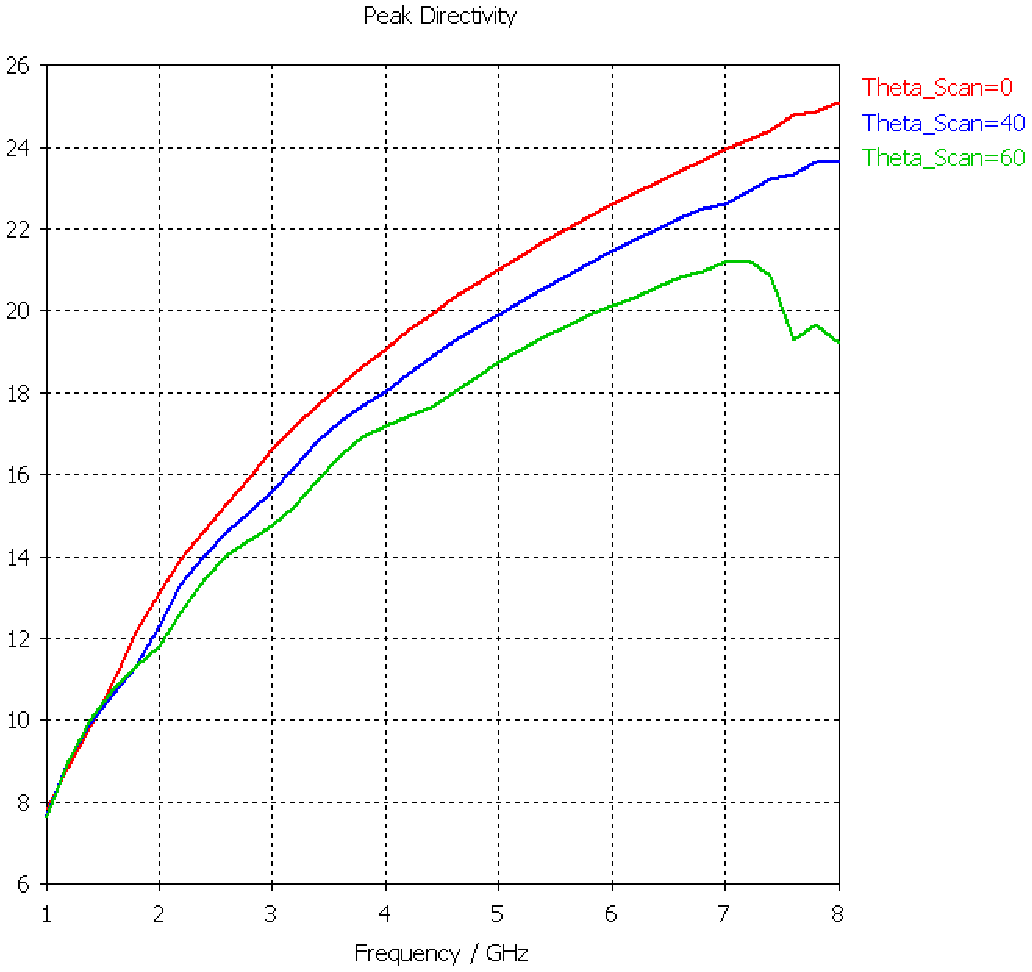
Type	Farfield
Approximation	enabled (kR >> 1)
Monitor	farfield (f=04.0000) [SimEx]
Component	Abs
Output	Directivity
Frequency	4
Rad. effic.	-0.5984 dB
Tot. effic.	-1.383 dB
Dir.	17.20 dBi



Frequency = 4
Main lobe magnitude = 17.2 dBi
Main lobe direction = 53.0 deg.
Angular width (3 dB) = 30.1 deg.
Side lobe level = -26.4 dB

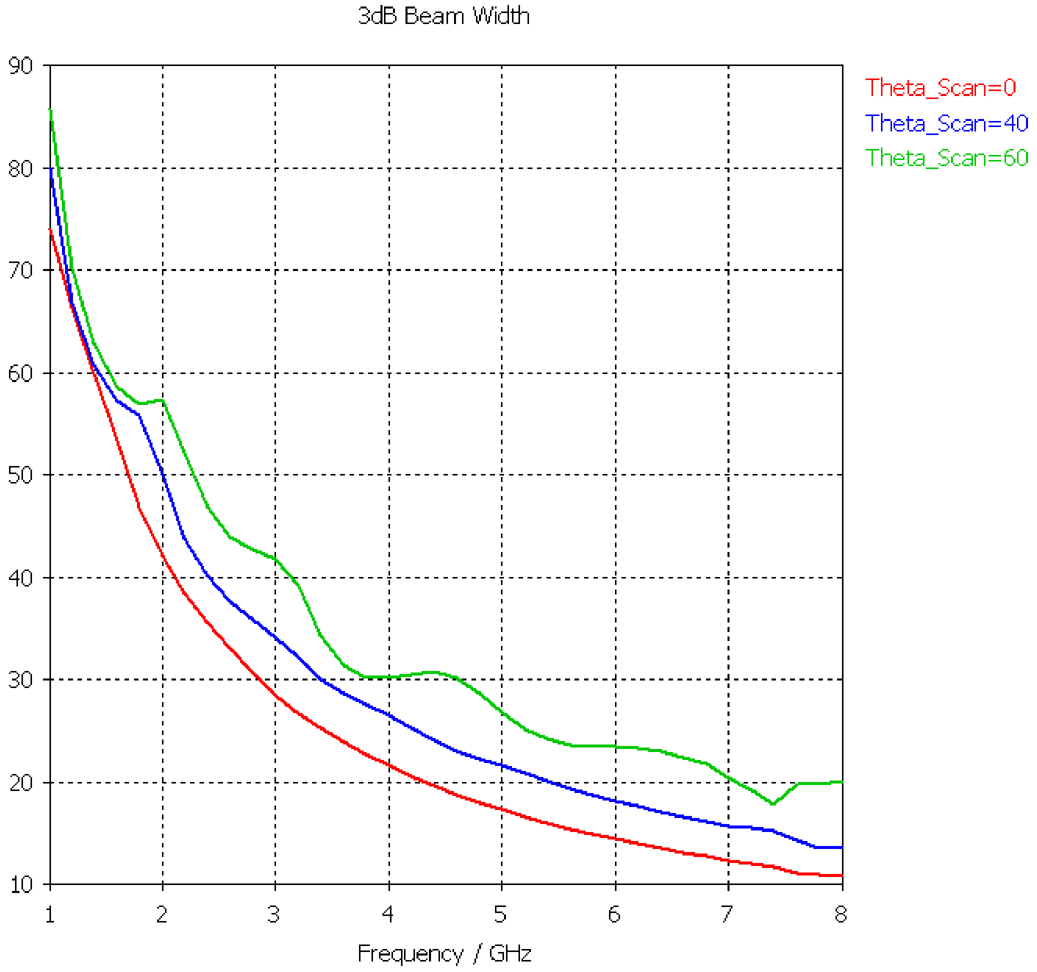
If the phasing is set to point the array factor off normal, the beam moves but not necessarily to where the array factor peaks. These figures show the array beam at 4GHz with the array factor set off axis by 60°. The beam with the coupled Vivaldi radiators peaks at 53°. A pointing error of 7°.

Peak Directivity vs. Frequency



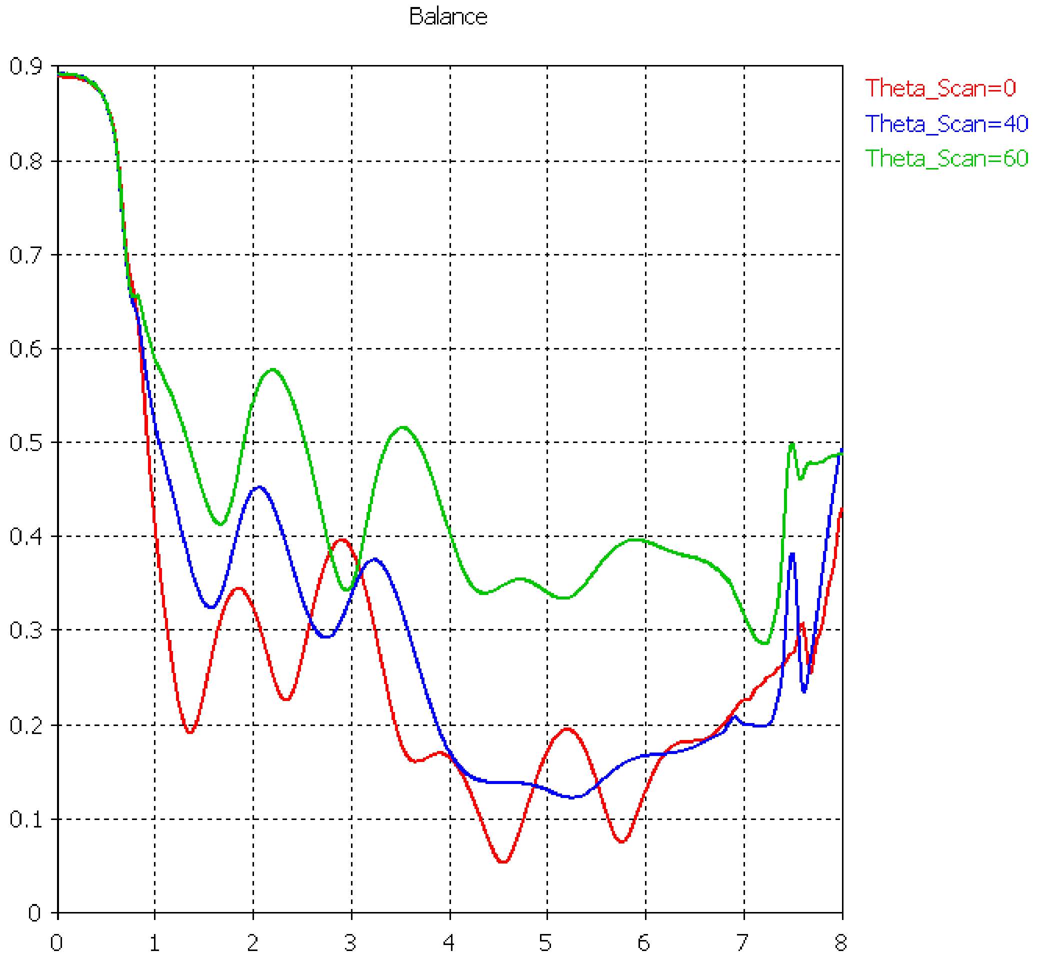
As the frequency increases the peak directivity increases in agreement with the unit cell results. As the peak is directed off axis, the peak directivity decreases. For a 60° beam, above 7GHz a grating lobe appears and the peak directivity drops.

3dB Beam Width



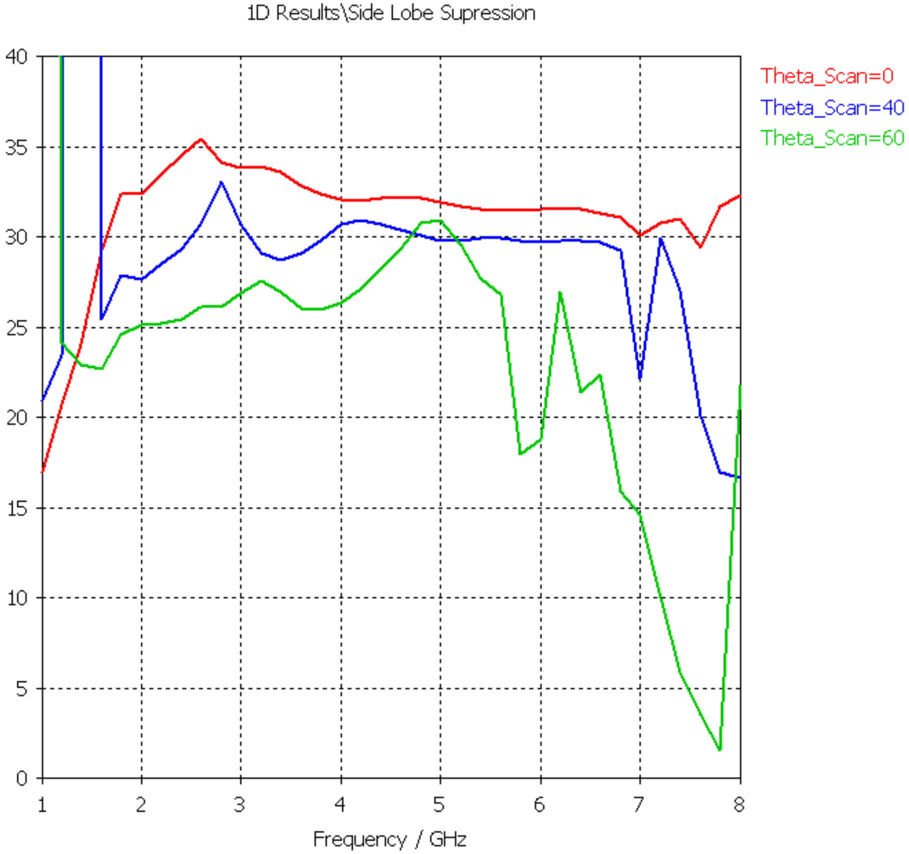
As the frequency increases the beam width decreases. As the beam is directed off axis the beam width increases and develops wiggles vs. frequency.

Energy Balance vs. Frequency



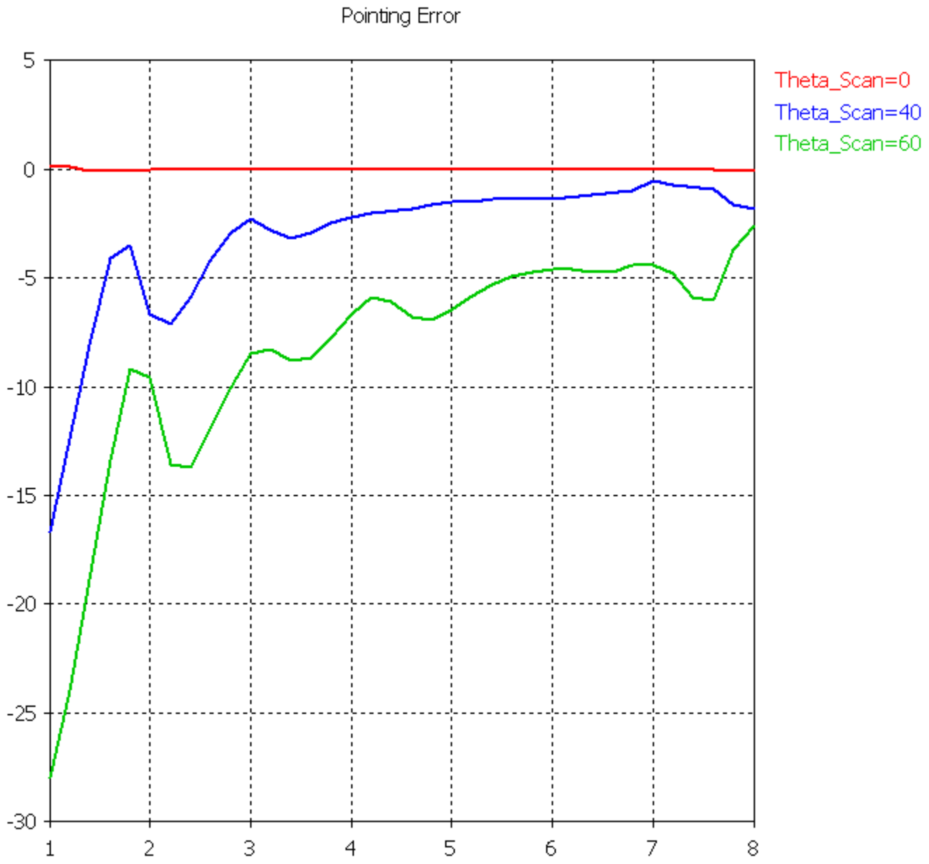
The energy balance for the array is much lower than for the individual elements shown previously; higher efficiency radiation. As the beam is directed off axis the energy balance increases.

Side Lobe Suppression vs. Frequency



The beam was design with a 30dB Taylor weighting and for the normal beam, side lobe suppression is better than 30dB from 1.5 to 8 GHz. As the beam is directed off axis the side lobe suppression decreases. For a 60° beam above 7GHz a grating lobe appears.

Beam Pointing Error vs. Frequency



The pointing error is the difference between the beam direction and the direction of the array factor. This error increase with array factor direction and decreases with frequency. For this 11x11 array of Vivaldi radiators the error with a 60° array factor can be in excess of 5°. This error is significant and might require calibration of the array; best done by simulation.

Summary

- Radiator arrays can be designed using unit cells with periodic or unit cell boundaries. These are infinite array models.
- Actual arrays are finite and may have effects coming from the coupling between the elements and the change in local environment over the array.
- Using elements which couple will result in arrays with properties which deviate from infinite array results. Accurate determination of these effects will require careful simulation of the full, finite array.
- The direction of the array beam will deviate from the array factor peak as the beam is directed off axis. This pointing error can calibrated out using design curves from Microwave Studio simulations.