Section 6
Antenna Array Design

from

A Collection of Thoughts, Tips and Techniques for Microwave Circuit Design

by

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This set of 40 pages is a section focusing on antenna arrays, taken from an extended presentation on microwave design.

If you have a question, feel free to write me at R.L.Eisenhart@ieee.org.

Antenna Array Design Outline

- Array Scanning Relationships
- Small (6-element) Arrays
- Sum & Difference (Σ & Δ) Feeds
- Large Arrays
    - Broadside
    - Scanned
- Mid-Sized Arrays

Now let's talk a bit about antenna arrays.

Start with some general discussion and then go to examples.

Why bother with arrays?

Why Arrays?

Advantages:

- Provides higher gain than available with a single element (many λ^2 effective area).
- Provides ability to shape beams into a variety of patterns, or to focus with reduced side-lobes

Disadvantages or Cost:

- Requires complex feed structures
- Requires taking into account element coupling

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Pretty fundamental reasons. The advantages

Remember the element gains are pretty low because their effective areas are small, so we need to integrate lots of elements, i.e. an array

As an examples of beam shaping, the comm. satellites shape the beam to fit the outline of the United States.

All high resolution radars want to minimize the size of side lobes to avoid false targets.

This doesn’t come free.

The big topic in arrays is electronic scanning, so let’s start with some scanning relationships

Important Array Scanning Relationships

Consider a linear array where:

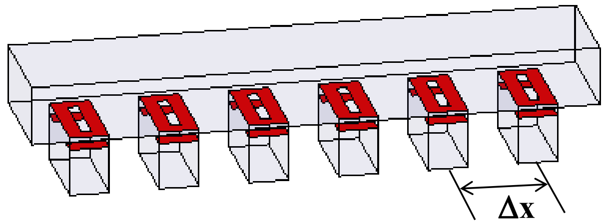
Lattice spacing = **Δx** = 0.9 in

Waveguide dimensions = 1.0 x 0.4 in

Frequency = 8.5 GHz

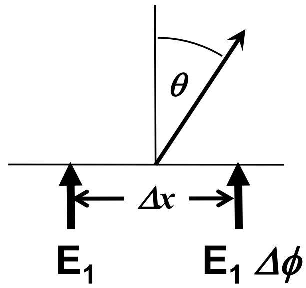
Wavelength = **λo** = 1.389 in

Scan phase ≡ element-to-element phase change



Element Phasing ($\Delta\phi$) for a given scan angle (θ):

$$\Delta\phi = \frac{360\,\Delta x \sin\theta}{\lambda o} \quad \textbf{degrees}$$



Generation of Grating Lobes:

Determines at what scan angle Gr. Lobes will appear at - 90 degrees.

$$\frac{\Delta x}{\lambda o} \le \frac{1}{(1+\sin\theta)} \quad \text{or} \quad \theta \le \sin^{-1}\frac{(\lambda o - \Delta x)}{\Delta x}$$

Typically Δx/ λo ≤ 0.5 to ensure a clear scan space.

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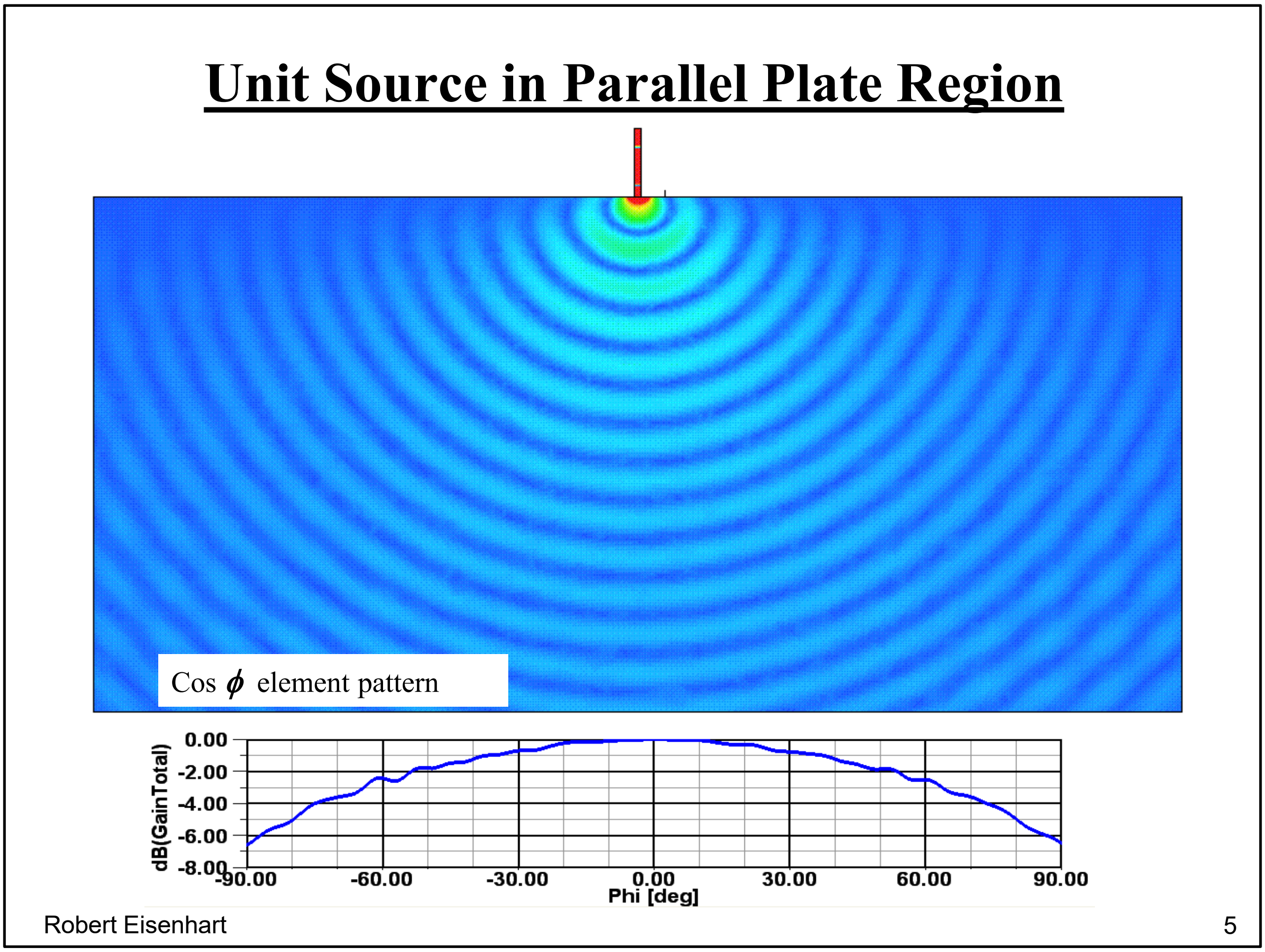
Most arrays operate at broadside (***Θ*** = 0 degrees) because of the expense of individual element phase control. Their beams are aimed with antenna gimbals. A large part of array design has to do with beam shaping which is primarily related to element excitation.

Scanning is another story. What makes scanning design difficult? When we include the phase to beam scan, the input match to the element changes, sometimes severely, creating a large reflection at the feed when transmitting, or a blind spot when receiving.

A second problem is that of grating lobes. We know generally how to control this but accurate prediction can be difficult.

It is best to include some safety margin

Consider a radiating point source

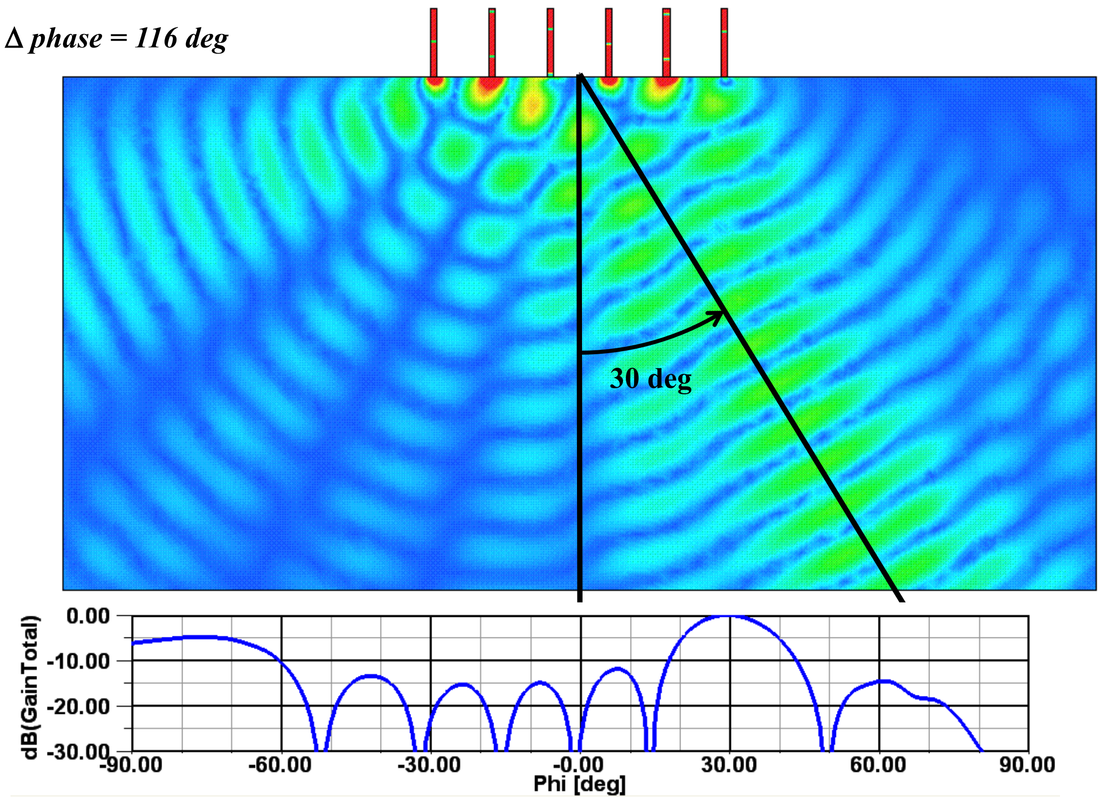


Here is radiation with parallel plates using a small aperture source (7% λ). Notice how this acts like a radial line, with the wavelength getting smaller with larger radius, approaching free space wavelength. Radial line fields are cylindrically symmetrical and are characterized by Bessel functions. These act like damped sinusoids with larger lambda at small radius.

This element pattern, a variation as cos(Θ) is called the projected aperture effect, and is down 3 dB at 60 deg due to the reduction of apparent aperture with scan away from the normal. This occurs with all phased arrays.

Now create a small array of point sources

Six Phased Sources in Parallel Plate Region



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6 phased point sources. We can see most of the energy is in the beam at 30 degrees with a grating lobe developing outside -60 deg. The spacing at **Δ**x/**λo** = 0.65 is too large to avoid these lobes. The rest of the radiated energy forms the sidelobes at the various angles.

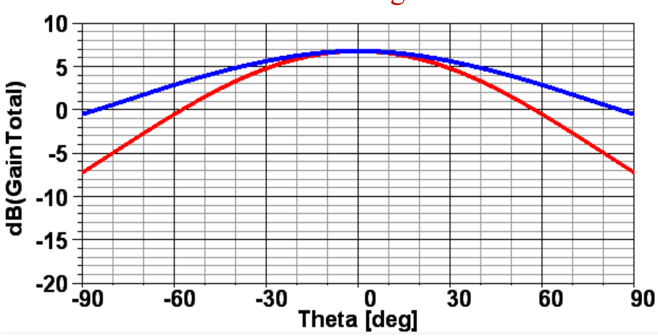
Now let's look at a 6 element linear array.

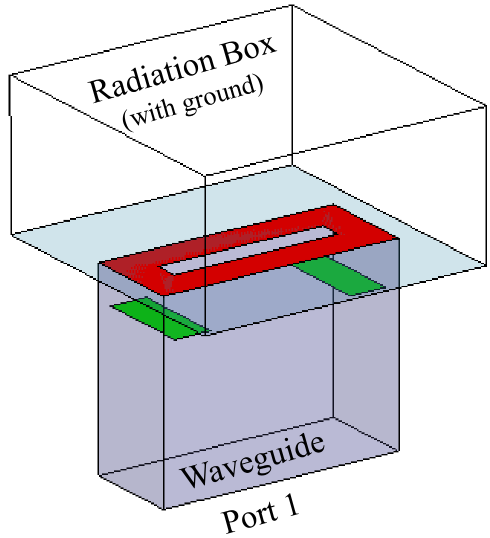
Small Linear (6-element) Array Single Element

Using an end slot element for an array

E-plane — Normal to slot

H-plane — Aligned with slot





ρ = 0.002 matched at 8.5 GHz

This array will be used to demonstrate:

- Single element vs. array
- Fan Beam array
- Scanning, with grating lobe growth
- Sum and difference patterns

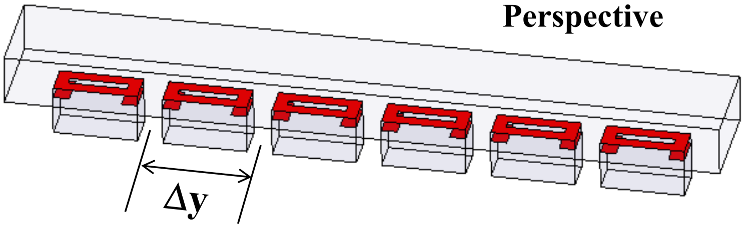
Consider a WG end-slot matched element for our array element from pages 6-8 in Section 5.

We'll use this to demonstrate various effects. Note the 7 dB gain.

Putting 6 elements together side-by-side gives an H-plane stack.

Six Element Linear Array – H-plane Stack(1300)

Perspective

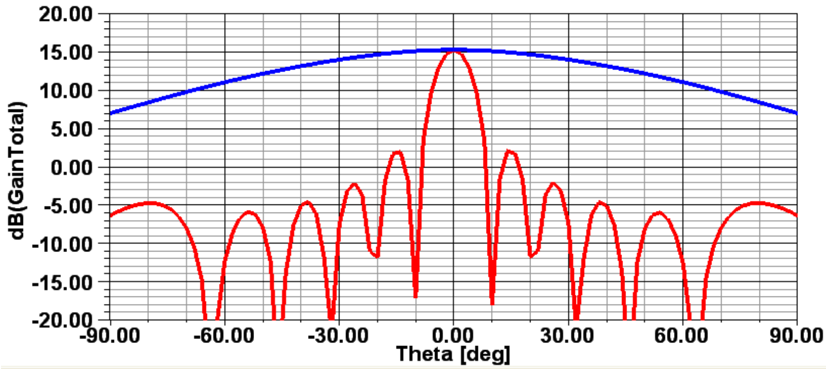


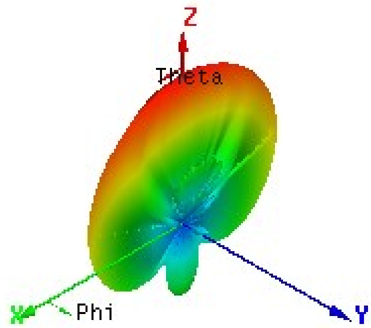
Slots and matching irises

$\Delta y/\lambda o = 0.94$ (< 4° scan)

$\rho = 0.09$ RL = -21 dB MuCou < -26dB $P_{RAD} = 5.95$ w

10 deg x 100 deg beam





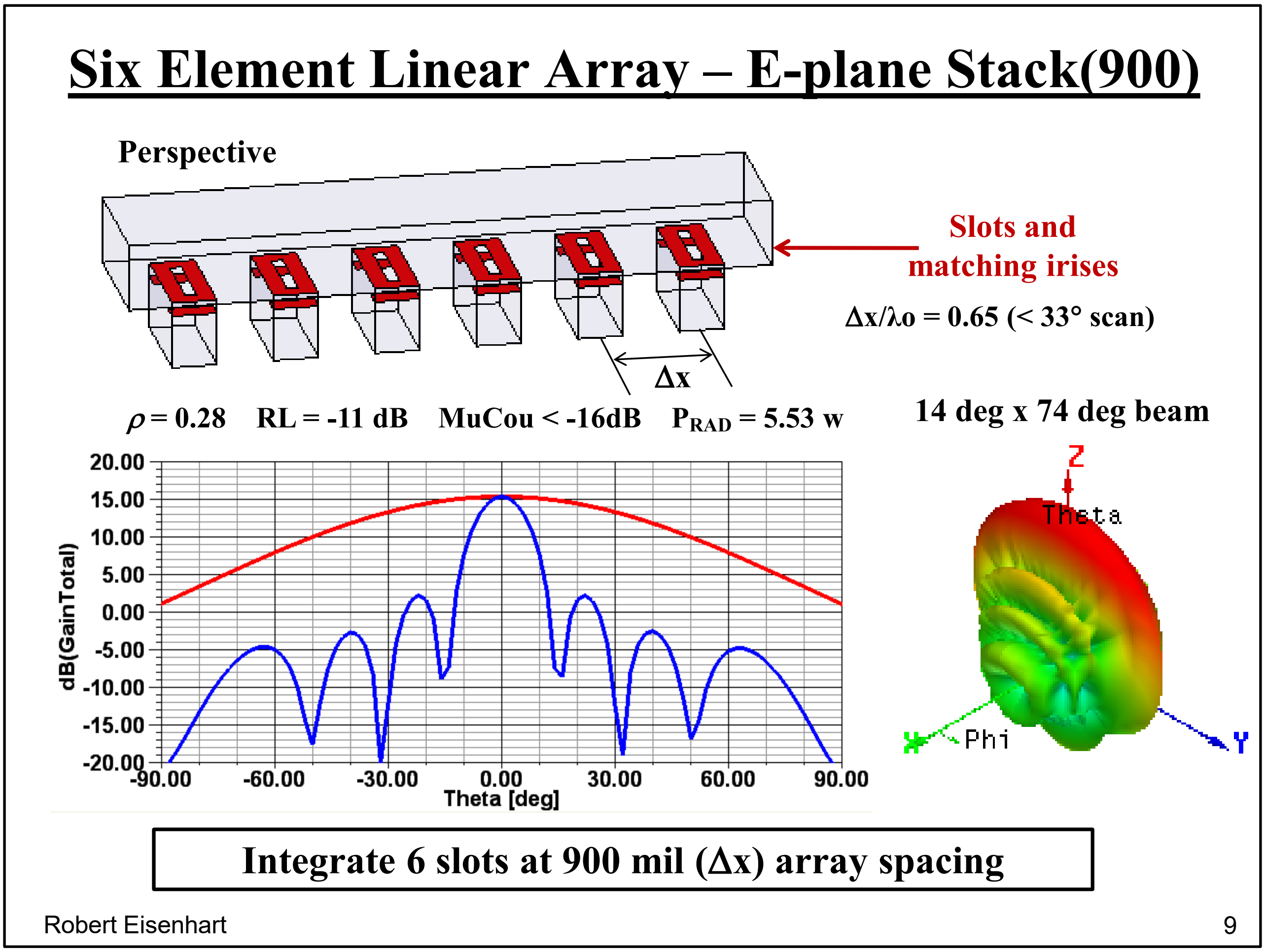
Integrate 6 slots at 1300 mil (Δy) array spacing for a fan beam

Configuration for a simple array.

6 elements gives 7.8 dB gain over a single element. These elements have very low mutual coupling (< -26 dB) so the single element match approach works well, resulting in a good array match
(< -21 dB). Total gain ~ 15 dB.

Results in a nice fan beam. $\boldsymbol{\Theta_E \Theta_H = 1000}$, so Gain = 30 ~ 15 dB check

Now look at an E-plane stack at closer **Δx** spacing.



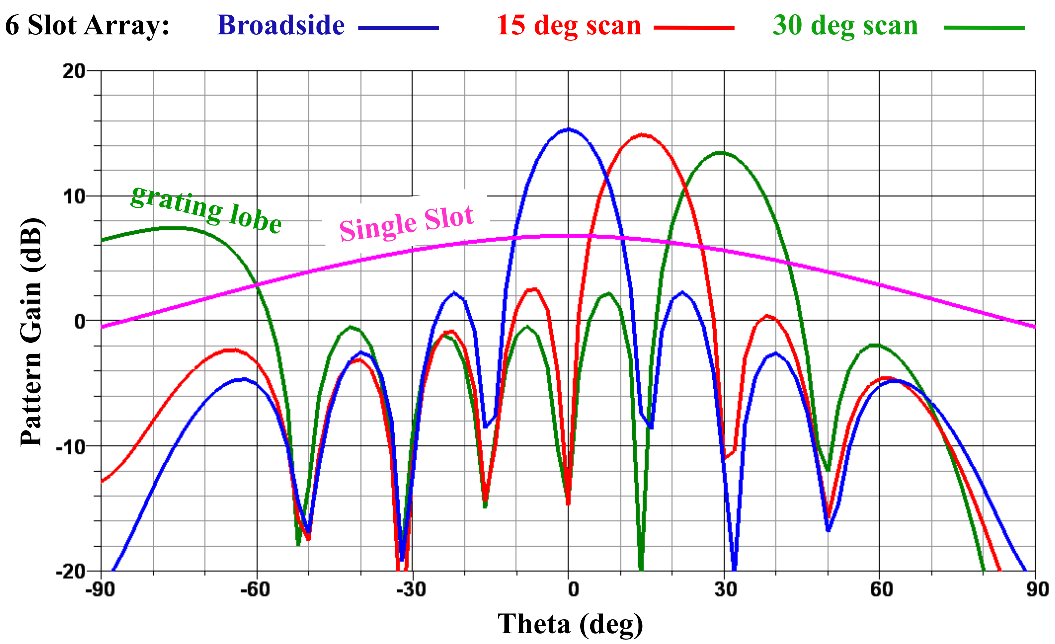
The mutual coupling has increased to -16 dB with the array match reduced to -11 dB, less radiation. Smaller **Δx** would lead to greater coupling and resulting in even poorer match.

Same gain but,

Little fatter fan pattern. $\boldsymbol{\Theta_E \Theta_H = 1036}$, about the same as before

To see scanned patterns simply change the phase excitation of the individual sources.

E-Plane Beam Scanning



Note the growing grating lobe on the minus side for the +30 deg scan

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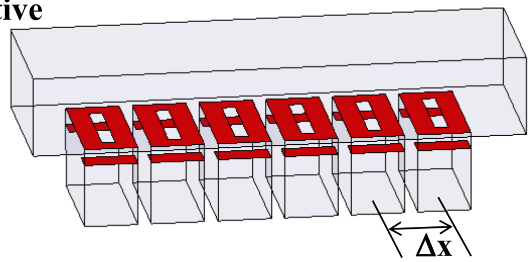
A 15 deg scan requires a progressive element phase shift of 58 degs. 30 deg scan is roughly double that. See also how the locus of the beam peaks follows the shape of the single element curve.

Here's a grating lobe on the left side for the 30 deg scan.

Let's back up and look at even stronger mutual coupling with a small **Δx**, say 500 mils.

Six Element Linear Array – E-plane Stack(500)

Perspective

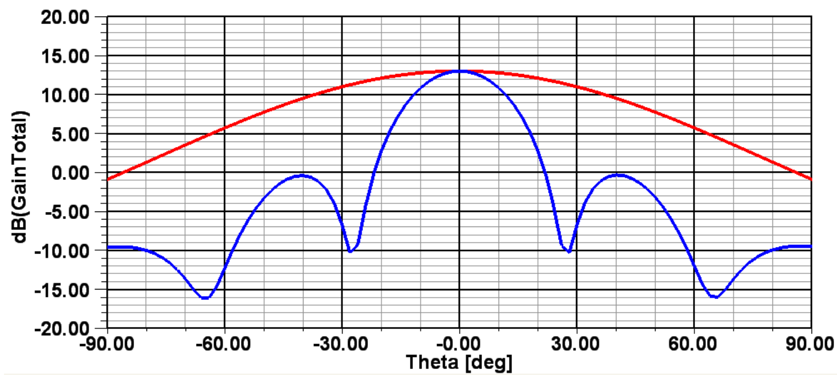


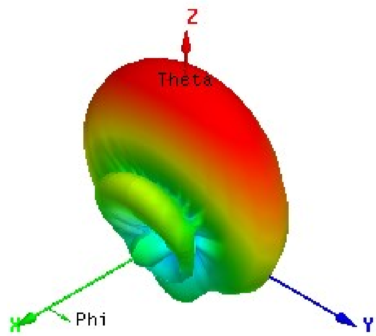
Slots and matching irises

$\Delta x/\lambda o = 0.36$ (90° scan)

$\rho = 0.35$ RL = -9 dB MuCou < -10dB $P_{RAD} = 5.27$ w

23 deg x 74 deg beam





Integrate 6 slots at 500 mil (Δx) array spacing

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So looking at a tighter element spacing. The mutual coupling has increased to -10 dB and the match is now down to -9 dB.

Notice that the beamwidth has grown from 15 to 23 degrees.

And note, the gain is down 2 dB from before. Since the additional match loss could only account for a couple tenths of dB, the reduction is due to smaller effective area, that is that the effective area of the individual elements is now overlapping.

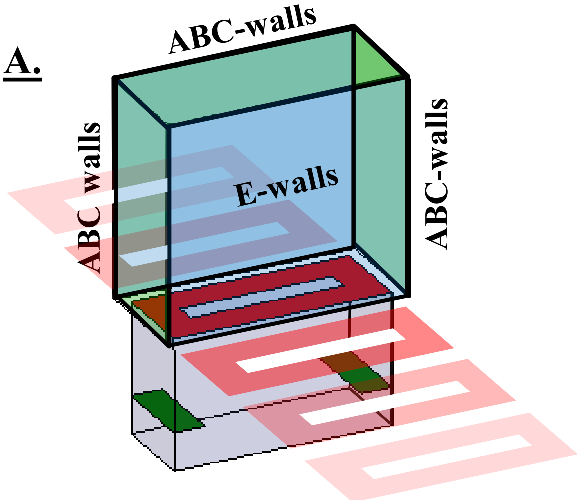
Fatter beamwidth in the E-plane but the H-plane stays the same.

$\Theta_E \Theta_H = 1702$ **or 12.5 dB**

Can we get the match loss back?

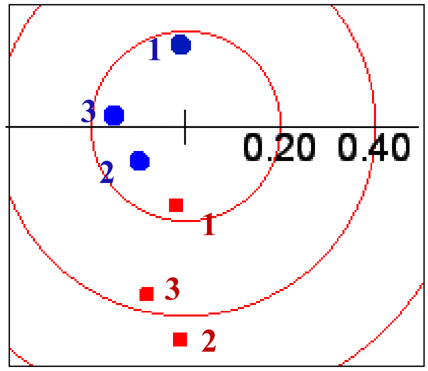
Six Element Linear Array – E-plane Stack(500)

A.



Array Matched

$\rho = 0.153$ $P_{RAD} = 5.87w$



$\rho = 0.35$ $P_{RAD} = 5.27w$

Radiation Matched

B. Precise but longer approach:

$$\text{Active } (S_{11}) = S_{11} + \underbrace{S_{12} + S_{13} + S_{14} + S_{15} + S_{16}}_{\text{Array mutual coupling terms}}$$

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Consider an interior element of a long linear array, with the tight E-plane coupling.

Approach **A.** - We can modify the radiation box to account for the mutual coupling by putting up electric walls. These walls create images which simulate the same environment as having the other radiating elements present.

But use Absorbing Boundary Conditions (ABC) on the other walls where energy radiates. Use this model to establish a match and use for all the array elements.

A more precise approach (**B**) is to match an "Active S-parameter", which directly deals with the other elements. Here the matching effort requires simulating the whole array rather than one element. The matching changes are applied to all elements simultaneously.

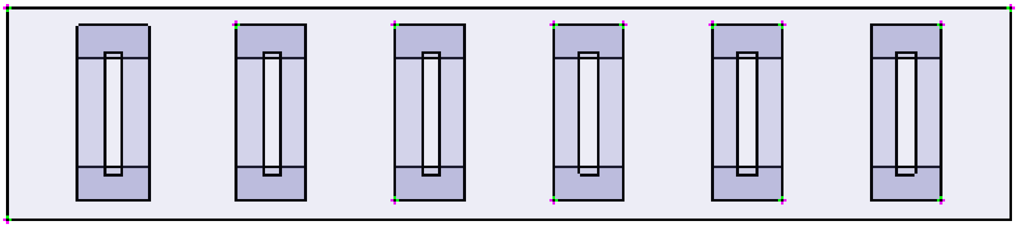
The expanded plot shows the input match results for the three different elements of the 6 element array (symmetry) with the initial "free-space" match (red) and the image-cell match (blue).

One last look at a scan with the closely spaced 6-element array.

Sum & Difference (Σ & Δ) Feeds

How would we use an array for direction finding?

Taking this 6 element linear Array for example (Δx = 900 mil)



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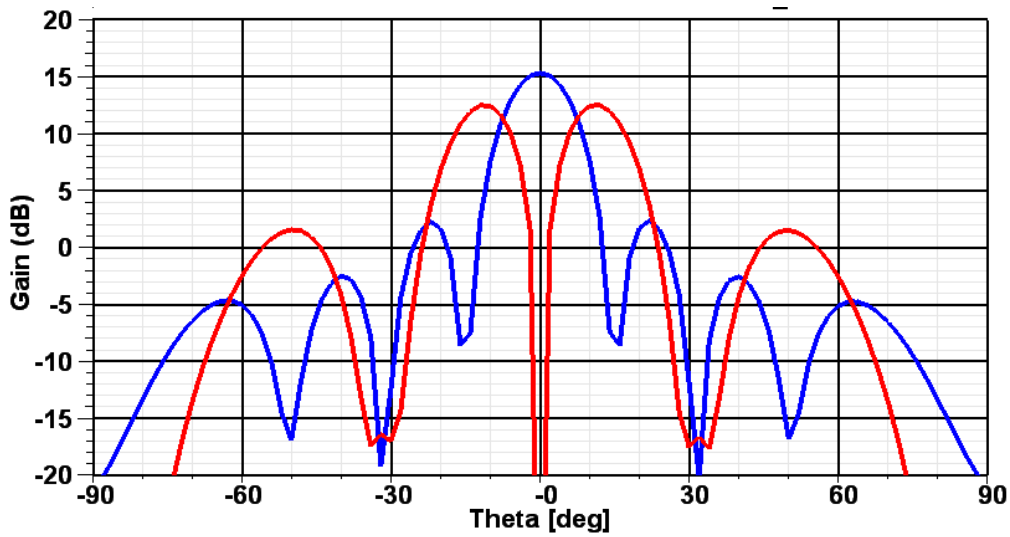
Nulls in the pattern are much more precise in direction than peaks so we need to manipulate the phase of the individual ports to produce a good null.

Try a Sum and Delta feed

E-Plane Stack(900) Beam Σ & Δ

Patterns Sum —— Delta ——

Port Phase = + + + + + + (Sum) + + + – – – (Delta)



The delta pattern would be the one used for the direction finding. The patterns are controlled within phase of the feed networks.

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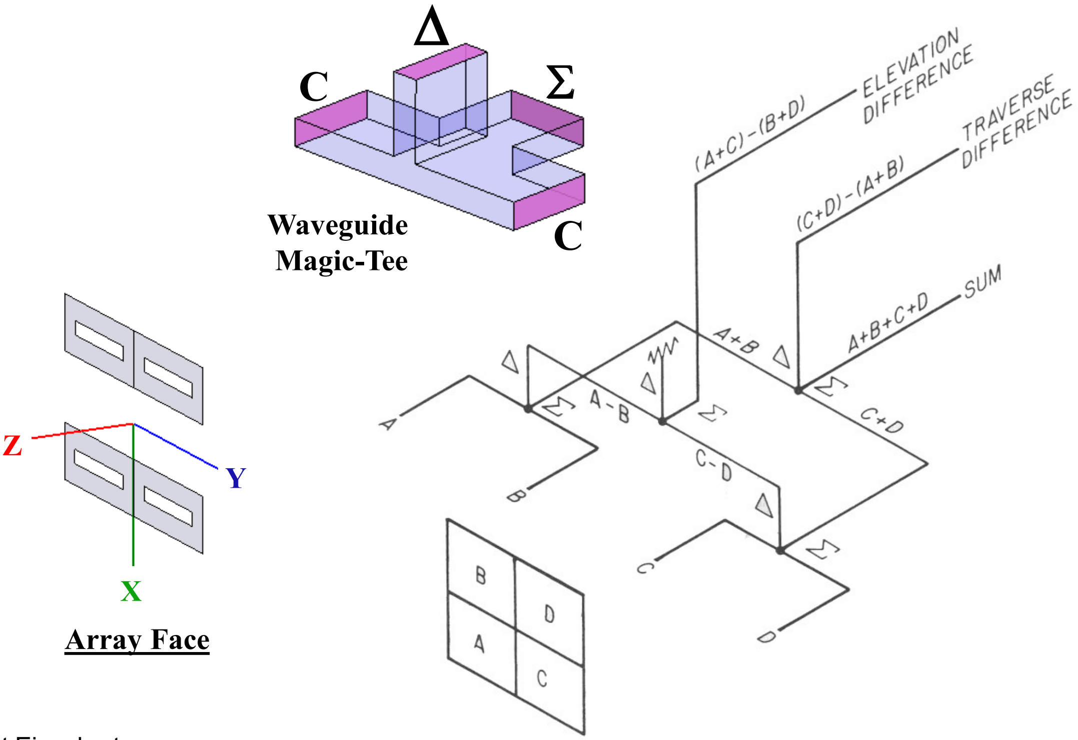
Sum and Delta patterns. Note the element phases as indicated at the top of the plot for the two patterns. Deep sharp null on axis for Delta pattern.

How do you know which null you're at?

On Delta receive, the signal phase flips plus to minus to plus etc. from lobe to lobe, using the transmit signal as reference.

How does a monopulse feed work?

2-Dimensional (Planar) Array
4 Quadrant Σ & Δ Feed Network



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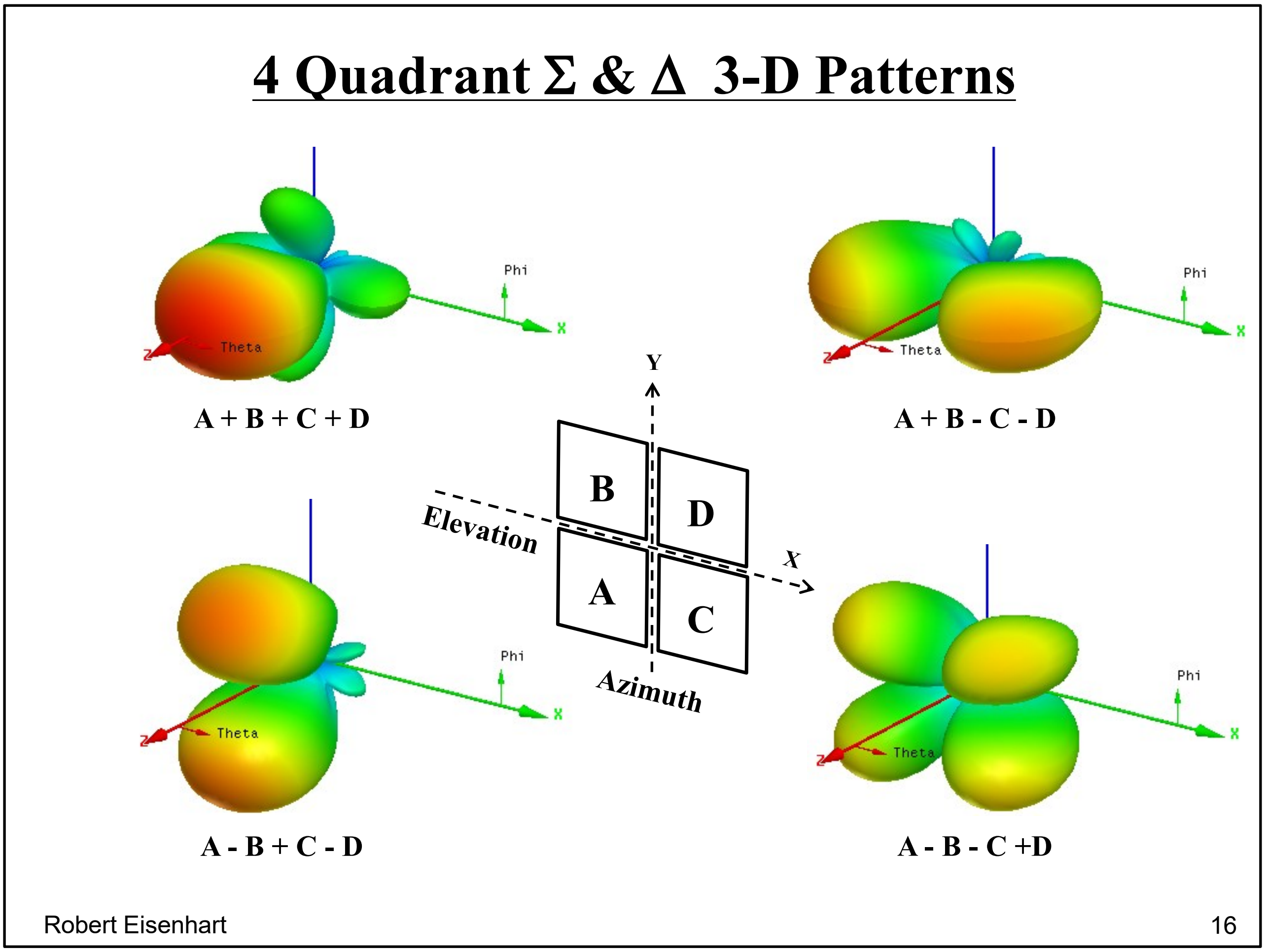
Consider any 2 x 2 element planar array where all 4 quadrants individually have the same pattern. (These quadrants could be sub-arrays within a larger array). When combined in different ways you get different patterns.

This feed has four ports, but not one for each element. The ports are connected to the elements through a network of four Sum & Delta junctions,
commonly called a “Magic-tee”. Signals at the two common (C) ports are added at the Sum port and subtracted at the Delta ports. Two levels of tees (4 total) create a monopulse feed.

Resulting beams



Assume your target object is not on the antenna axis. As a monopulse locator system you transmit in the sum feed (upper left) and receive in the sum feed plus two difference feeds. Think of it as one transmitter and three receivers.

Looking with the first delta feed receiver, the 1st pattern at upper right determines left or right for azimuth.

The 2nd pattern determines up or down for elevation. The received data places the target reflection in a quadrant . You can then steer the main beam (or the missile) until the target is directly on axis. This will be a maximum sum feed return and zero return in both of the difference feeds (that's both the up and down feed and the left or right feed).

How about the pattern for the Δ-Δ signal? Not to useful because data is ambiguous. Port is usually terminated.

Moving along to large arrays.

Large Antenna Arrays

An array is considered large if it can't be totally modeled*. Modeling, with some limitations, is then directed at the individual antenna element and falls into two categories:

1. Broadside Arrays, and
2. Scanned Arrays

* This aspect of arrays is rapidly changing with improvement in computers, programs and memory availability.

Considering just for now the broadside array,

what can we do?

Broadside Arrays

Element Modeling Procedure:

1. Define the desired array lattice dimensions and shape
2. Determine symmetry planes
3. Set up a "broadside" unit cell, and
4. Match the radiating element

First application of the HFSS software for simulation of arrays

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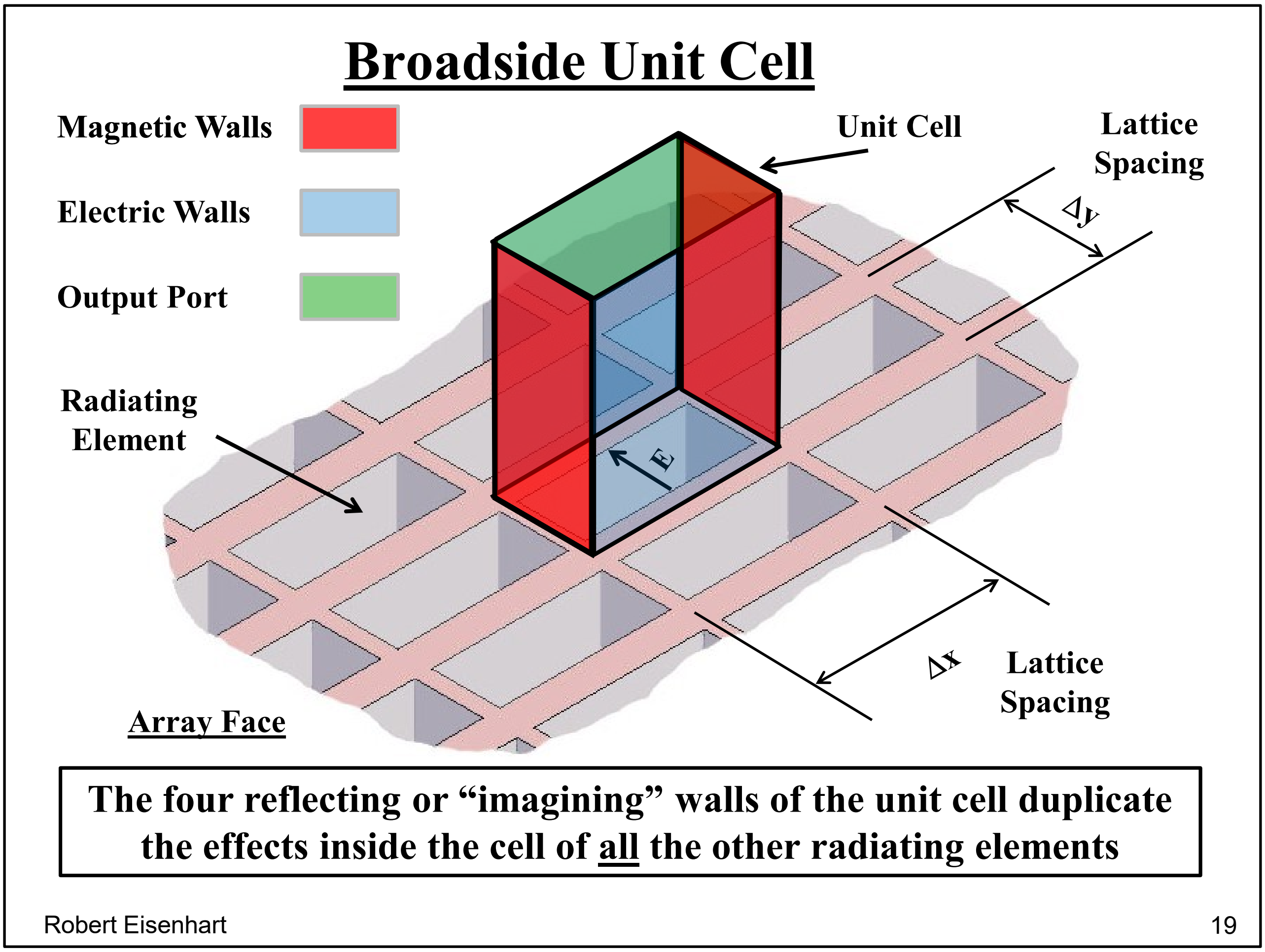
Address modeling the individual element which is done by establishing a unit cell. This model takes into account the coupling between the individual elements.

Used in Gimballed missile arrays.

What would this look like?



Here we have . . . Array Face, with defined lattice dimensions.

Add the magnetic walls, imaging the lateral cells (for vertical polarization).

Add the electric walls, imaging the top vertical cells.

Altogether creates all 2-D images.

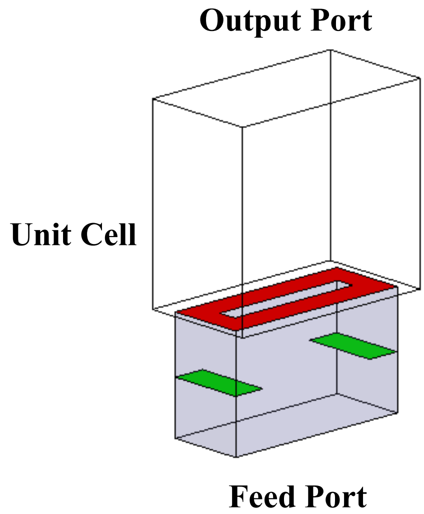
Add the output port. This is particularly valuable in providing element radiating phase information.

In other words, all of the mutual coupling is accounted for in this model. Our example shows an open-ended waveguide but the technique works just as well for any complicated element such as a flared notch, dipole etc. The only limitation is that this approach assumes an infinite uniformly excited planar array, which is a good approximation.

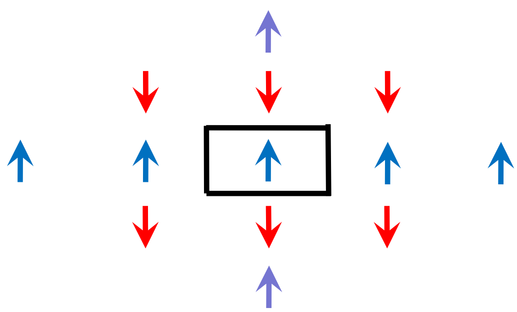
So applying this to the End-slot element

Applied to our previous End Slot Element

1. Unit Cell size is set by the lattice dimensions of the array
2. We get a benefit of the phase value at the output port



Representative Waveguide Cell with Imaging



Unmatched Input Comparison

ρ = 0.274 ∠-49°	**ρ = 0.284 ∠+10°**
Free space	**Unit cell**

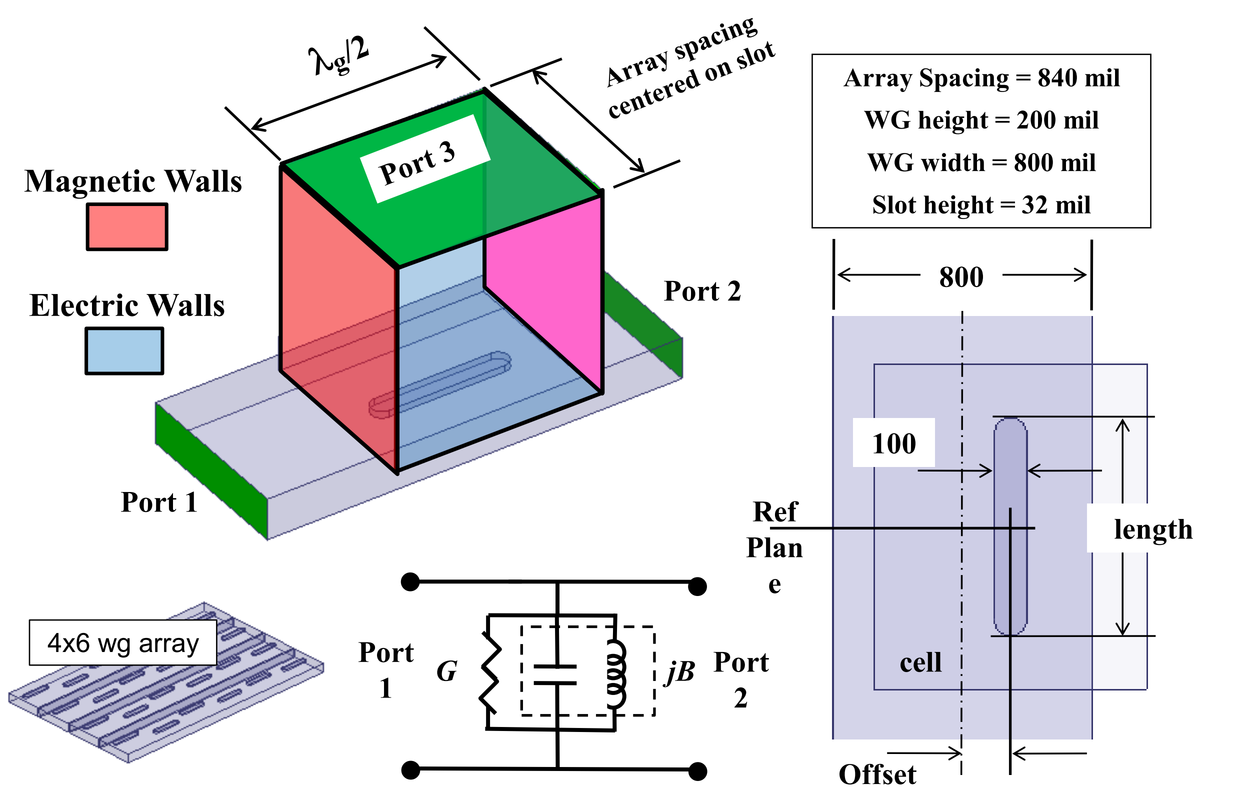
The requirement for uniform excitation is not too sensitive as the most important elements outside the cell are the near neighbors, and with smooth tapering the variations are usually not too big. Edge elements of the array will not be exact but make up a small % of a large array.

All outside slots in all directions are imaged.

Changing the unit cell boundary conditions from our previous non-array model changes the slot impedance to be matched.

Next let's look at a waveguide broadwall slot.

Broadwall (Shunt Slot) 2D-Array Element Model



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The shunt slot array element is used where you don't need to phase vary the individual excitation control for each element. This is a large simplification because now you need only one input port for a whole array within one waveguide. The signal can then be distributed to these waveguides through a feed network of splitters, establishing a given fixed excitation at each element. The main signal passes through the waveguide under the slot, allowing a controlled amount of "leakage" out the slot, set by the slot offset from centerline. By offsetting every other slot to the opposite side of the previous slot, the phase is shifted 180 degrees, resulting in all slots in one waveguide radiating in the same phase.

Since all effects are normalized to the WG impedance, you can use a reduced height WG, typically 100 - 200 mils at 10 GHz. The slot height is the thickness of the top metal wall. The electrical effect of the slot is to appear as a shunt admittance across the WG, tuned to resonance by the slot length and conductance by slot width.

What would this slot look like electrically?

Conductance and Susceptance Values

At the centered reference plane of the slot, where the:

Reflection Coefficient $= \boldsymbol{\rho\angle\varphi}$

The normalized equations for Conductance and Susceptance are:

$$G' = \frac{-2(\rho^2 + \rho cos\varphi)}{(1 + 2\rho cos\varphi + \rho^2)}$$

$$B' = \frac{-2\rho sin\varphi}{(1 + 2\rho cos\varphi + \rho^2)}$$

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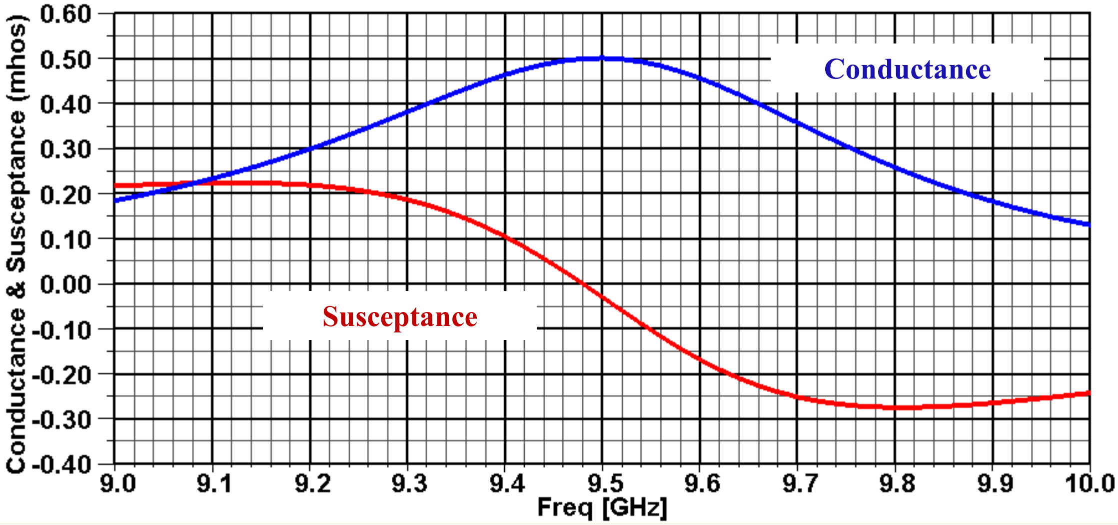
The main thing to see here are the equations for the Conductance and Susceptance based on reflection coefficient, magnitude and angle.

The input match is a check on our calculations, shown on the next page.

100 mil Shunt Slot Admittance Resonant @ 9.5 GHz, w/ G'=0.5

Length = 662 mil Offset = 63 mils



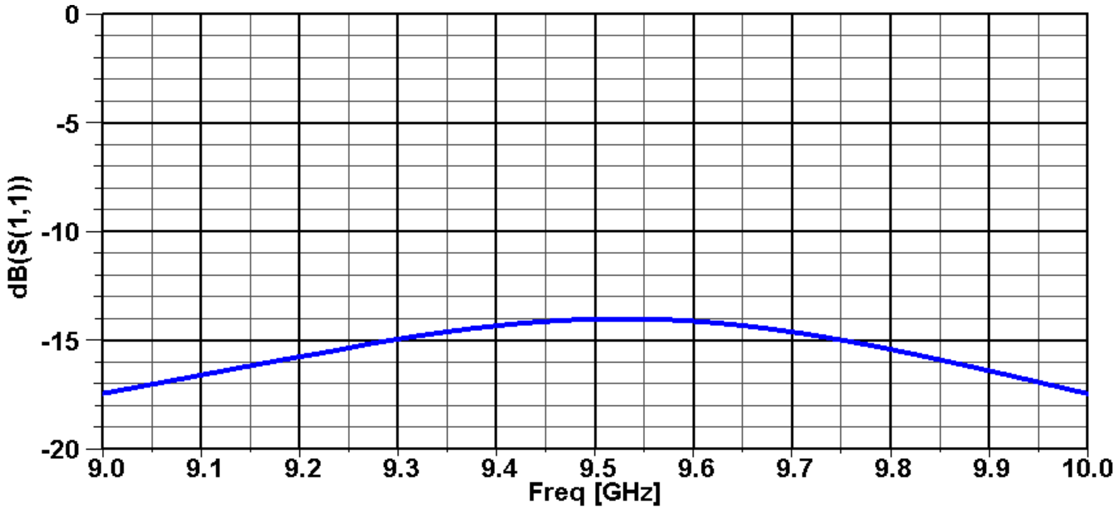
Length and offset tune resonance and conductance

This conductance is fairly big, needing only two slots to match the guide.

Two independent variables

100 mil Shunt Slot Match Resonant @ 9.5 GHz, w/ G'=0.5

VSWR = 1.5   Return Loss = -14 dB



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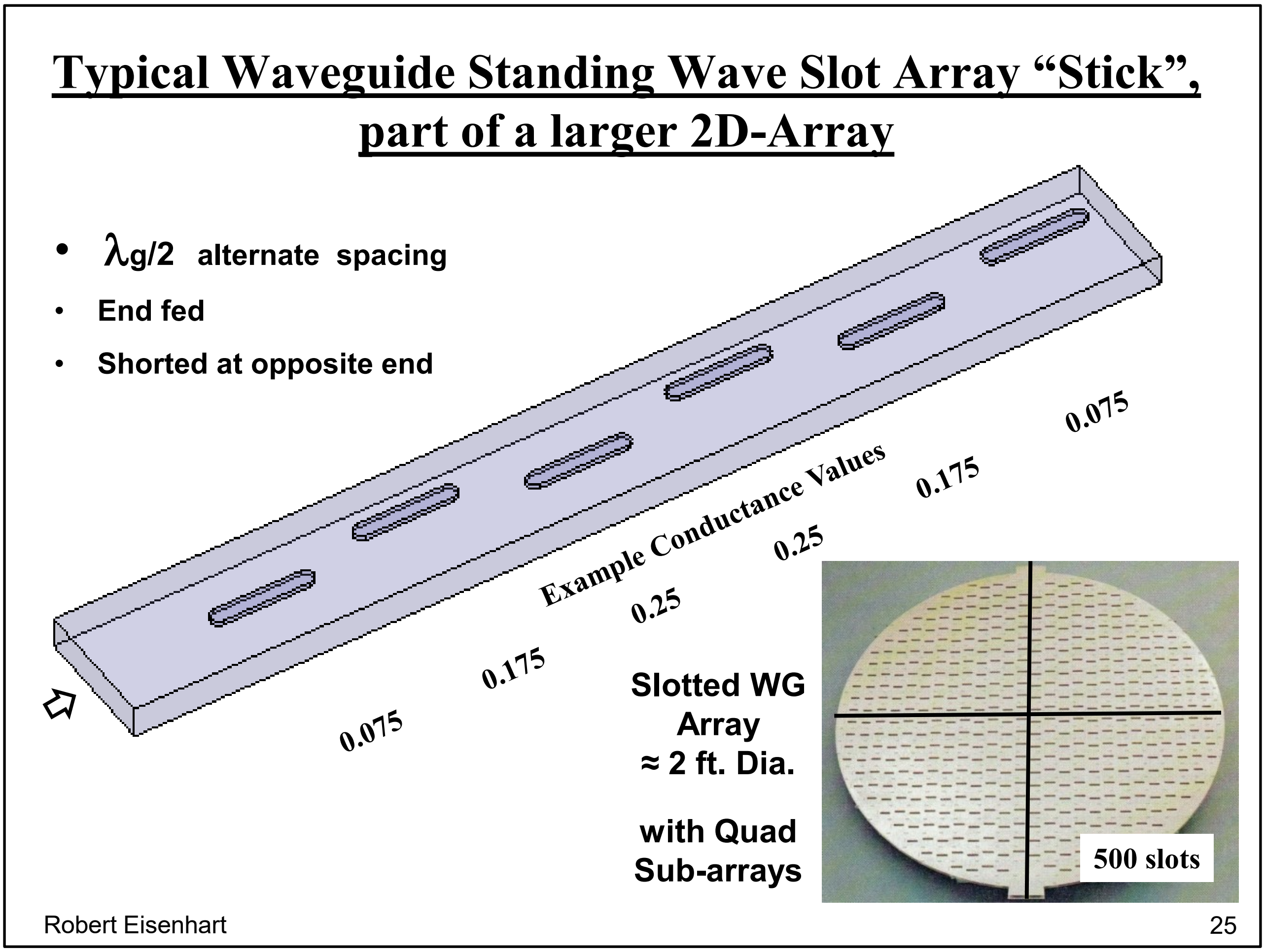
Sanity check, this single (G=0.5) slot would couple out 1/3 of the power for a VSWR of 1.5 at center band, resulting in a Return Loss of -14 db. The other 2/3 of the signal passes through to the second port.

Consider a linear sub-array out of a larger 2D-array.



Notice a few things.

a) Fed on the left end the slots alternate about the centerline to be in phase.

b) The end is closed off at $lambda_g/4$ from the slot center.

c) With the slots at half-wavelength ($lambda_g$) spacing they all appear in parallel, therefore input conductance = Sum Gs.

d) A major advantage of this type array is that the feed transmission line is integrated with the radiating structure in layers behind the array face to provide accurate element control and a mechanically rigid assembly, capable of very high powers.

Here we have a medium size array for a fighter aircraft radar.

The feed supports monopulse operation with quad subarrays.

AMRAAM and Phoenix missiles also used this type gimbaled array, only about 6 inches and 14 inches diameter respectively.

We’ll finish this section with a few pages on scanned arrays.

Large Scanned Arrays

Problem:

When scanning an array beam by changing the excitation of the elements, the resultant change of the mutual coupling also changes the match of the elements.

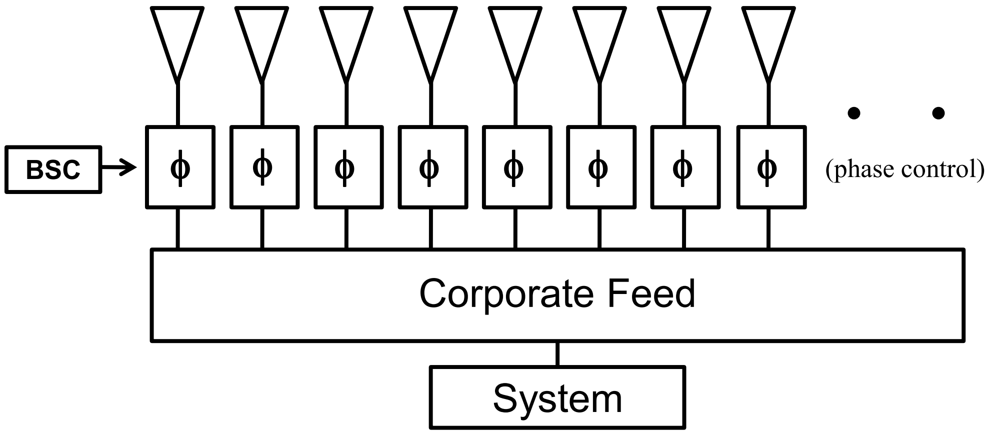
Initial Solution (1963-1993):

Once upon a time there was an array analysis technique called **Waveguide Simulation**. This approach was complicated, hardware intensive, time consuming, very limited in results, but it was the only way to characterize a scanning array, **without building it first!** A short discussion of the Waveguide Simulation Technique is in Section 7 for those interested.

Today,
EM simulation has made it possible to resolve the mutual coupling issues and is summarized in the following pages.

Next see a Large Array block diagram

Large Scanned Arrays



Main Issues related to scanning –

1. **Phase shifter design/control within the Trans/Rec Module**
2. **Analysis of the mutual coupling on Array Performance**

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Here we have a typical block diagram for a scanned array. You have the array, the phase controlling elements and the feed. There are many ways to address each of these issues,

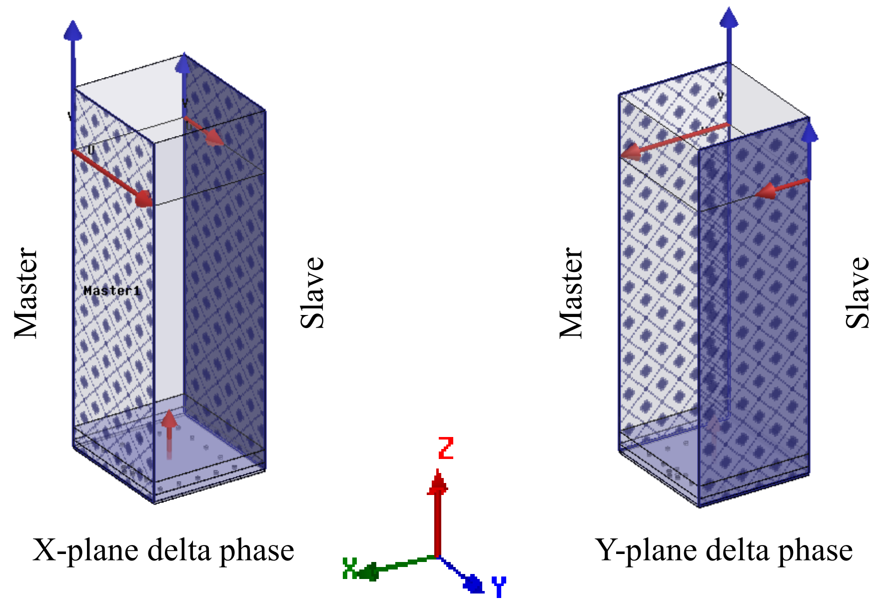
However, the two main scanning issues are BSC (Beam Steering Computer) which is more a device type problem,

and being able to analyze the effects of mutual coupling on the input match during scanning. This is addressed by the master-slave analysis built into HFSS and is applied to the array Unit Cell as boundary conditions during analysis.

A basic discussion of the Waveguide Simulator Technique which led to the master-slave analysis used here is discussed in Section 7, pages 31-37.

Next we see an Array Unit Cell with the Master/Slave boundaries applied.

Scanning Match Can be Simulated with a Unit Cell

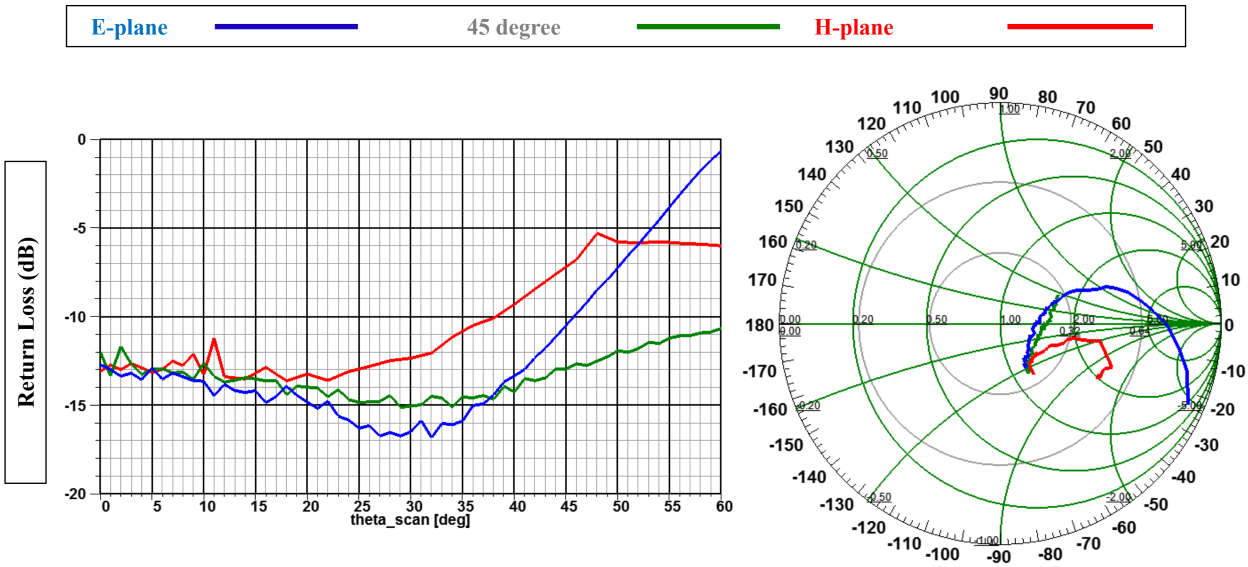


Mutual Coupling Effects on Scanning Match Incorporated with Master/Slave Boundaries

Here the scanning boundaries are shown separately for two axes for a simple rectangular array unit cell. During analysis, the phase relationship between the master and slave walls are varied in accordance with the respective scan angle desired, allowing scanning in any Theta/Phi combination. (The boundary conditions shown in page 29 are unique for the broadside scan of Theta = 0.

Consider what can be done with this analysis

Scanning Match Can be Simulated



Using the Master/Slave boundaries for tuning the match at 30 degrees scan at the high end of the band results in acceptable performance over the whole frequency band.

The inner circle is the -10 dB limit for the three curves. The impedance is at the port entry to the element at the bottom ground plane.

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Here the Master/Slave analysis has been applied to the design of an element with excellent results for the goal of wide scanning angles.

And we have the accompanying impedance plots for the three scans.

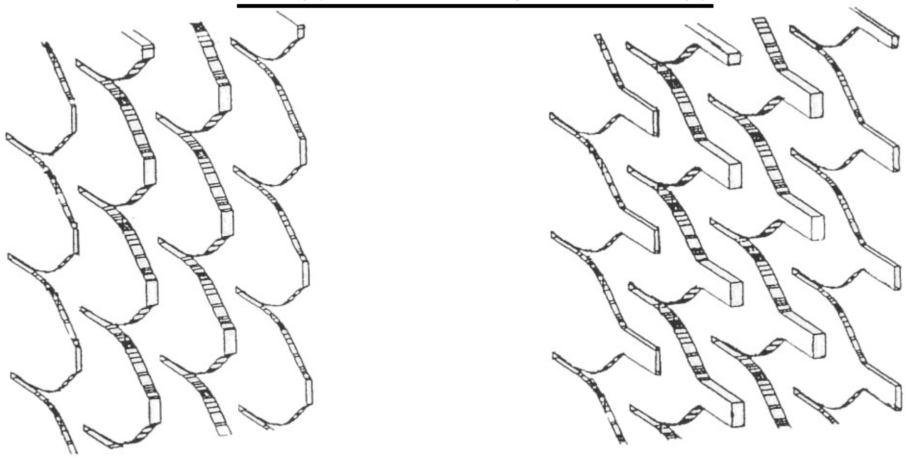
Just a few years ago we needed hardware for analyses like this.

For example, what if you wanted to study the effect of the tip length on an array element?

Flared Notch Triangular Array (circa 1992-3)

Array variations are easily studied

This? or This?



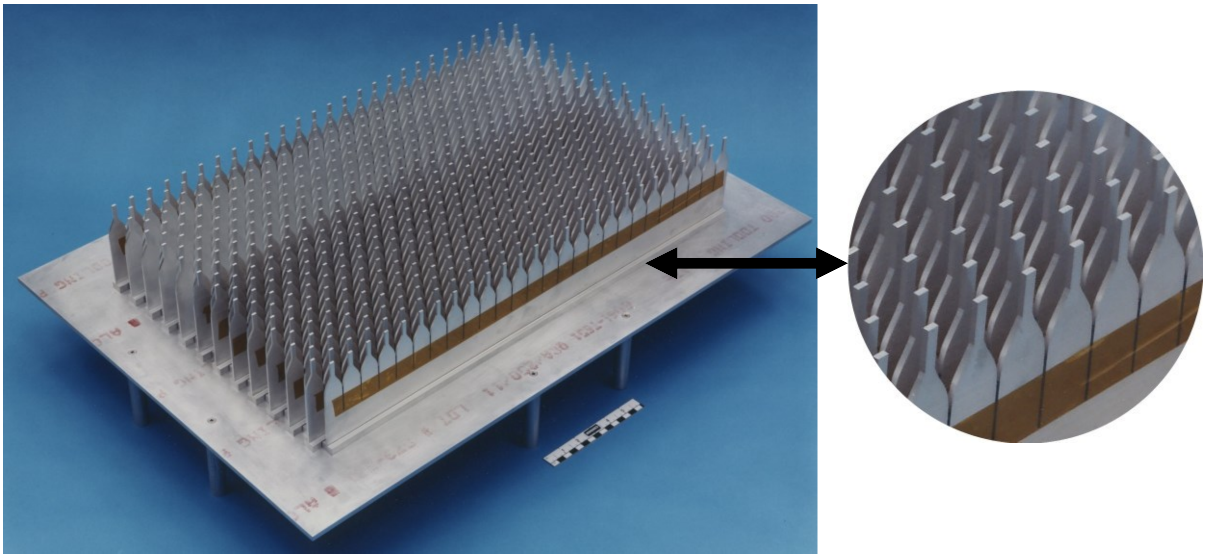
Easily handles complex, 3-dimensional elements

Now it is just a matter of changing a dimension on the element unit cell and rerunning the software.

Typical previous test hardware for scanning measurement.

Flared Notch Array Hardware (circa 1990s)

Large array example of a complex element



Avoiding costly test hardware like THIS is a big deal!

Before HFSS, big bucks.

Now lastly let us consider the mid-sized arrays.

Mid-Sized Arrays

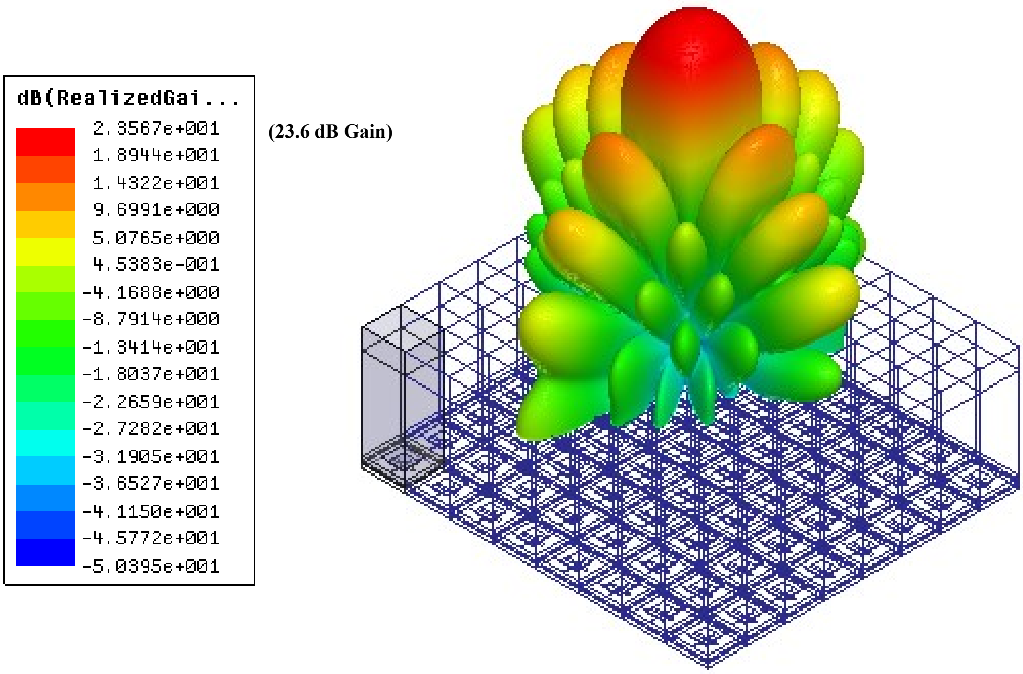
A separate category because:

1. They are the most difficult to analyze
2. Too small to be considered infinite
3. Too large to model conventionally
4. Requires High Power Computing Capabilities
5. Automatically treats the array edges
6. Provides full scanning analysis

A short description of the mid-sized array modeling

Fortunately, in recent years the limitations have been overcome, consider an 8x8 array with a complex patch element design.

8x8 Finite Array Mid Band 3-D Polar Patterns w/Uniform Excitation



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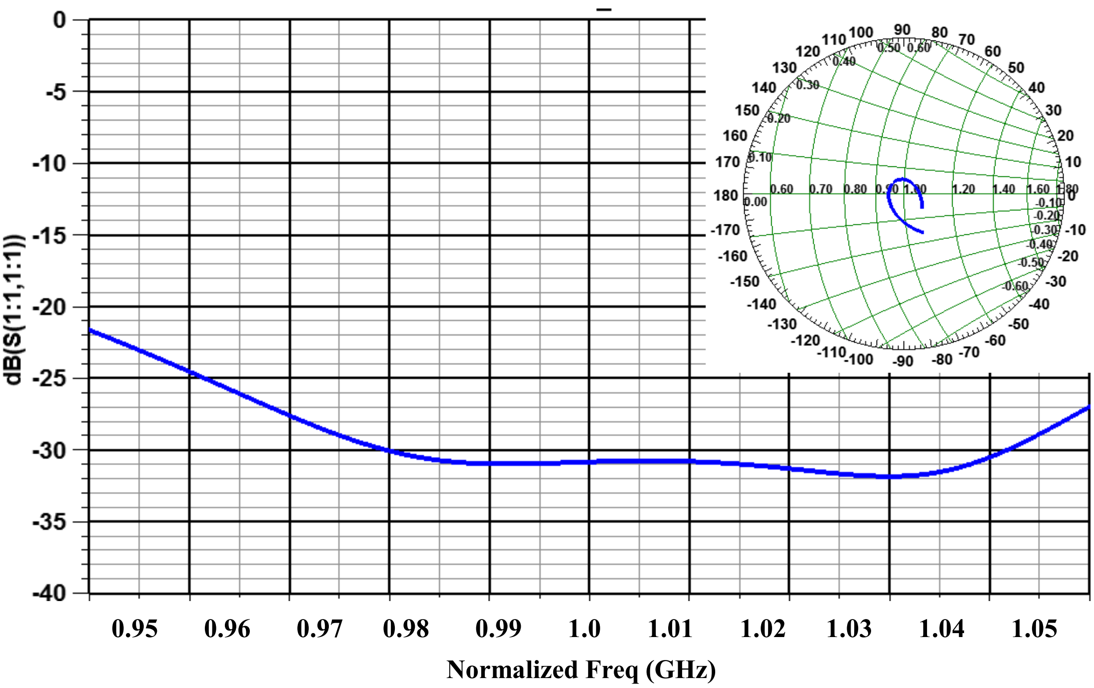
Run time 1.1 hours using 1.6 GB RAM

Starting with a well designed array element.

Patch Type Single Element Match in an Infinite Array



An excellent match was achieved across the band.

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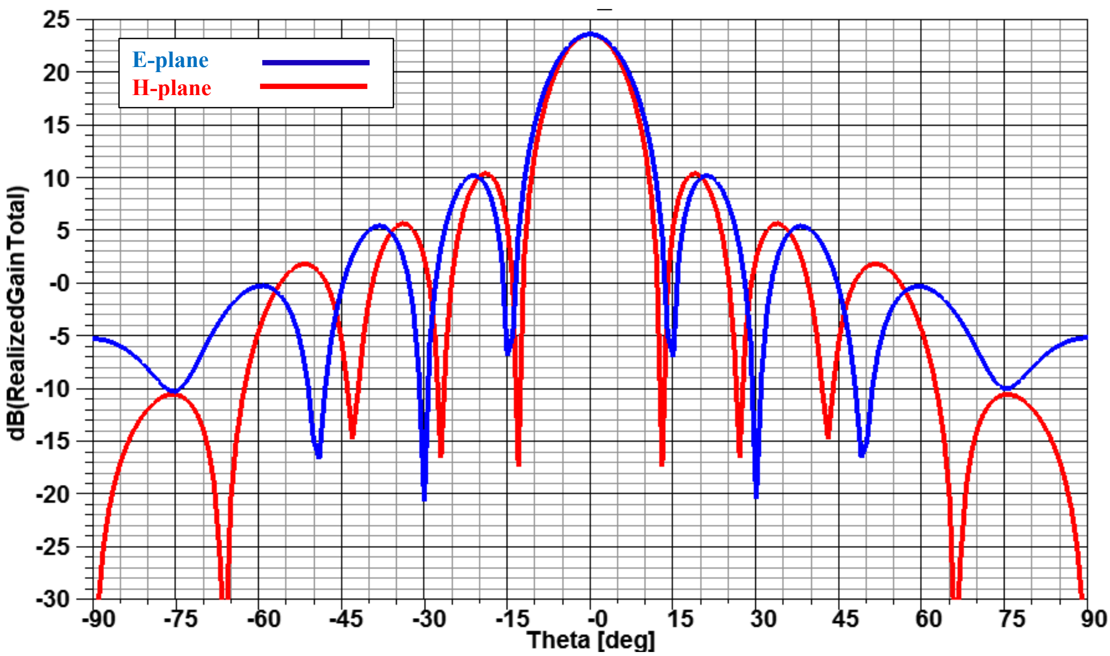
Wide band element design

Looking next at the E & H plane patterns for uniform array excitation.

8x8 Finite Array Mid Band E & H Patterns w/Uniform Excitation

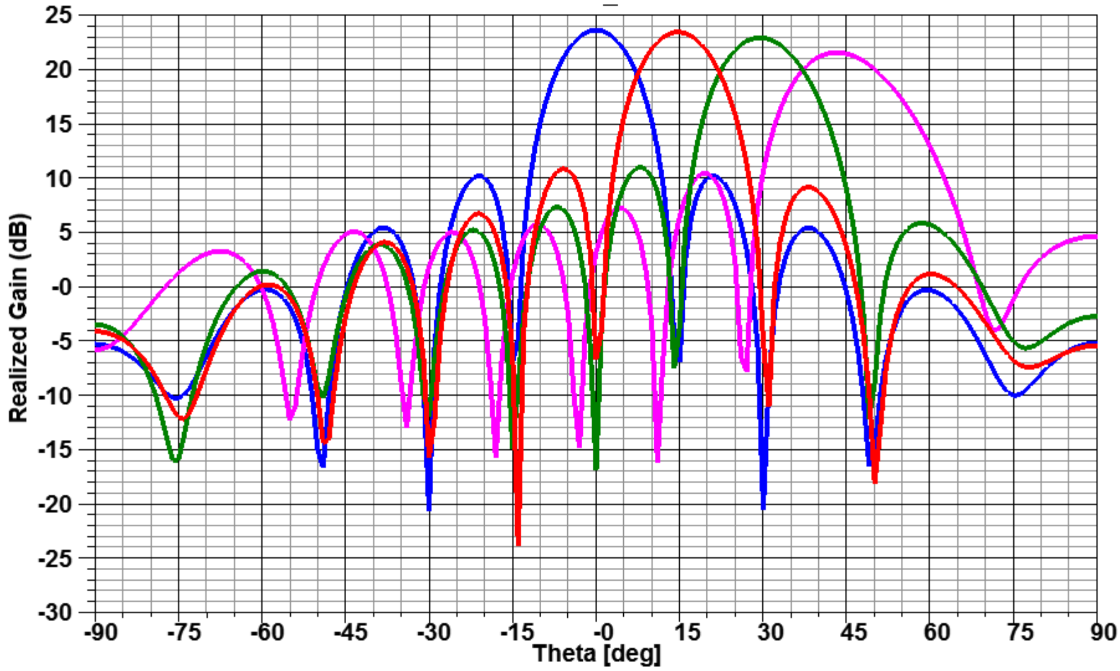


We see the expected -13 dB sidelobes for the uniform excitation

Notice the patterns indicate that the element is not square.

Next consider scanning the beam in the E-plane

8x8 Finite Array Mid Band E-Plane Scanned w/Phase Excitation



The array scans easily to 45 degrees without grating lobes

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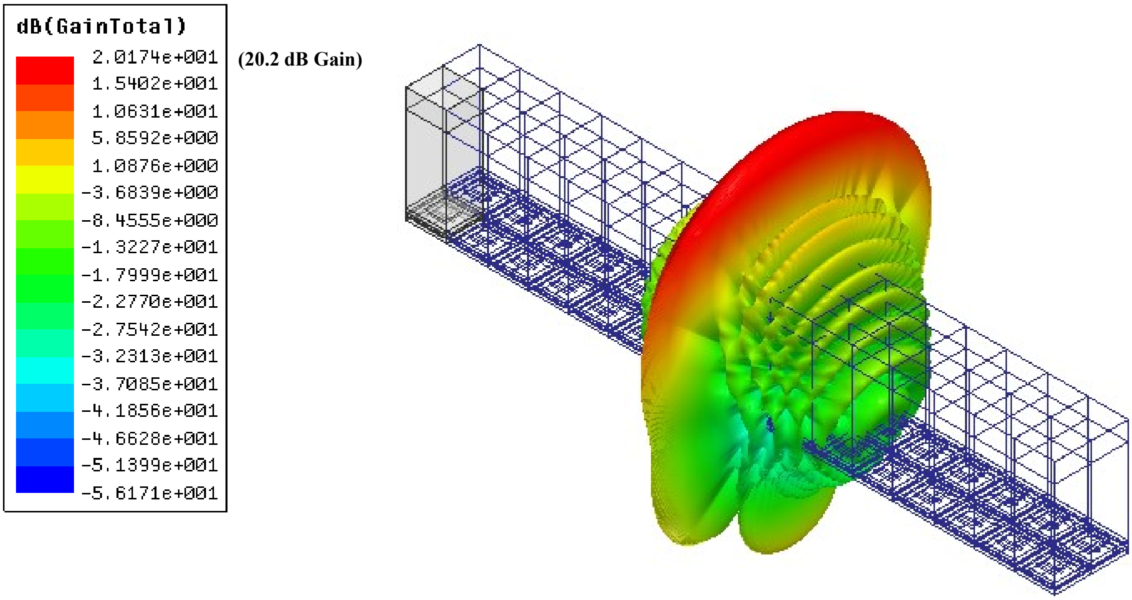
The array scans easily to 45 degrees without grating lobes. A separate element excitation file (64 mag/phase values) is generated to apply to the array elements, with appropriate phase shifting for each scan desired.

Next see a different excitation, as applied to a 2x16 fan beam.

2x16 Finite Array Mid Band w/Taylor 18dB Excitation for H-plane



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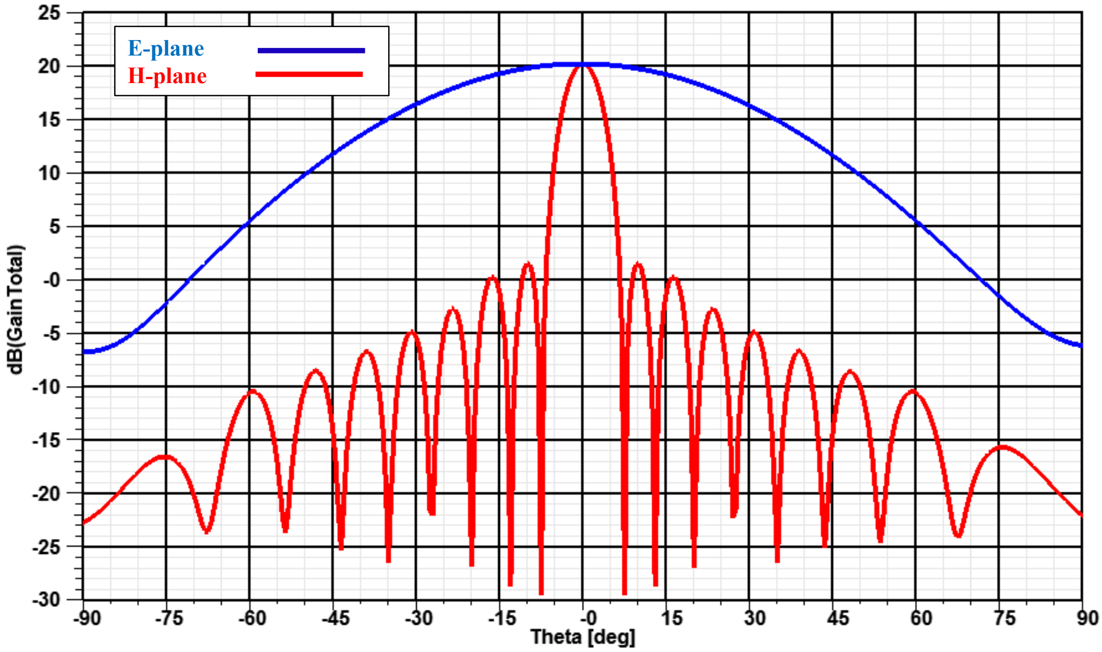
Using the same element with an H-plane Taylor distribution, and

We have the E & H plane patterns.

2x16 Finite Array Mid Band
w/Taylor 18dB Excitation for H-plane



First side-lobes are at -18 dB from peak

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Note the total gain is down by 3 dB because we're only using half the elements relative to the 8x8 array. These last two arrays were shown as examples of what can be analyzed.

So to summarize HFSS for antennas.

Summary

A variety of examples demonstrate the capability of EM simulation to quickly and easily provide performance predictions for antennas.

Simple examples were used for discussion, yet, the approaches and techniques are just as applicable to more complex structures.

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And…

Whether you think you can or cannot do something, you're probably right.

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Attitude counts a lot