Basics of Antenna Arrays

Developed and curated by the Ansys Education Team

Based on the Ansys Innovation Course: **Basics of Antenna Arrays**

Original Developer: Kathryn Smith

Updated and curated by Dimitrios Tzagkas and Celia Gomez Molina

education@ansys.com

Learning Objectives for this Lecture Presentation

Intended Learning Outcomes	
Knowledge and Understanding	Understanding fundamental concepts of Array Theory
Skills and Abilities	Ability to create an antenna array and estimate the array factor on Ansys Electronics Desktop - HFSS
Values and Attitudes	Awareness of wavelength and frequency of a signal, directivity of an antenna

Resources

- "Engineering Electromagnetics," by Nathan Ida, 3rd ed. (2015)
- "Antenna Theory", by Constantine A. Balanis, 4th ed. (2016)
- Software: Ansys Electronics Desktop v23R2 (please note that all project files are available in the downloaded folder)

Further reading/information

- Ansys Academic
- Ansys Innovation Courses
- Ansys Education Resources

Built-in Assessment

- Simulation instructions
- Exercise

Introduction

When two or more radiating elements are operated in close proximity to one another, the interference of their radiated fields can become a major factor in determining their collective radiation pattern. Antenna engineers leverage this fact to their advantage by creating antenna arrays – collections of proximate antennas that are designed to operate cohesively to produce a desired pattern of radiation.

In this module we will focus on uniform arrays – arrays consisting of a collection of identical elements, all driven with the same signal amplitude, having equal spacing between neighboring elements and a progressively-stepped phase shift along the length of the array.

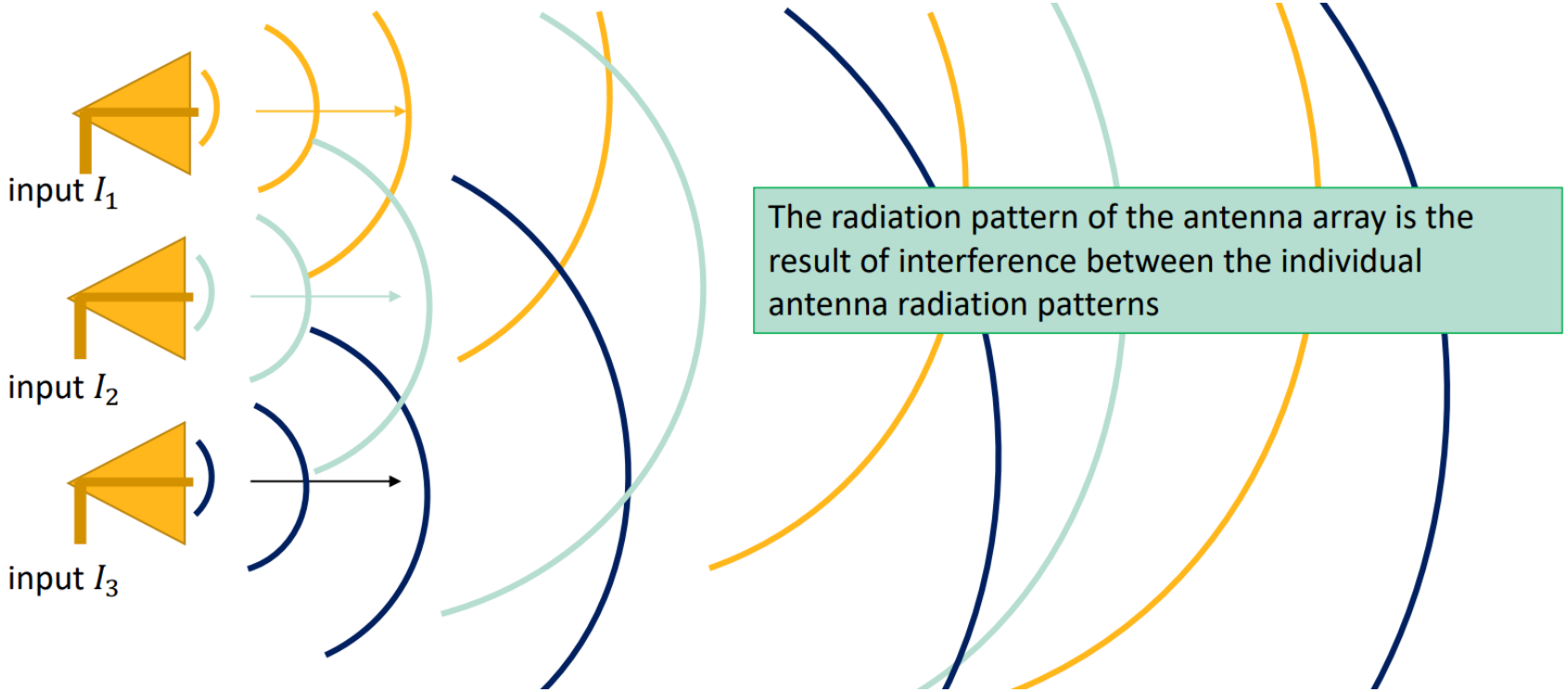
Our focus will be primarily on linear arrays – where the elements are arranged along a single dimension and analyze the effects of

- Antenna element spacing
- Number of antenna elements
- Phase shift between the antenna elements
- Brief look at planar arrays, which consist of a 2D grid of radiating elements

And finally, we will have a quick overview of the antenna array tool in HFSS

What is an Antenna Array?

An antenna array is a collection of antennas which are operated in close proximity to one another, and designed to work in tandem. It leverages the interference pattern of the fields radiating from the various elements to achieve a desired radiation pattern. Antenna arrays are often used to enable tighter directivity than could be achieved with a single-element design.



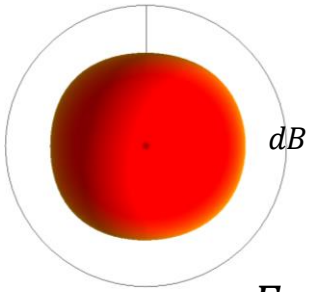
The Array Factor (AF)

Antenna arrays consisting of a collection of identical elements are usually characterized in terms of their “Array Factor.” The Array Factor of any given array of identical antenna elements is a product of the number of elements, the relative input signals (magnitude and phase) of the various elements, and the geometric arrangement of the elements.

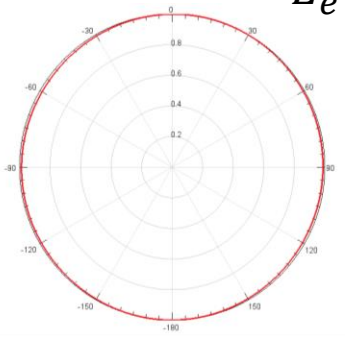
The total electric field, E_{tot}, radiated from an antenna array is equal to the product of the array factor, AF, and the electric radiation pattern of a single antenna element, located at the origin, E_e .

$$E_{tot} = E_e * AF$$

Electric Field of Patch Antenna

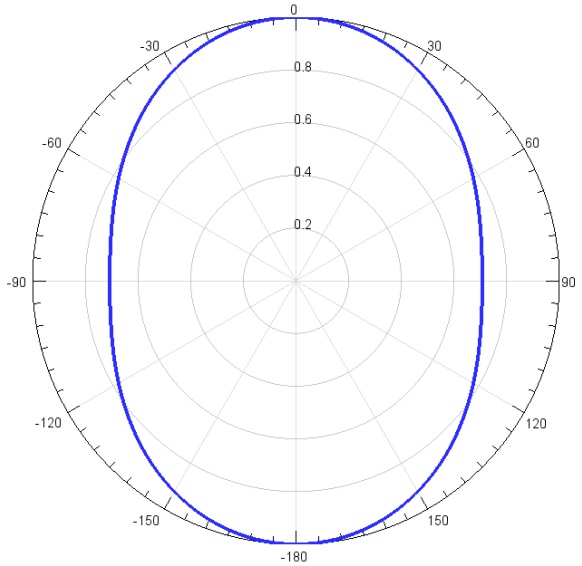


E_e

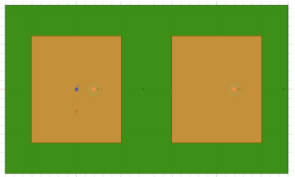


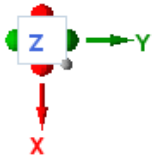
$Normalised$

Array Factor of 2 element array

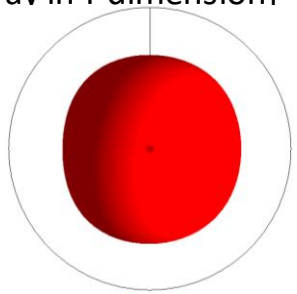


2-Element Antenna Array

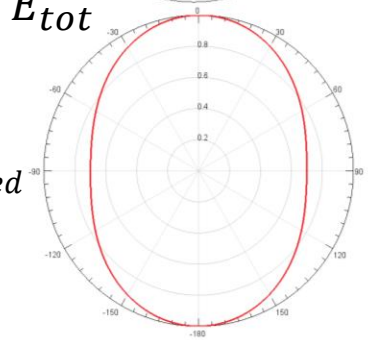




Electric Field of 2-element Antenna Array [Array in Y dimension]



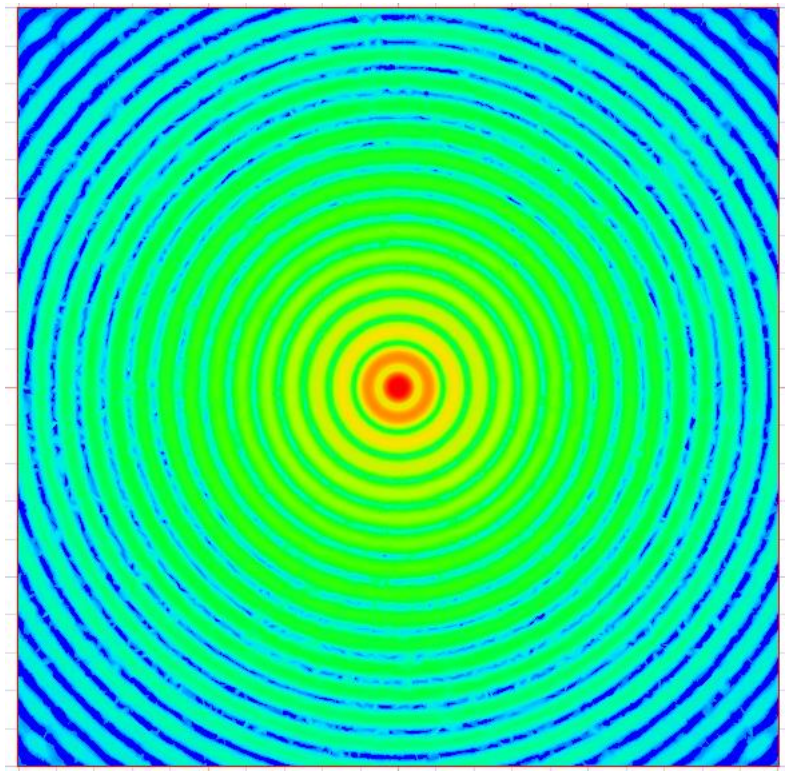
E_{tot}



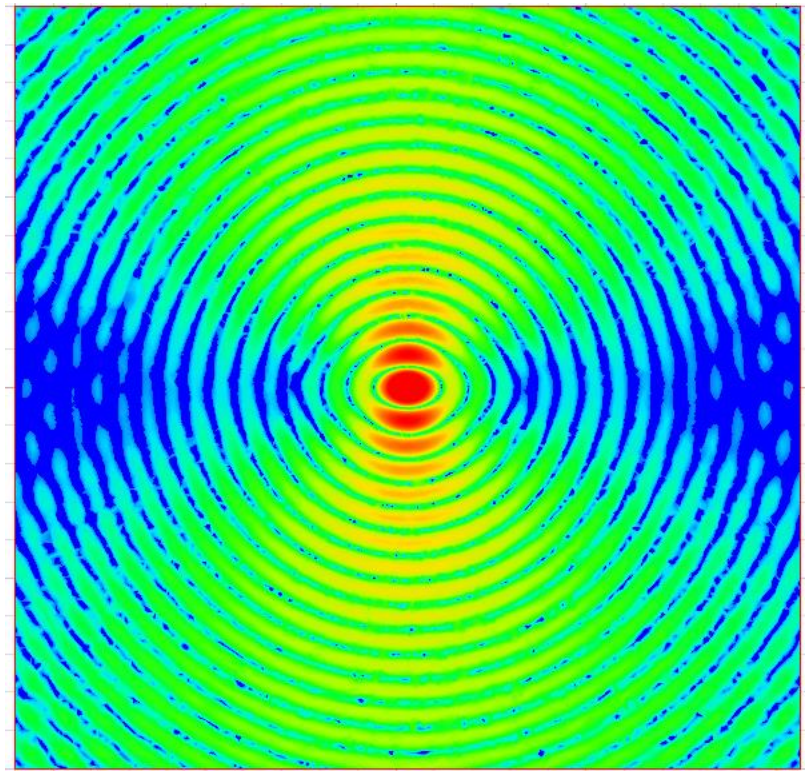
$Normalised$

Radiation examples

The interference pattern of the total radiated field constitutes the array factor for each array.
Below there are examples of normalized total radiated electric field for the cases of single radiator and 2-element array.



A Single Isotropic Radiator

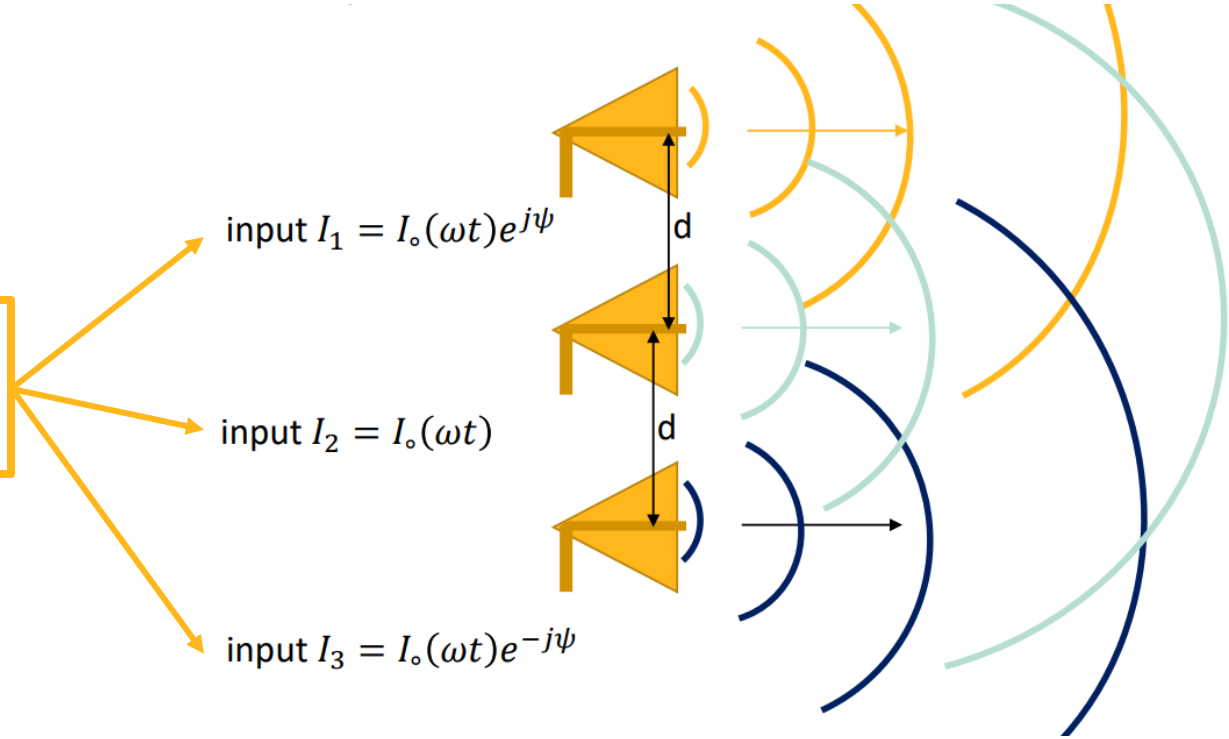


Array of Two Isotropic Radiators, horizontal separation of $\lambda/2$

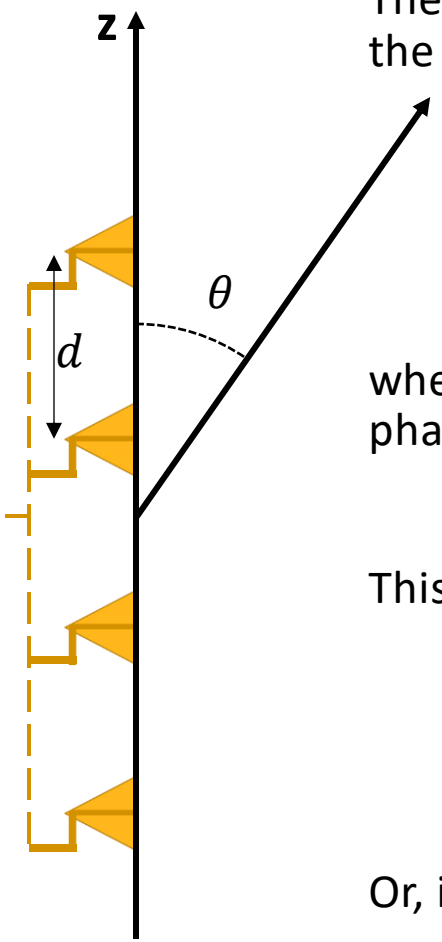
Uniform Antenna Arrays

A uniform antenna array is an array of identical elements, all driven with the same signal amplitude, having equal spacing between neighboring elements and a progressively-stepped phase shift along the length of the array. This electronic phase shift augments the phase shift effected by the physical separation of the elements, and allows dynamic adjustment of the array factor without physical rearrangement of the antenna elements.

In a uniform array, each antenna is driven with the same magnitude signal, but with a progressively-stepped *phase* shift



Array Factor for Uniform Antenna Arrays



The array factor of an N-element uniform antenna array, arranged in a line along the z-axis, centered at the origin, and viewed from the far field, is given by:

$$AF = \sum_{n=1}^{N} e^{j(n-1)(kd\cos\theta+\psi)}$$

where k is the wavenumber and is equal to $2\pi/\lambda$, d is the separation between elements and ψ is the phase difference between neighboring elements.

This may also be written as:

$$AF = \left[\frac{\sin\left(\frac{N(kd\cos\theta+\varphi)}{2}\right)}{\sin\left(\frac{kd\cos\theta+\varphi}{2}\right)}\right]$$

Or, in the special case of N=2,

$$AF_2 = 2\cos\left[\frac{1}{2}(kd\cos\theta+\varphi)\right]$$

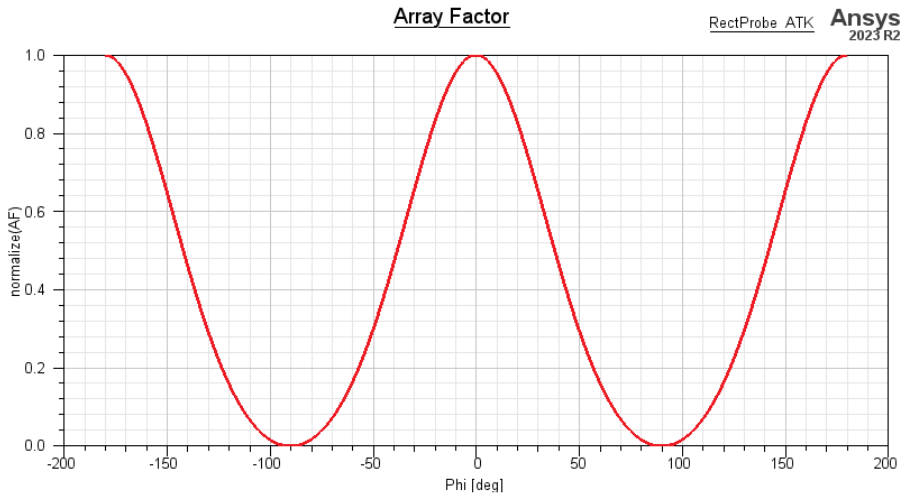
Array Factor of Uniform Antenna Arrays

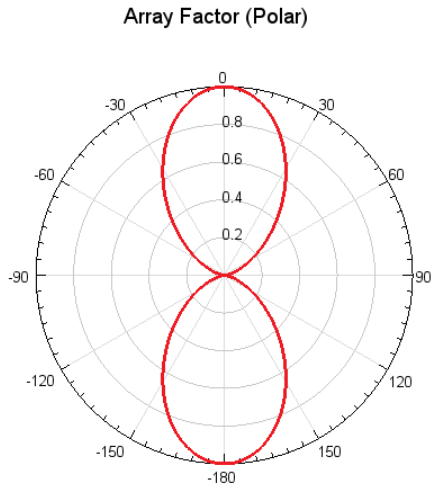
From the equation of the Array Factor, we can understand that the array factor is a function of the array setup as:

- The number of elements that form the antenna array (N)
- The spacing between the antenna elements with relation to the wavelength (d/λ)
- The phase difference between neighboring elements (ψ)

$$AF = \sum_{n=1}^{N} e^{j(n-1)(kd\cos\theta+\psi)}$$

The array factor can be plotted in cartesian or polar plots as below *(AF for N=4 and d=λ/4)*:

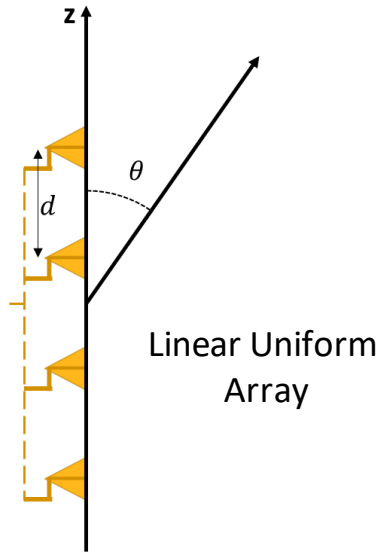




Array Factor of Uniform Antenna Arrays – Key notes (A)

- For an array where each element is driven with the same current magnitude, the strength of the radiation will naturally increase as the number of radiating elements increases. However, this does not necessarily reflect a system improvement, since the higher power output is proportional to a higher power input. In order to avoid conflating this effect with an actual gain improvement, the array factor is often reported as a normalized value.
- A **linear uniform array** (developed along an axis) can steer the radiation in the direction of the array. For instance, an array of isotropic radiators arranged along the z-axis may be used to steer the beam in the θ direction, angled from the z-axis.

$$AF_n = \frac{1}{N}\sum_{n=1}^{N} e^{j(n-1)(kd\cos\theta+\psi)}$$



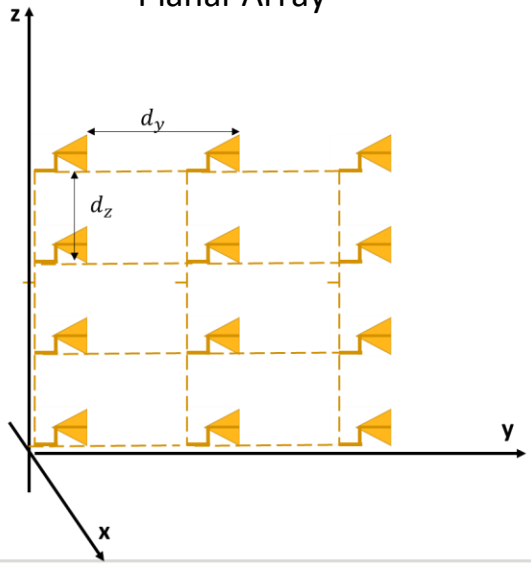
Linear Uniform Array

Array Factor of Uniform Antenna Arrays – Key notes (A)

- A **planar array**, in which elements are arranged along two dimensions, may be used to enable steering around a second axis. Here, the y-directed spacing between elements is d_y, and each column of elements arranged in the y-direction has a relative phase difference between neighbors of ψ_y. Similarly, the z-directed spacing between elements is d_z, and each row of elements arranged in the z-direction has a relative phase difference between neighbors of ψ_z.

  For the case of a uniform planar array with [M x N] elements distributed in the y-z plane (as shown) the normalized array factor becomes:

Planar Array



$$AF_n = \frac{1}{MN} \cdot \sum_{m=1}^{M} e^{j(m-1)(kd_y \cdot sin\varphi \cdot cos\theta + \psi_y)} \cdot \sum_{n=1}^{N} e^{j(n-1)(kd_z \cdot sin\varphi \cdot cos\theta + \psi_z)}$$

Array Factor of Uniform Antenna Arrays

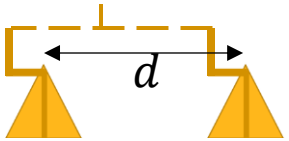
Effect of Element Spacing

The spatial separation between elements in an antenna array increases the *apparent electrical size* of the effective radiator. This increase in electrical size enables a compression of the radiation pattern in the dimension of the array. For a fixed number of elements, increasing the separation d between elements increases the observed compression of the primary lobes of the radiation pattern.

With:

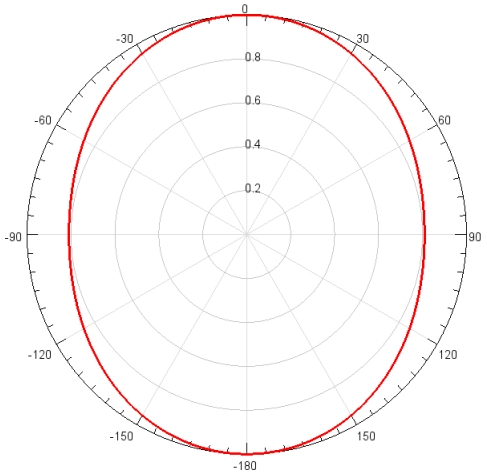
$\mathrm{N} = 2,$

$\psi = 0\ deg$

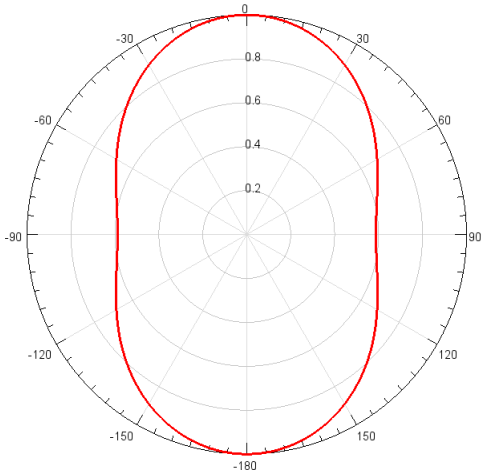


- As shown below, a two-element array has progressively more compressed radiation as the two elements move further apart.
- However, as d increases beyond 0.5λ, a secondary set of lobes appears, pointing in the dimension of the array (see next slide).

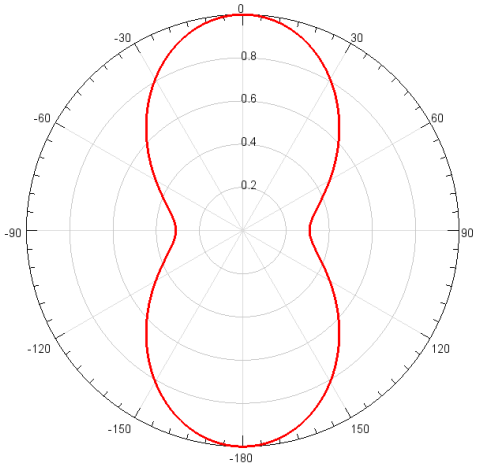
AF for $d = 0.2\lambda$



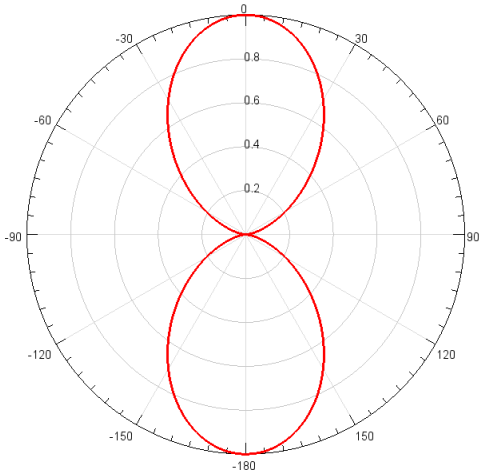
AF for $d = 0.3\lambda$



AF for $d = 0.4\lambda$



AF for $d = 0.5\lambda$



Array Factor of Uniform Antenna Arrays

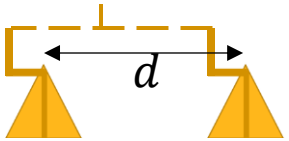
Effect of Element Spacing

As shown below, the secondary lobes of a two-element array increase in strength, and the primary lobes narrow, as d increases from 0.5λ and approaches λ.

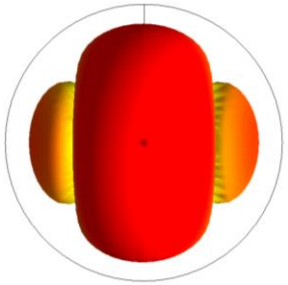
With:

$\mathrm{N} = 2,$

$\psi = 0\ deg$



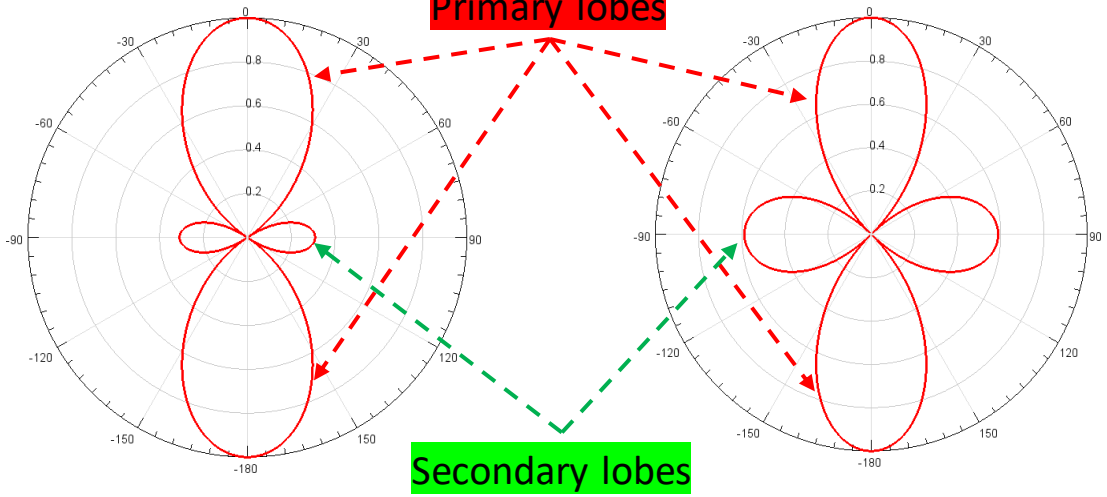
Electric Field [in dB] of 2 element antenna array with $d = 0.7\lambda$



AF for $d = 0.6\lambda$

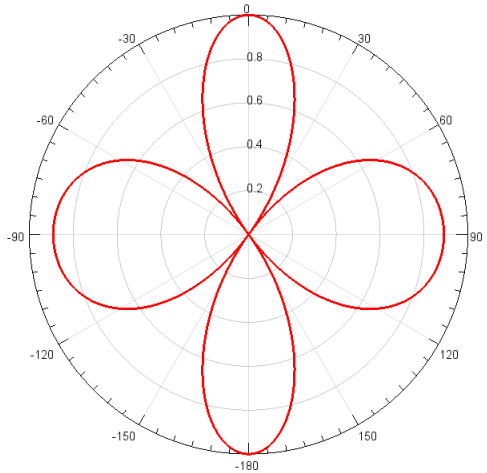
AF for $d = 0.7\lambda$

Primary lobes

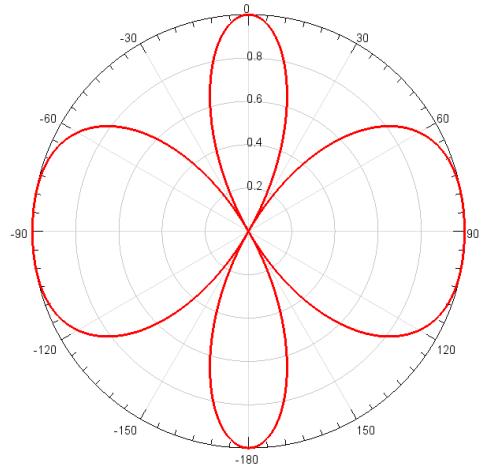


Secondary lobes

AF for $d = 0.85\lambda$



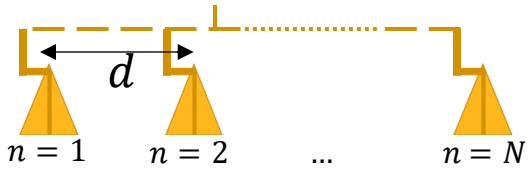
AF for $d = 1\lambda$

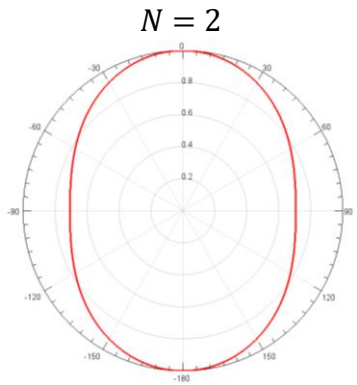


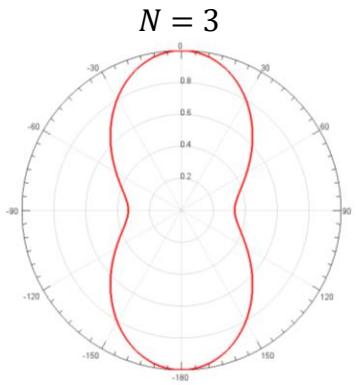
Array Factor of Uniform Antenna Arrays

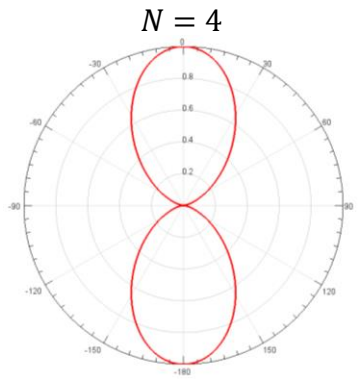
Effect of Number of Antenna Elements

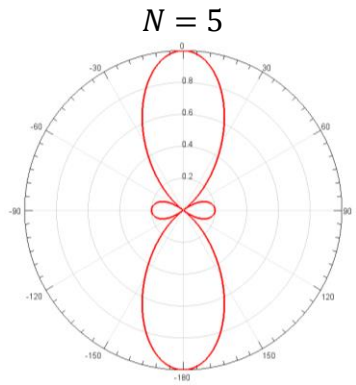
For an array with a fixed spatial separation between elements, increasing the number of elements similarly results in compression of the radiation pattern. The array factor patterns shown below have a fixed element spacing of $d = 0.25\lambda$, but a progressively increasing number of elements N.







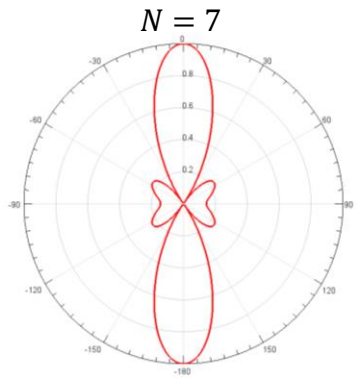


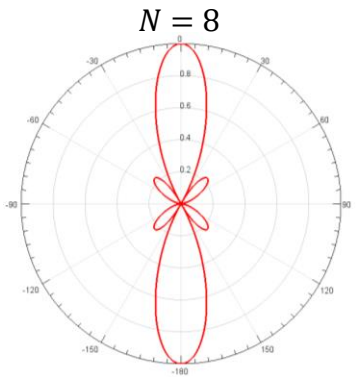


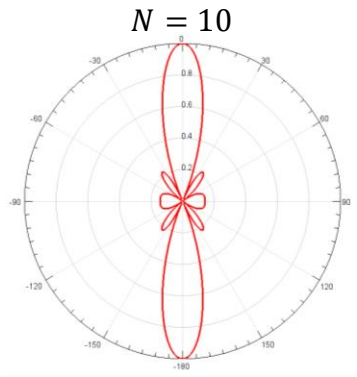
With:

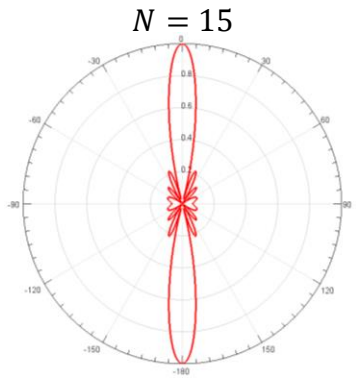
$d = 0.25\lambda$

$\psi = 0\ deg$





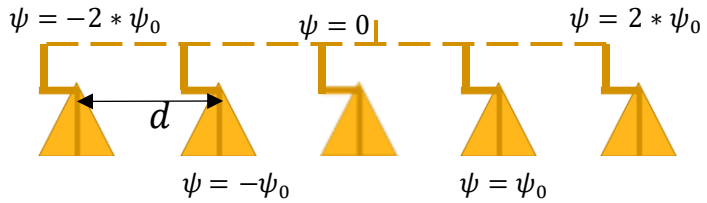




Array Factor of Uniform Antenna Arrays

Effect of linearly-stepped Phase difference between Elements

Another valuable control variable at our disposal is the linearly-stepped phase difference ψ between neighboring elements in the array. An array that utilizes such a variation in the phase of the driven signal is called a "**phased array**" and can be used to dynamically steer the beam without physically rearranging the elements.

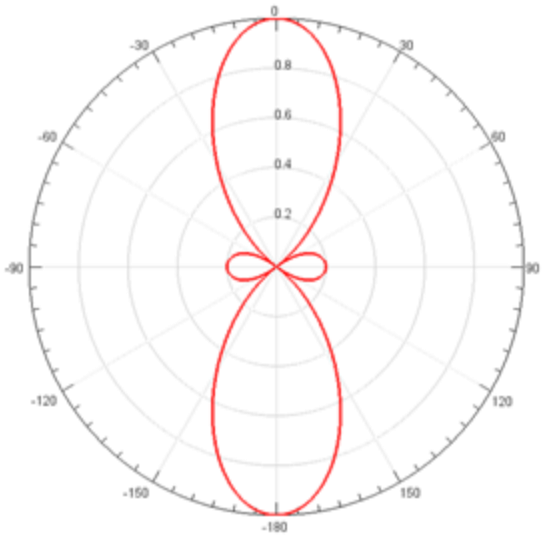


With:

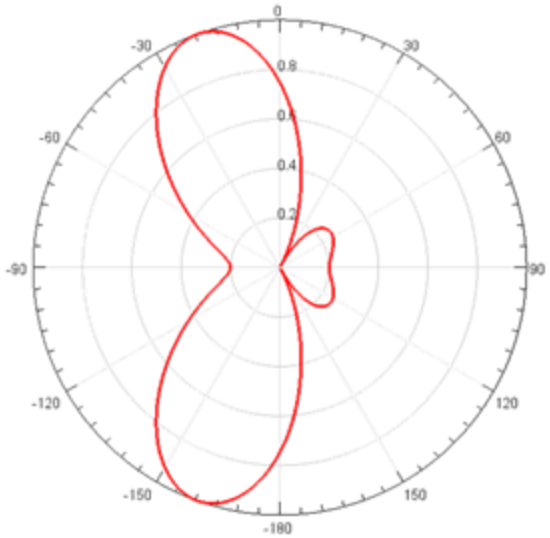
$N = 5$

$d = 0.25\lambda$

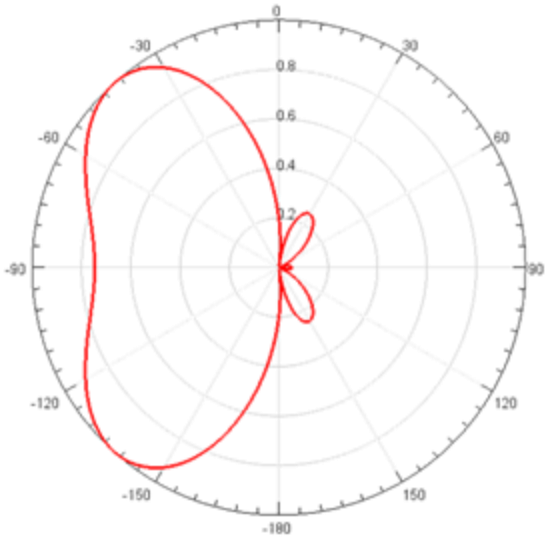
$\psi_0 = 0\ deg$



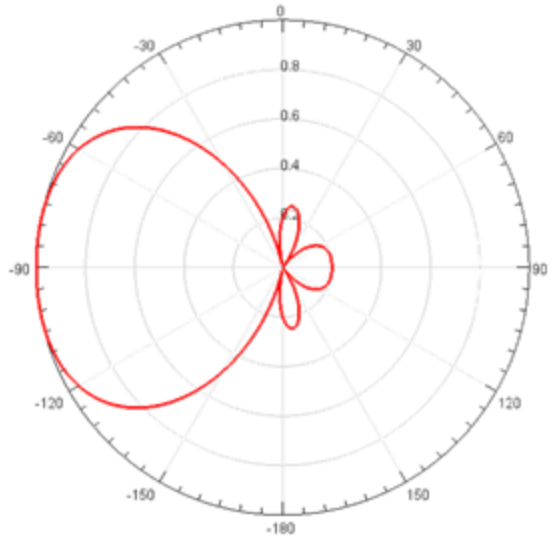
$\psi = 30\ deg$



$\psi = 60\ deg$



$\psi = 90\ deg$



Antenna Array - Exercise

Case: A uniform antenna array is used to steer the antenna beam and it is steered to an angle of 20 deg off boresight.

- Question 1 – Critical thinking:

Does this mean that each antenna element transmits energy mainly to that direction?

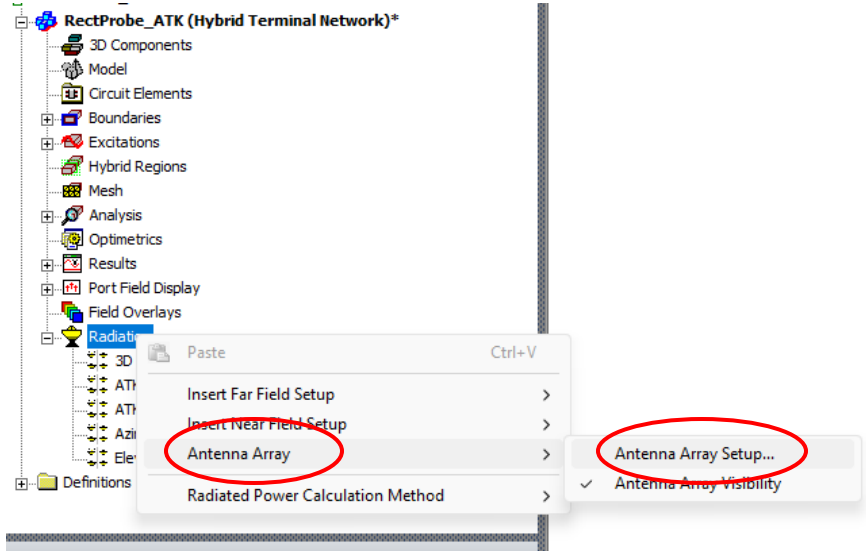
- Question 2 - Analysis:

The directivity of an antenna OR antenna array is measured by the angular opening of the 3dB beamwidth of the primary lobe.

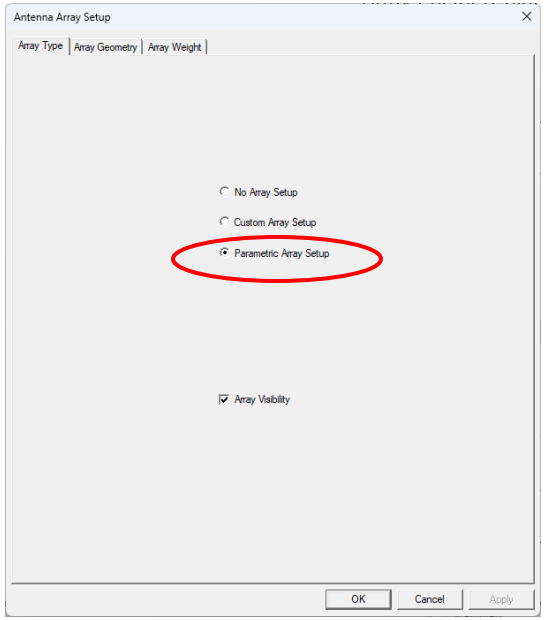
If the beam is steered, is the directivity affected?

HFSS Antenna Array tool - Intro

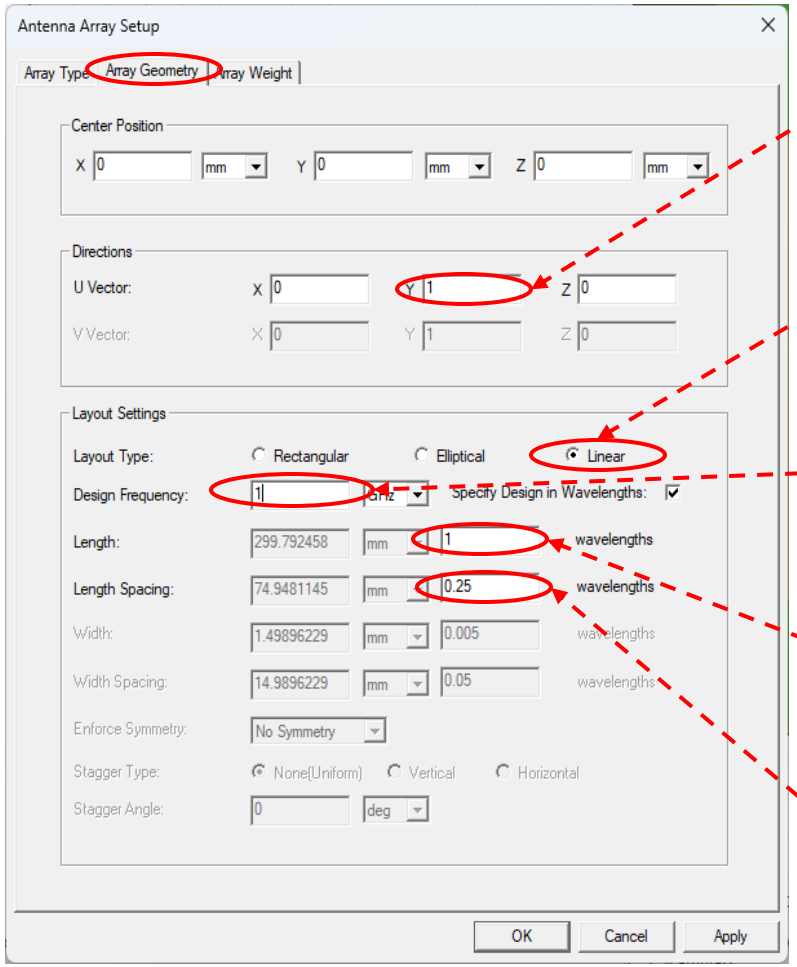
- An antenna array consists of multiple instances of a single antenna element.
- HFSS provides the ability to study the performance of an array having the single antenna performance. The radiation and the performance of the antenna array can be analyzed using the *Antenna Array* tool.



The *Antenna Array Setup* can estimate the radiation of an antenna array by using as single element radiation of the existing radiation of the antenna generated already. In a *parametric setup*, the array parameters can be defined, and the results will be updated without analyzing again the design and setup of the single antenna.



Array configuration



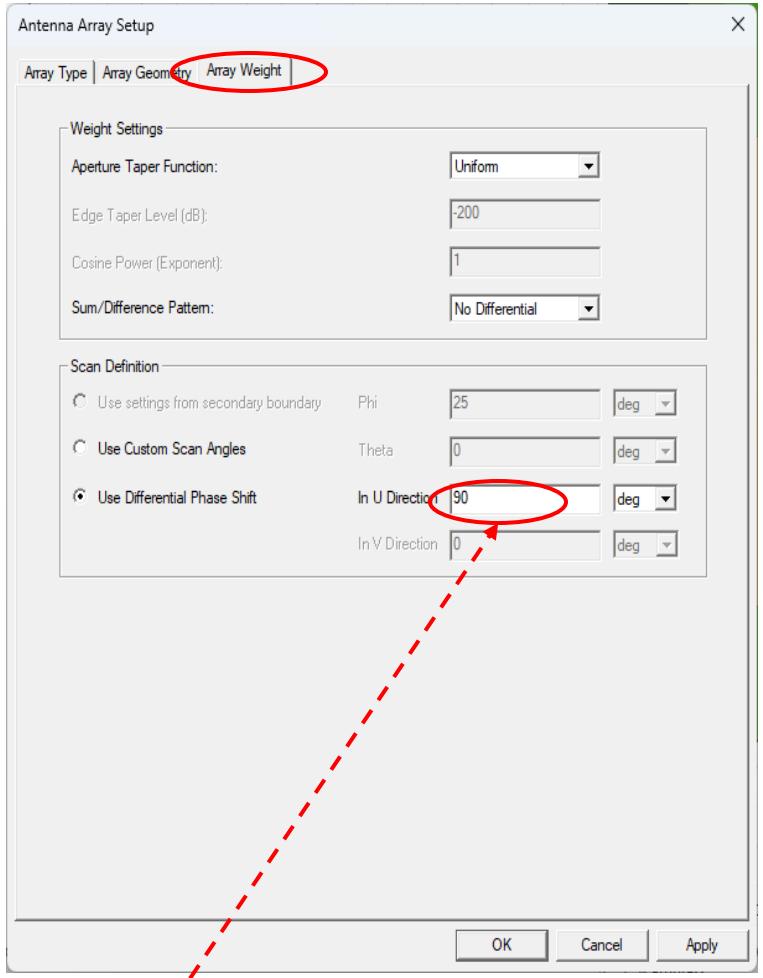
Array Axis

Array dimensions and shape

Reference frequency/wavelength

Total antenna dimension - length

Antenna element spacing

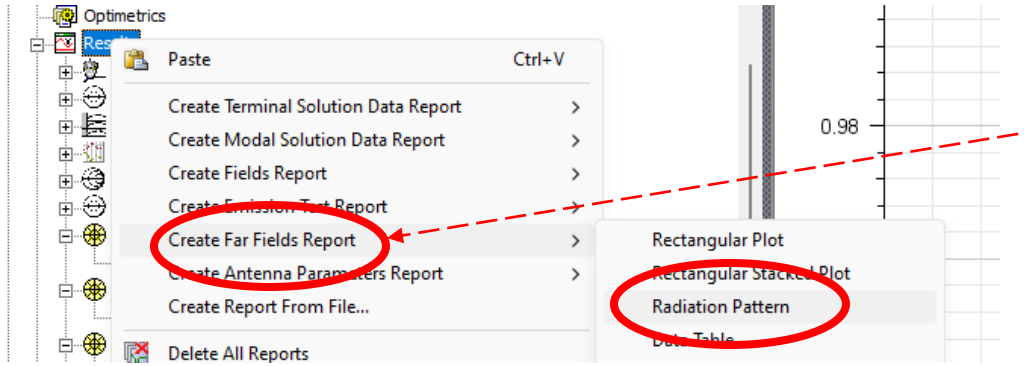


Linearly-stepped phase shift between antenna array elements

How to plot Array Factor (A)

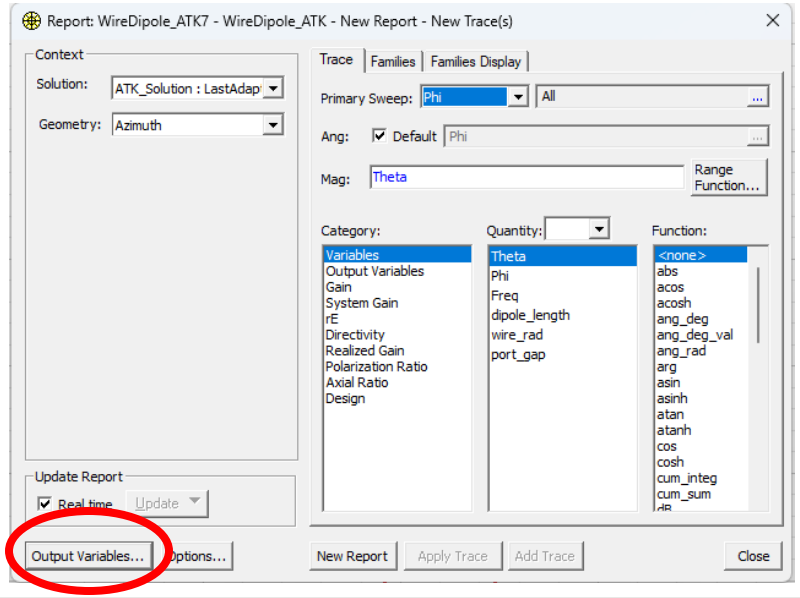
When using the array tool, the array factor can be plotted on ***Far Field plots*** (ArrayFactor vs Angle) using the below method.

1. Create Far Field plot

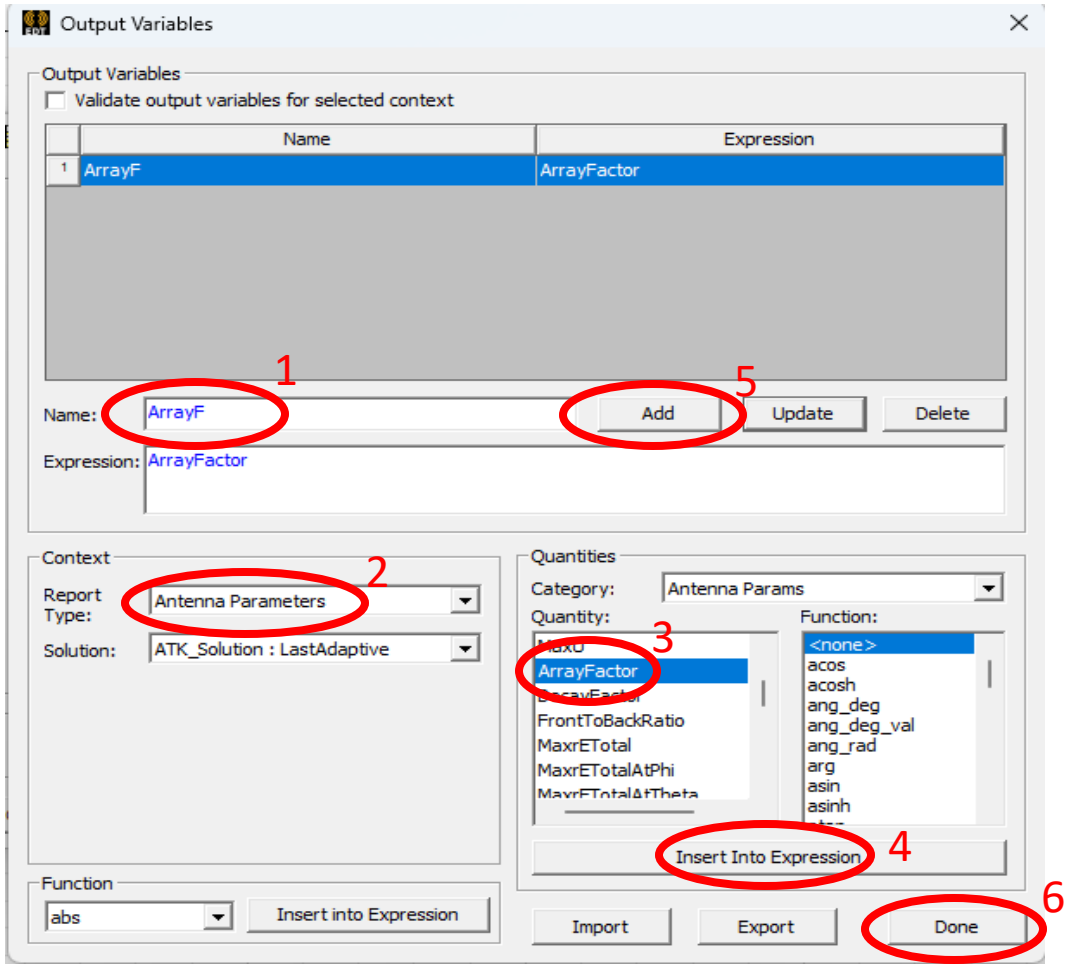


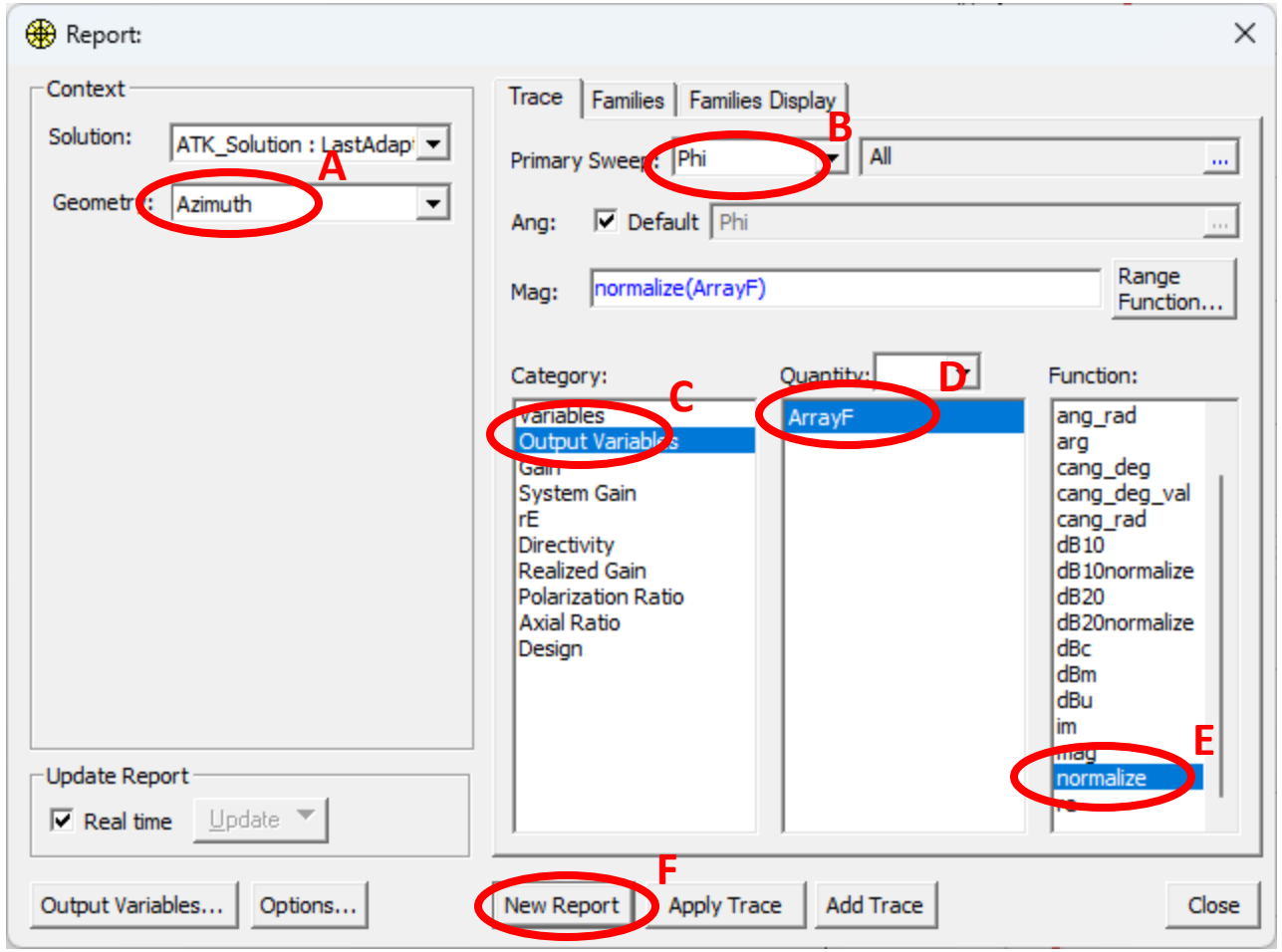
If the "*Far Field report*" option does not exist, a Radiation Surface needs to be defined

2. Create Variable



How to plot Array Factor (B)





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