Phased Arrays and Interference Mitigation

CORF Spring Meeting: May 9, 2025

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Phased Array Lead

Agenda

- Understand what is a phased array, why is it important, and how does it work

Topics:

- Phased Array Physics and Comparisons
- Phased Array Types and Architectures
- Characteristics: Array Size, Array Lattice, Element Spacing
- Interference Mitigation
- Links/References

Me

Brigham Young University, 1995-2004

- Integrated B.S. / M.S. Electrical Engineering
- Radio Astronomy Research Group
  - Thesis: Adaptive Nulling using Phased Array Fed Reflector
  - Advisors: Karl Warnick, Brian Jeffs

Mission for Church of Jesus Christ of Latter-day Saints

- Paraguay, 1996-1998

Joined Northrop Grumman (Space Park) 2004

- Antenna Products Dept (2004-2016), Comm System Engineering Dept (2016-)

Roles at Northrop Grumman:

- Antenna Lead and Phased Array Test lead on Comm Programs (AEHF, TSAT)
- Technical Lead/Program Manager on several Phased Array programs
- Proposal lead on several technology development programs
- Currently working as Business Development/Strategy Lead

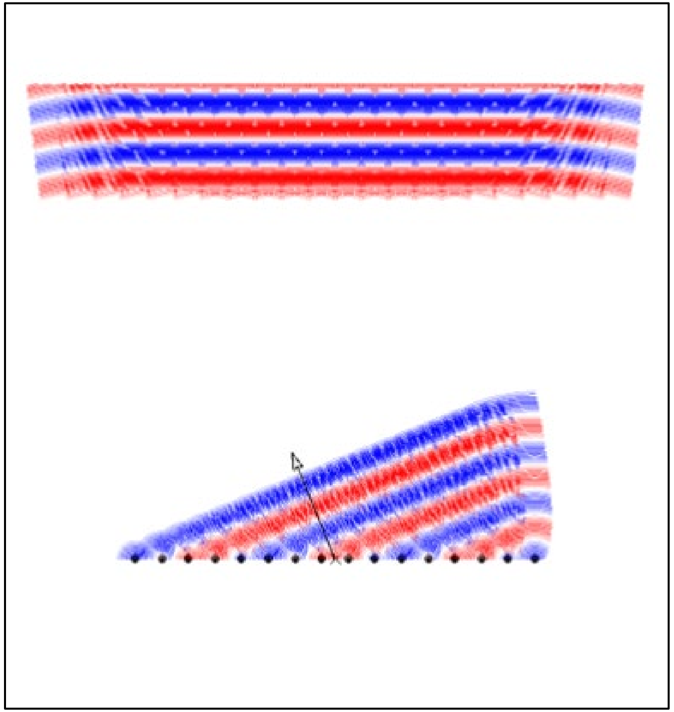
What is a Phased Array?

What is a phased array?

More than one source added together for purpose of "spatial filtering" is considered a phased array

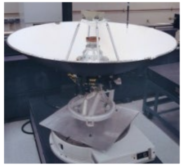
Phased array is essentially a "vector alignment"

- Planar Wave front calculations of weights is subset of "Conjugate Field Matching" Theory
- Different array configurations and methods may produce non plane wave fronts



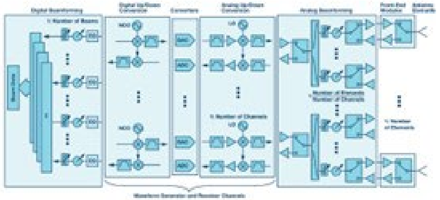
Reasons to use Phased Array over Reflector

- Multiple simultaneous coverage areas
- Rapid Scanning of beam over coverage area
- Dynamic shaping of coverage area



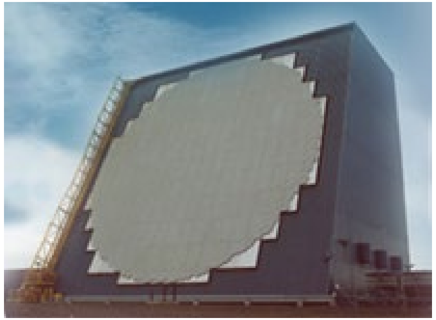
Phased Arrays are Complicated and EXPENSIVE!

- **Phased Arrays should be a last resort**
- **If you can get away without using one, Do!**

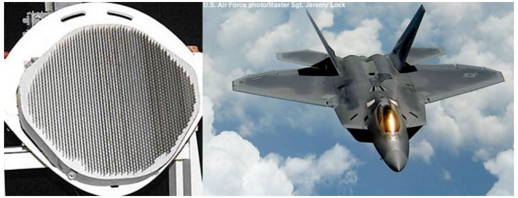


Why are phased arrays important?

- Agility of Phased Arrays enables superior capabilities
  - Multi-Target Tracking
    - Complete hemispherical search with automatic target selection and handover to tracking
  - Illuminate targets for missile guidance
  - Variable Search and Track Rates
  - Dynamic Bandwidth Assignment
  - Techniques for Low Observability
  - Anti-Jam
- Flexibility of Phased Arrays saves space
  - Multi-Function in One Aperture
    - RADAR Transmit and Receive
    - Monopulse Direction Finding
    - IFF (Identify Friend or Foe)
    - Communications
- Reliability of Phased Arrays reduces lifecycle costs



AN/FPS-108 Cobra Dane Radar System 1976



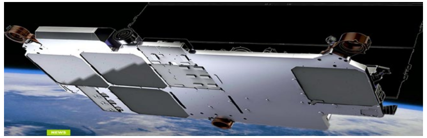
Northrop AN/APG-77 used on F22

Boeing-737 Airborne Early Warning and Control (AEWC)

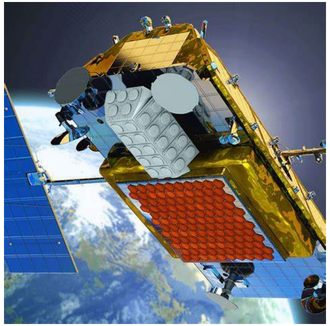
Examples of Phased Arrays

Military Comm – NG *AEHF*

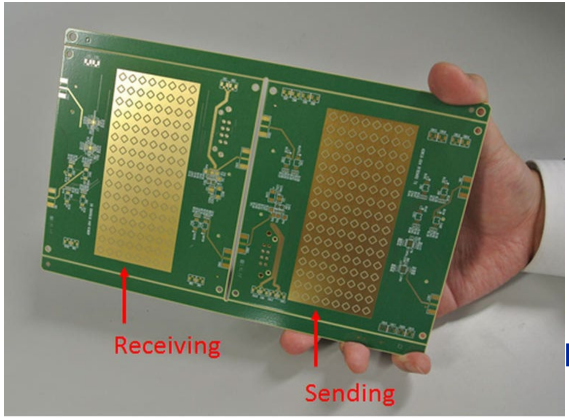
Commercial Comm - *Starlink*



Commercial Comm - *Iridium*



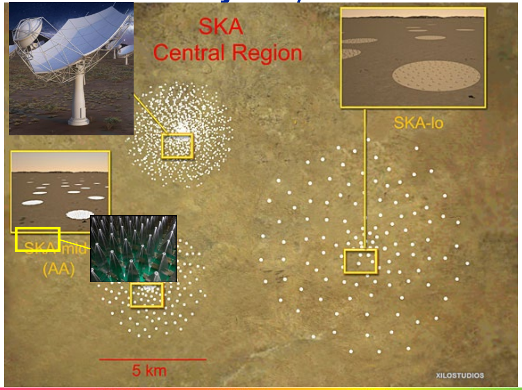
5G Antenna - *Fujitsu 10Gbps*



Radar: NG *F-35 Radar*

Space Tracking - *Space Fence Radar*

Radioastronomy - *Square Kilometer Array*



In the movies!

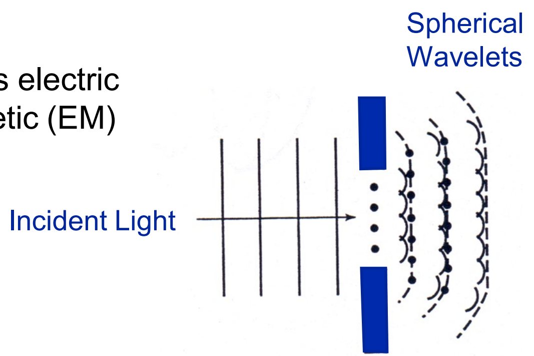
PAs Cover entire RF Spectrum!

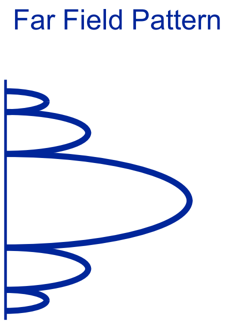
Introduction to Aperture Theory

- **Huygens' Principle** explained the diffraction of light waves around objects by viewing each point on a wavefront as a secondary source of spherical wavelets.
- Diffraction by an opening in a plane is explained using Huygen's Principle as shown:

Christiaan Huygens
1629-1695

Antenna:
Transformer that converts electric current into electromagnetic (EM) waves or vice versa.

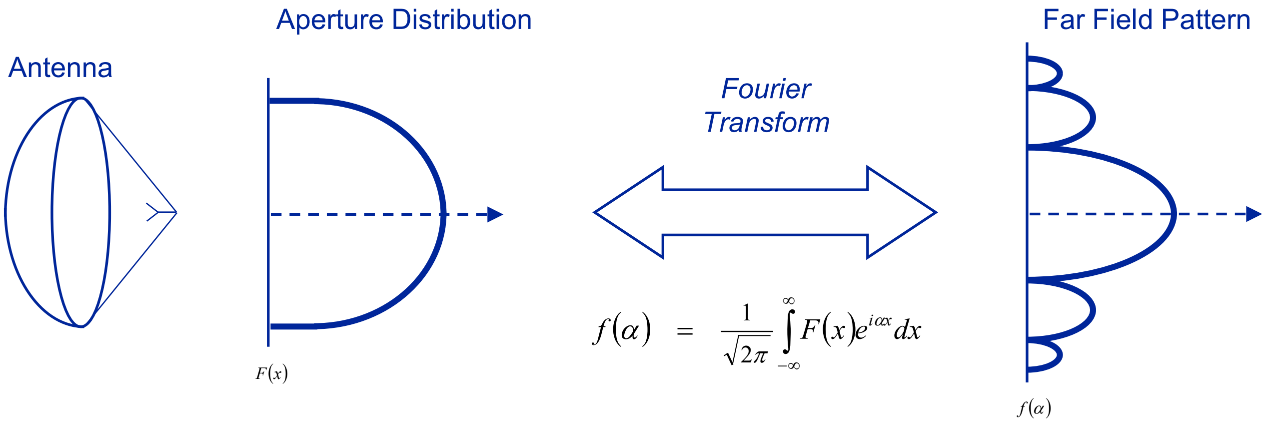




Far field pattern (Antenna pattern, radiation pattern):
The directional (angular) dependence of the strength of the radio waves from the antenna.

Introduction to Aperture Theory

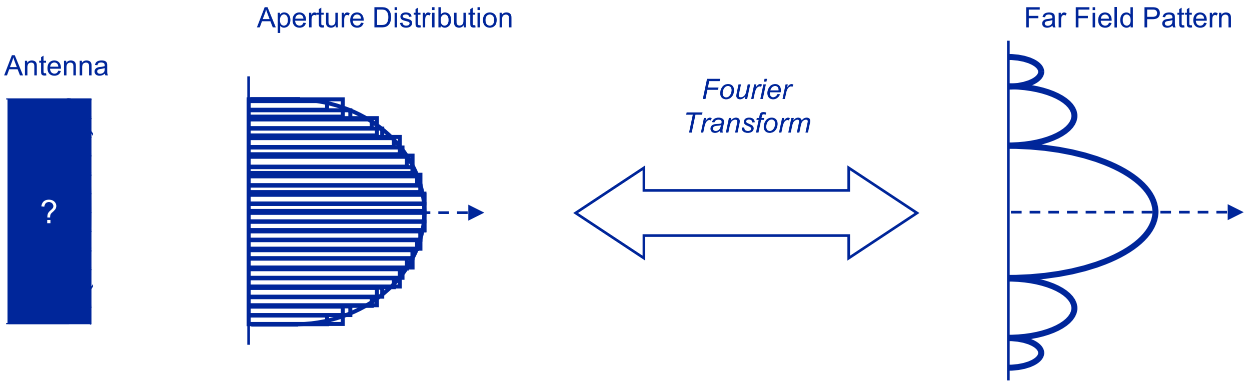
- Analysis of aperture antennas follows Huygens’ Principle.
- We determine the field pattern at the aperture (Aperture Distribution) and use it to calculate the Far Field pattern.
- Fourier Transform relationship:



$$f(\alpha) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} F(x) e^{i\alpha x} dx$$

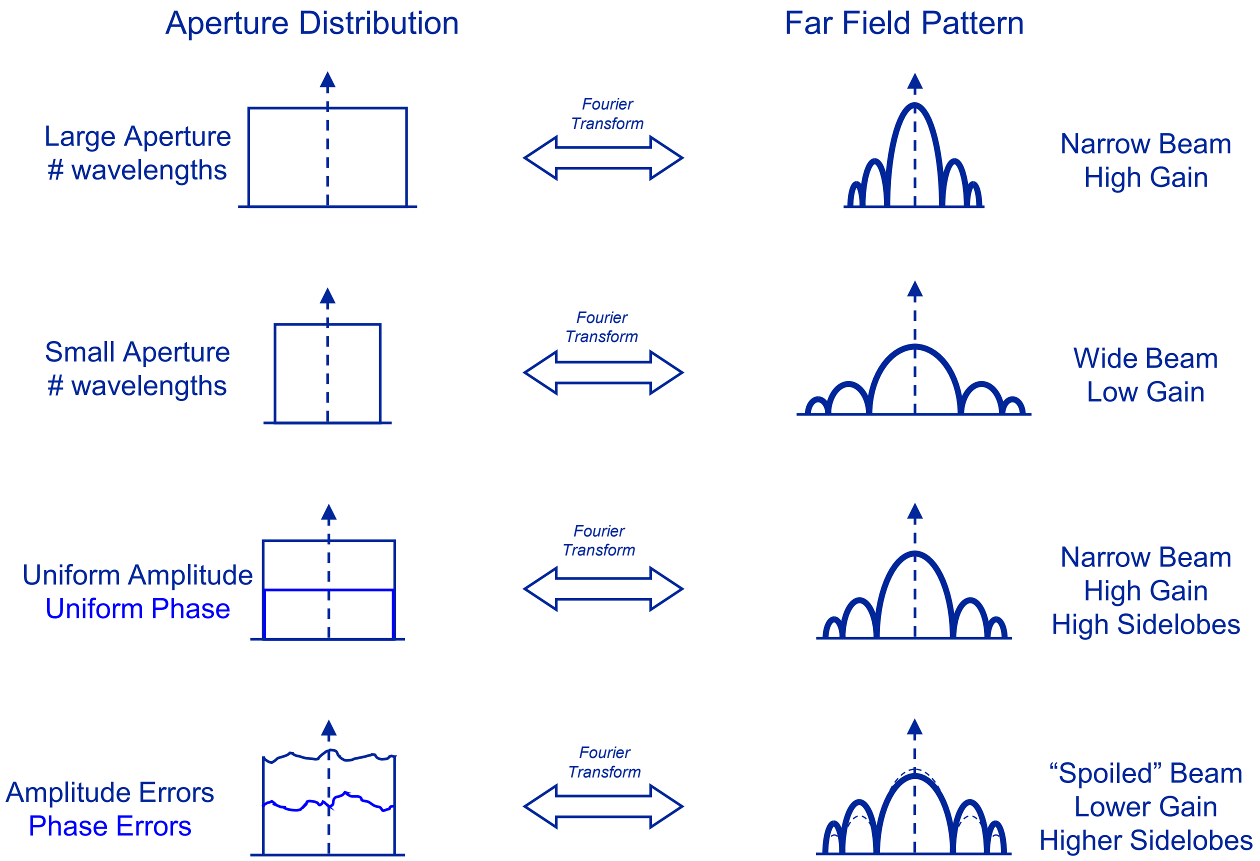
Introduction to Aperture Theory

- Antennas with identical Aperture Distributions will have identical Far Field Patterns

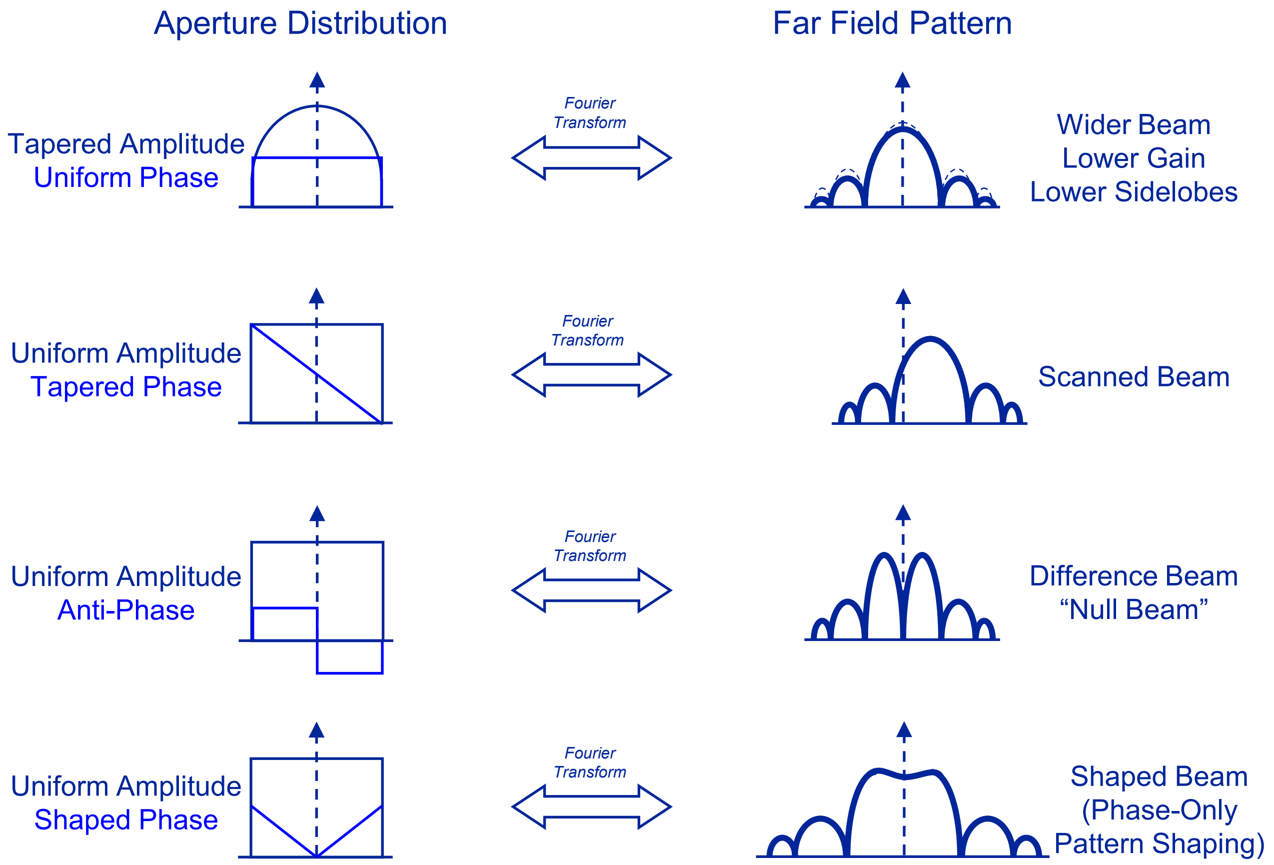


Phased Arrays make the Aperture Distribution programmable

Introduction to Aperture Theory



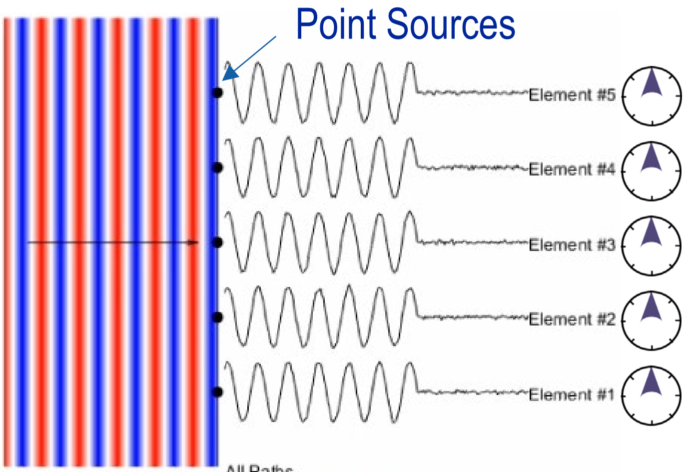
Introduction to Aperture Theory

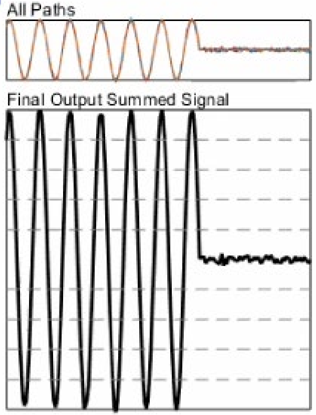


Wavefront and Vector Alignment

Wavefront Example - Broadside

Electromagnetic
Wave

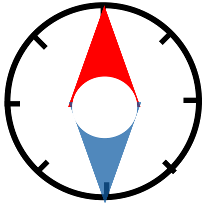




All Elements Simultaneously

Al Elements Final Summation
Final Beam Output

Element Phase Shifter Compass

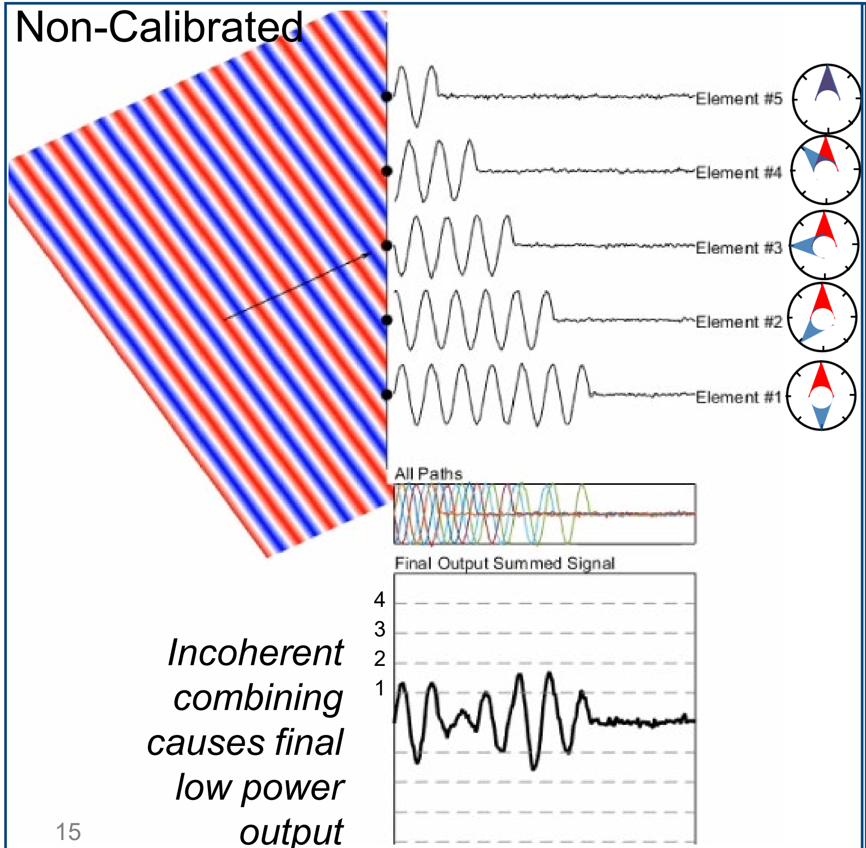


Element Phase Shifter Setting

EM Phase seen at element

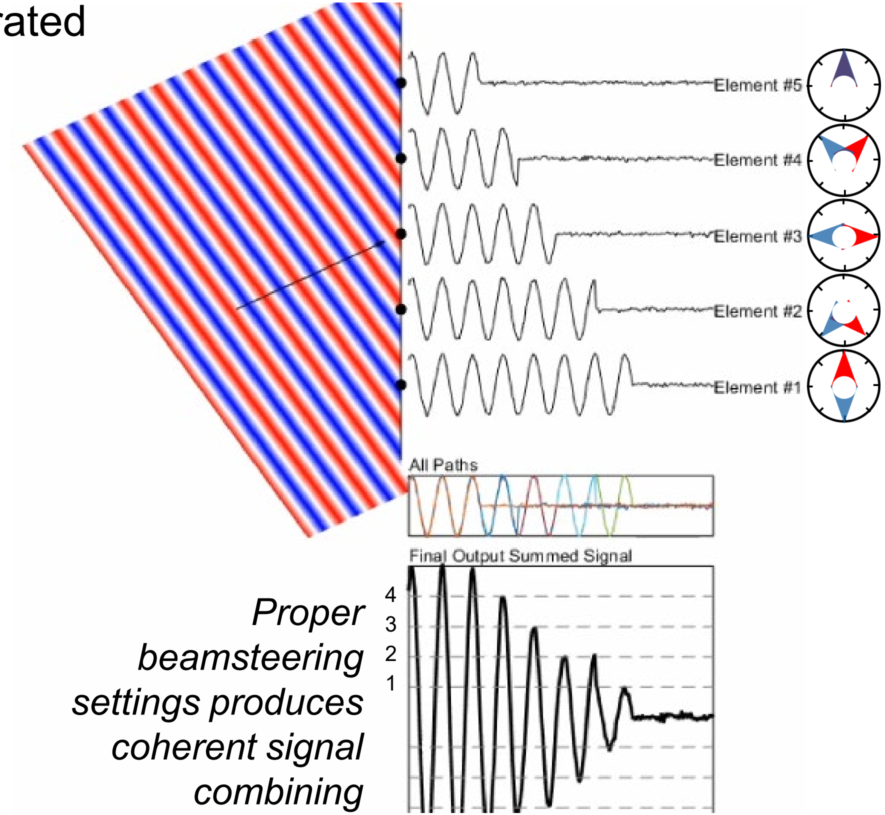
Wavefront Example – Off Axis

Non-Calibrated



Incoherent combining causes final low power output

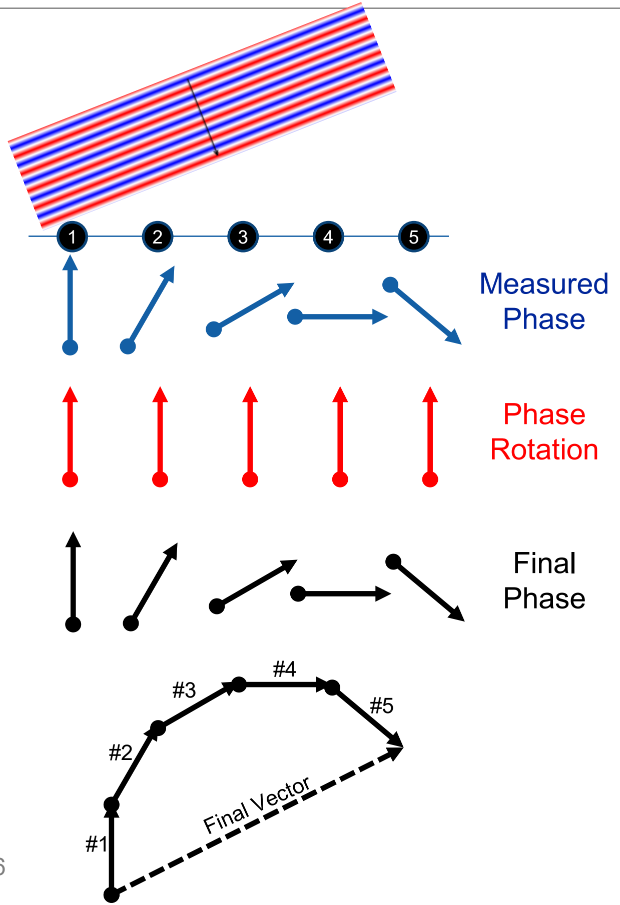
Calibrated

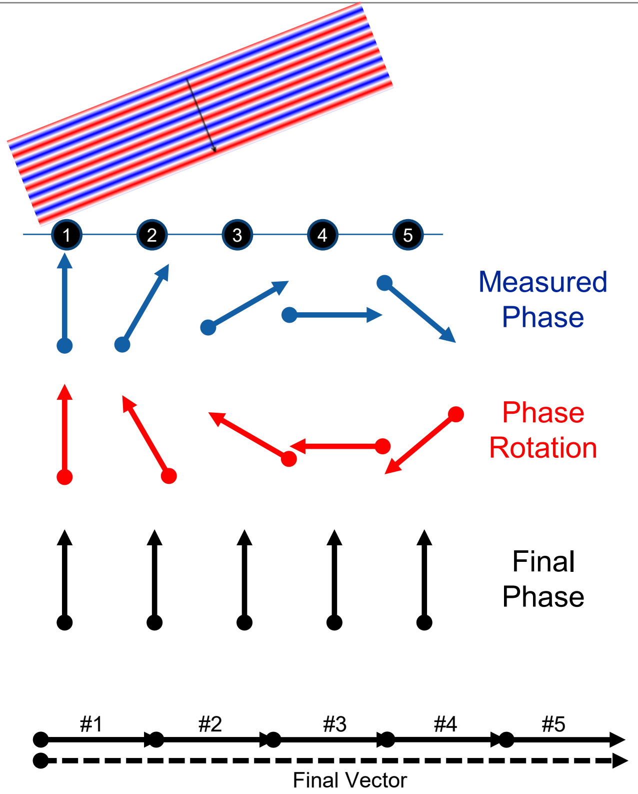


Proper beamsteering settings produces coherent signal combining

15

Phased Array - Vector Summer/Averager





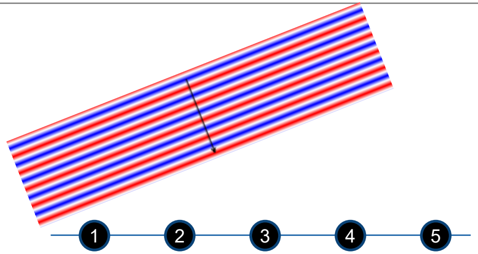
Graceful Degradation

1024 Element Example

Element Failure	ΔdB
1 (0.1%)	-0.004
2 (0.2%)	-0.009
4 (0.4%)	-0.02
8 (0.8%)	-0.03
16 (1.6%)	-0.07
32 (3.2%)	-0.14
64 (6.3%)	-0.28

Don't try to detect 1 element failure…just don't

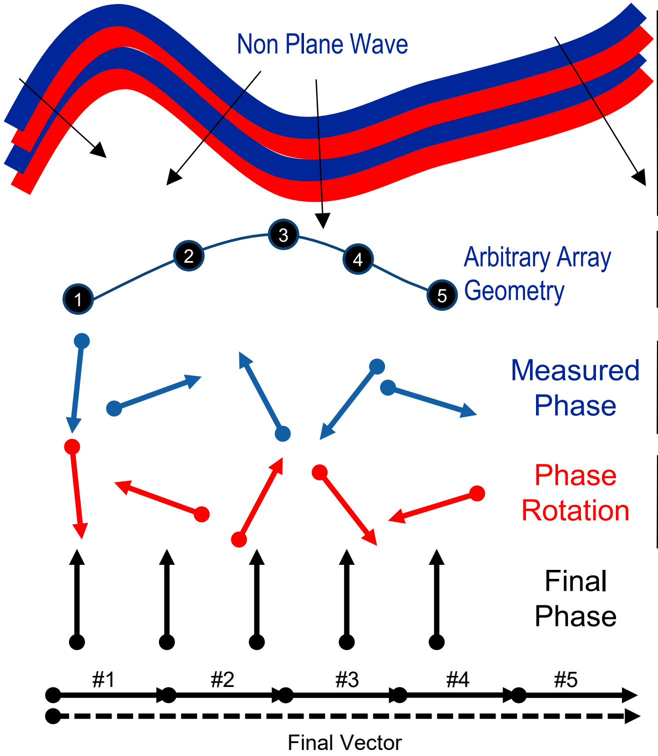
Phased Array – Conjugate Field Theory



Books will discuss phase weight settings for planar arrays under plane wave conditions…ideal

Must have knowledge of:

- Wave Direction
- Element centers
- Electronic paths
- Element patterns
- Mutual Coupling,etc, etc



Unknown incoming EM
- Reflections from Aircraft
- Nearfield of Reflector
- Unknown test environment

Elements in unknown spatial and rotational geometry

As Measured amp/phase contains all channel quantities needed

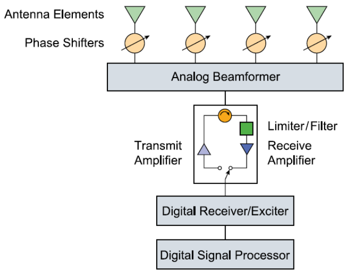
Proper phase shifters are conjugate of measured phase

Conjugate Field Match (CFM) generalizes and simplifies many real world issues

Phased Array Architectures, Types, and Characteristics

Active Electronically Scanned Array (AESA) Architectures
AESA Technology Evolution Over Time… Passive → Active → Digital

1

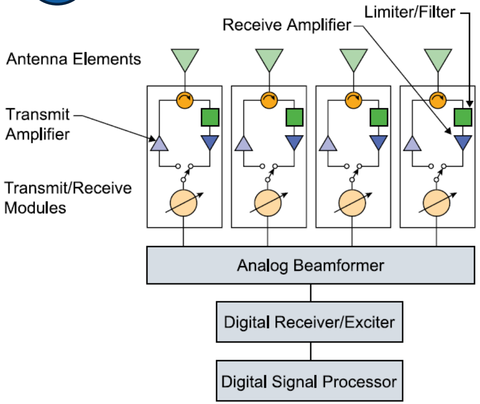


<u>Analog Passive</u> Phased Array (Analog PESA)

Primarily in Older Radars Systems, Uncommon Today

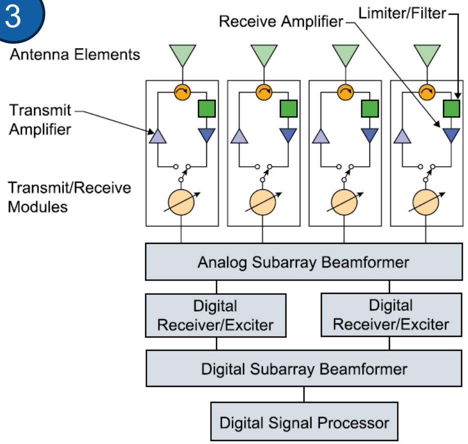
- Single Beam
- Lower DC-RF Efficiency

2



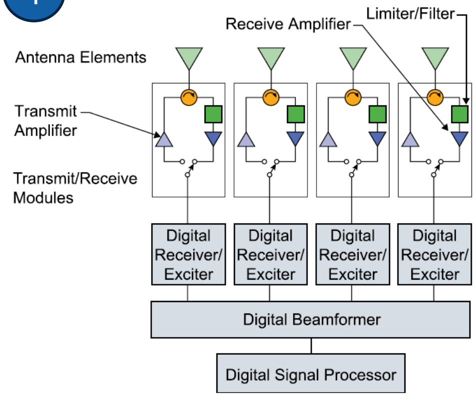
<u>Active</u> Phased Array (Analog AESA)

3



<u>Active</u> Subarray <u>Digital</u> Array (Subarray <u>Digital</u> AESA)

4



<u>Active</u> Elemental <u>Digital</u> Phased Array (Elemental <u>Digital</u> AESA)

Digital Beamforming (DBF)

Today's Primary "Workhorse" AESA Architectures. These Architectures Deliver Significant Capability and Meet the Needs for Most of Today's Missions.

- A Few Simultaneous Beams (Possible) via Multiple Analog RF Manifolds

- Many Simultaneous Beams (Over Limited FOV)
- DBF Addresses Beam Squint (No Time Delays)

Primarily Development AESAs… Some Fielded Systems for Comm Applications

- Many Simultaneous Beams (Over Full FOV)
- DBF Addresses Beam Squint (No Time Delays)

~1970 ~1990 ~2000 ~2015

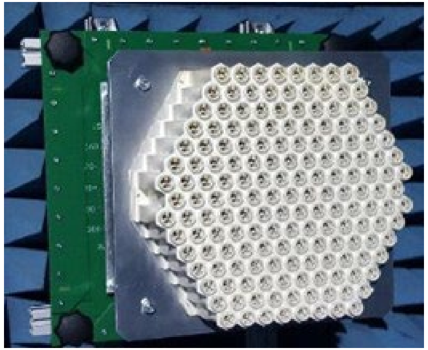
All 4 Block Diagrams are Courtesy of J. S. Herd and M. D. Conway, "The Evolution to Modern Phased Arrays," in *IEEE Proceedings 2016*.

Phased Array Types

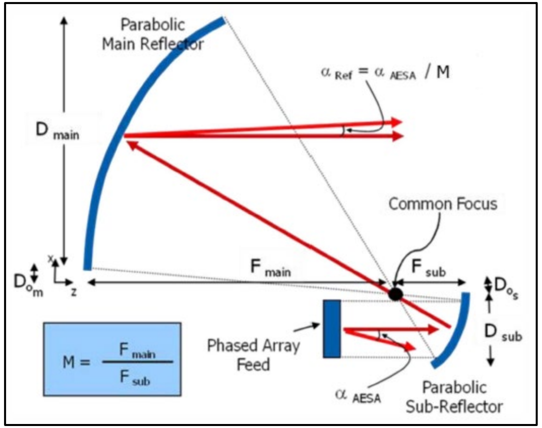
- 2 main types of Phased Arrays
- Direct Radiating Array (DRA) (Focus Today)
- Phased Array Fed Reflector (PAFR)
  - Phased Arrays can be combined with reflectors to overcome limitations of both systems
  - Confocal Reflector Systems
    - Reflector acts as a lens providing magnification
    - Utilizes nearfield region of phased array to scan beams
    - Requires phased array to be in “near field” region
  - Phased Array Fed Reflectors
    - Phased Array required extensive beamshaping algorithms
    - Phased array acts like “matched filter” to incoming wave
- Multi-beam Antenna (MBA) are often mixed up with Phased Array Fed Reflectors
  - Key difference is the multiple beams are not combined
  - Usually got through switch matrix with multiple receivers

DirecTV MBA Receiver

ESA DRA



Confocal PAFR



Pattern Multiplication

Fourier Transform produces this useful result

$$f(\theta,\phi) \times \sum_i a_i e^{jk\mathbf{r}_i \bullet \hat{\mathbf{r}}} = E(r,\theta,\phi)$$

Element Pattern × Array Factor = Antenna Pattern

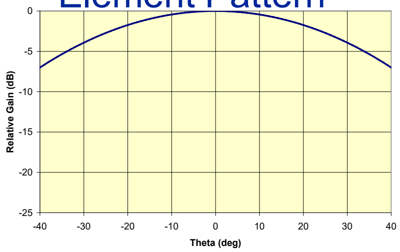
Depends only on the element characteristics

Depends only on the element locations (grid) and relative weightings

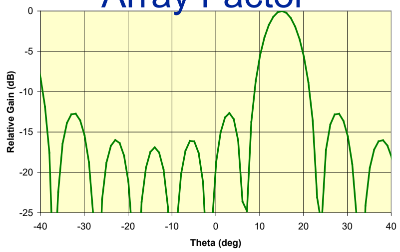
$$AF = \sum_{n=1}^{N} I_{n1} \left[\sum_{m=1}^{M} I_{m1} e^{j(m-1)(kd_x \sin\theta \cos\phi + \beta_x)} \right] e^{j(n-1)(kd_y \sin\theta \sin\phi + \beta_y)}$$

*Farfield Pattern is the amount of Received/Transmitted Energy in a given direction

Element Pattern



Array Factor



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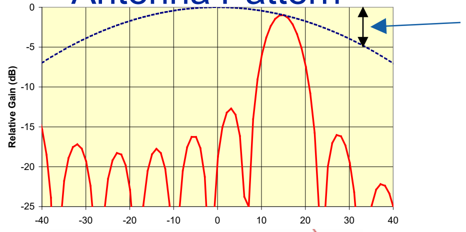
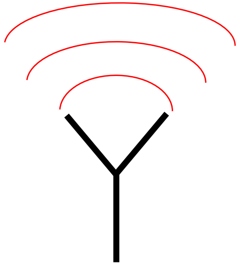
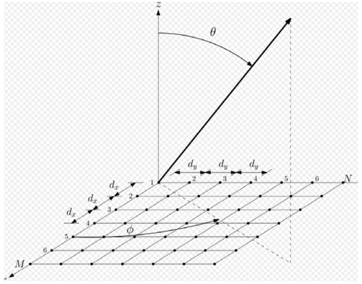
Antenna Pattern



Scan Loss from Element Pattern



X



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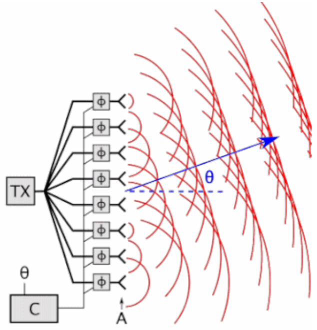
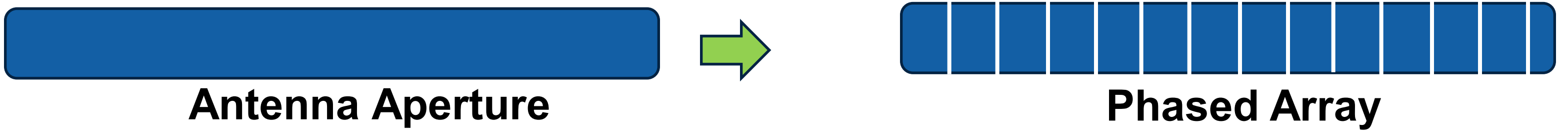
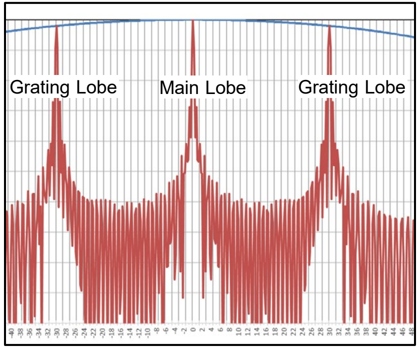


Element Spacing and Grating Lobes



- A Phased Array essentially breaks up the aperture into smaller chunks (elements)
- Two main factors affect element spacing: Maximum Scan angle and Bandwidth
- The aperture is ‘sampled’, similar to Digital Signal Processing sampling rate
- Greater than Nyquist element spacing (λ/2) causes grating lobes
  - In practice the element spacing is adjusted per the max scan angle required
  - Ex: In GEO orbit, using λ/2 spacing will over design system, increasing cost
- Grating Lobes are NOT Sidelobes, but have a similar structure to SLL
  - They have different effects on the overall system
  - Grating Lobes may be acceptable if they are outside the Field-of-View (FOV)
    - Ex. GEO arrays often use ~2.8λ which places GLs just off Earth for a scanned beam



- Regarding Bandwidth, typically larger bandwidth → Smaller element spacing
  - Smallest element spacing is usually λ/2 at the highest frequency

Array Size

Array Gain based on physical area collected/transmitted with array and frequency

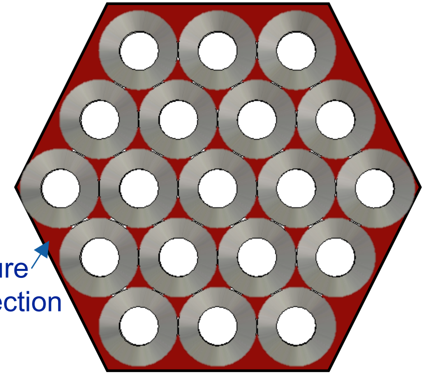
$$D_{pa} = D_A = D_e + 10\log_{10}(N)$$

As antenna systems become more directive with increased area or frequency the beamwidth decreases

$$HPBW \cong 60\,{}^{\lambda}/_{Diameter}$$

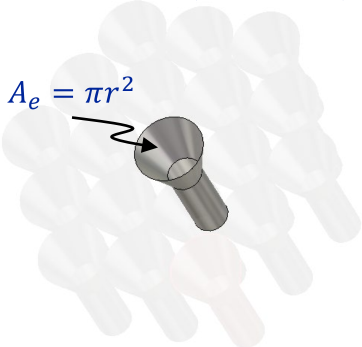
Larger Diameter/λ = Higher Array Gain

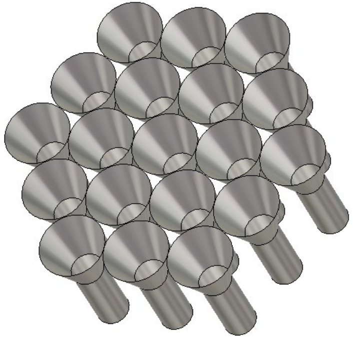
$$D_{pa} \cong 10\log_{10}\left({}^{4\pi A_{pa}}/_{\lambda^2}\right)$$



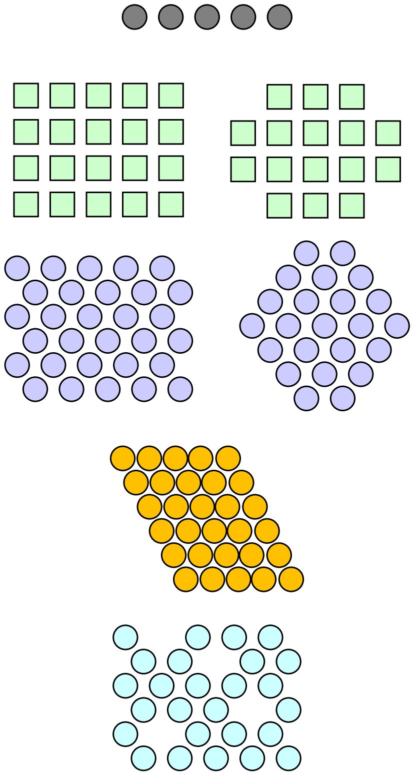
A_e: Effective Aperture Area

$$D_e = 10\log_{10}\left({}^{4\pi(A_e)}/_{\lambda^2}\right) \qquad D_A = 10\log_{10}\left({}^{4\pi(NA_e)}/_{\lambda^2}\right)$$





Element Lattice



Periodic

- <u>Linear</u>
  - Scanning in one direction
- <u>Rectangular lattice</u>
  - Simplest, Easier BFN
- <u>Triangular lattice</u>
  - Fewer elements for same Array Gain
  - Complicated Aperture to BFN routing
- <u>Platform lattice</u>
  - Low RCS

Aperiodic

- <u>Thinned or Random arrays</u>
  - Reduces Grating Lobes

When to Use a Phased Array

- Phased Arrays are much more expensive than other types of antennas
- Only used when your application requires the unique features of arrays

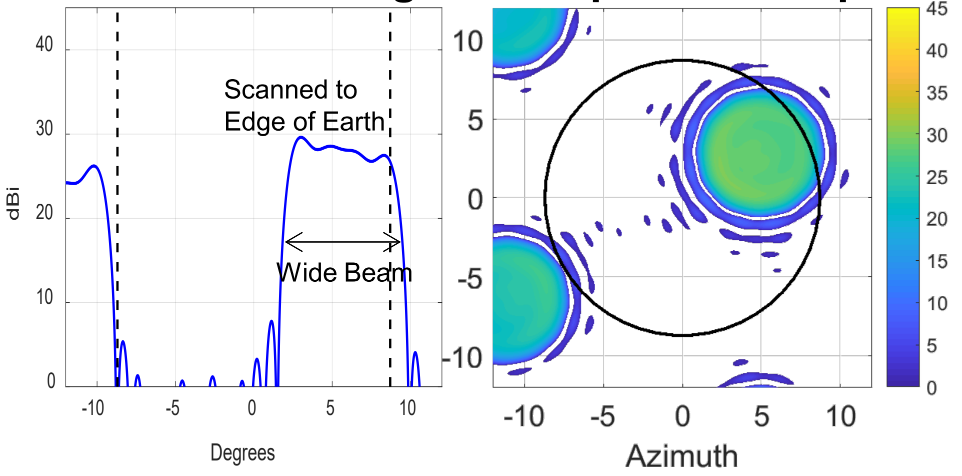
Feature	Benefits
Electronic Switching	Agility (Fast Reconfiguration) Reliability: No Moving Parts
Programmable Aperture Distribution	Flexibility - Change the Scan Angle on Command - Change the Beam Shape on Command
Possible to Form Multiple Simultaneous, Independent Beams	Save Space (All-In-One Aperture) Increase Capacity Multi-Function Systems
Constructed of Many Building Blocks (Elements)	Form Factor - Conform to odd shapes and surfaces - Low Profile / Flush Mount Convenient to make large antennas from simpler elements - Very Large Apertures - High RF Power from Low Power Amplifiers - Efficiency (Amplifiers close to the elements) Reliability: Graceful degradation if elements fail

Beam Shaping and Interference Mitigation

Beam Scanning & Beam Shaping

- Phased arrays have a unique capability in that they can quickly change the beam location and/or the beam shape
- Beam location/shape adjustment determined by speed of phase shifter electronics (Often just a few ms or even μs)
- Beam shape can be adaptive (using a Digital Array) or can have a fixed shape
- Adaptive Array can require significant processing needs depending on # of elements
- Several algorithms available to shape phased array beams
- Shapes can be of arbitrary shape or size
  – Ex: CONUS Shape, Isoflux pattern (GPS)

Beam Scanning & Flattop Beam Shape



Interference Mitigation with Phased Arrays

- Adaptability of Phased Arrays makes them ideal for interference mitigation

Interference Mitigation Options:

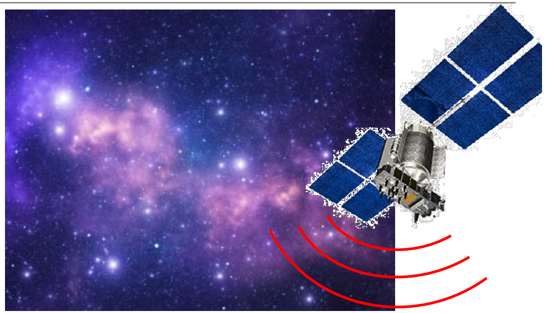
- Frequency Channels can be turned off or be unused in known interferer bands

  → Requires Adaptive Receiver/Transmitter

- Pattern Nulls can be placed in known interferer directions
  - Algorithms can place nulls in multiple locations
  - Have N-1 degrees of freedom where N=Number of Elements
- Adaptive Interference Mitigation can be used if exact Interferer location/frequency is unknown

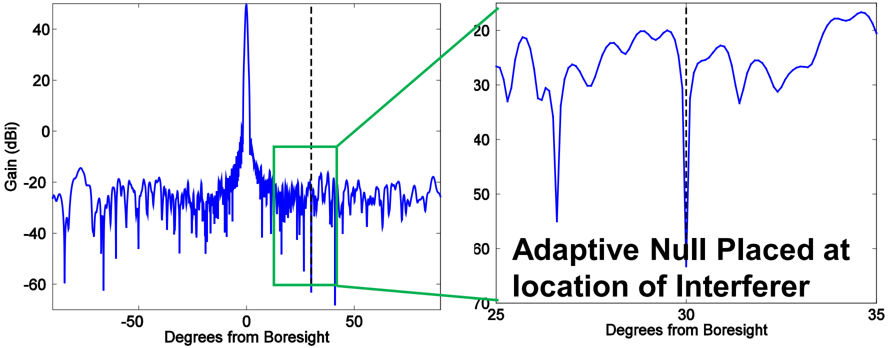
  → Requires Digital Array

- <u>Some SNR performance degradation is expected</u>
- Several research groups involved (i.e. BYU Astronomy Group)



Interference Mitigation Options

- Best type of interference mitigation is <u>cooperative</u>: SpaceX Starlink Example
  - "the company developed software that's both smart and fast enough to fine-tune the satellite radio transmissions. "SpaceX will leverage efficient beam-planning software to ensure that its . . . radio signal operations do not cause in-band or cross-border interference" – PCMag 2023
  - "the teams from SpaceX and NRAO have developed techniques that enable Starlink satellites to <u>avoid transmissions into the line-of-sight of radio telescopes</u> by leveraging Starlink's advanced phased array antenna technology, which can <u>dynamically steer satellite beams away from telescopes in milliseconds</u>. These techniques are made possible by a <u>real-time data sharing</u> framework between radio astronomy observatories and Starlink that provides the Starlink network with a telescope's planned observation schedule, including the telescope's pointing direction (aka "boresight") and its observed frequency band." https://www.starlink.com/public-files/Telescope_Boresight_Avoidance.pdf
- When cooperation is not achievable, nulling algorithms can be used
- Algorithms available for both known and unknown interferer locations
- Example adaptive nulling with PAFR (25m dish)



Interference Mitigation Algorithms

- Several algorithms have been used with phased arrays, both as DRAs and as PAFs
  – Simpler Post-processing algorithms can be used, but require significant high data rate recording
  – Some algorithms can use auxiliary antenna (or beam) pointed at interferer to improve performance

Array Nulling:

- Sidelobe Cancellation algorithms: Simple algorithms used with a known interferer location
  – Difficult to use if sidelobe structure has significant variation (ex. GBT)
  – Matlab Tutorial: “Array Pattern Synthesis Part I: Nulling, Windowing, and Thinning”

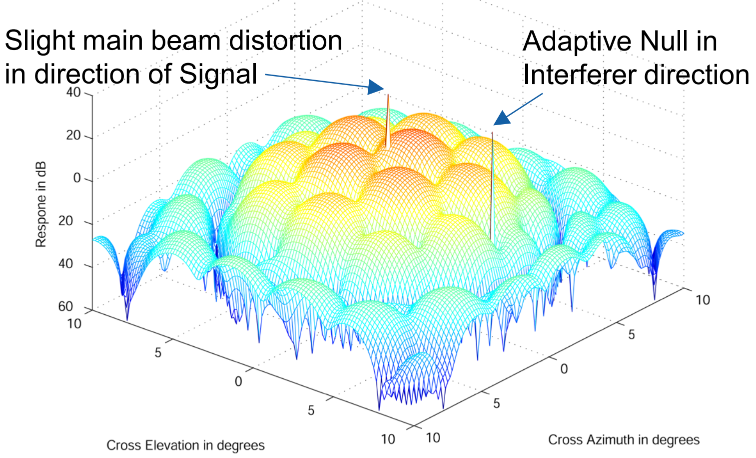
Adaptive Beamforming/Nulling:

- Can be used with real-time processor
  – Eliminates need for large data storage
- Adapts to interferer location and power levels

Example Algorithms

– GSC: Generalized Sidelobe Canceller
– MSC: Multiple Sidelobe Canceller
– SPSN: Subspace projection spatial nulling
– LCMV: Linear Constrained minimum variance
– MSNR: Maximum Signal-to-noise Ratio

Adaptive Null Example



BYU URSI 2002

Summary

- Phased arrays are complicated/expensive and should only be used as a last resort
- Important phased array characteristics include size, element spacing, and architecture
- Phased arrays are versatile and can be reconfigured to quickly steer beams or change beam shape
- Phased Arrays can be used for Interference mitigation, both as DRAs and PAFRs
- Phased Arrays are AWESOME!
- Did not cover many topics:
  - Nonlinearities analysis
  - Transmit phased array (EIRP)
  - Digital phased array
  - Phased Array Processing
  - G/T and Noise Figure
  - Electronics and MMICs
  - Multiple Beams/Carriers
  - Assembly and Manufacturing
  - Array Calibration and Test
  - Polarization
  - Gain Budgets
  - Adaptive Array Processing
  - Cost
  - Reliability
  - Brick vs Tile Architecture

Links/References

- [Phased Array Antenna Handbook, Second Edition (Artech House Antennas and Propagation Library) 2nd Edition]()
- [Phased Array Antennas by Robert Hansen]() ***I used tell people he's my uncle to get street cred. . .***
- [Phased Array Antennas by Arun Bhattacharyya]()
- M. Cooley, “Phased Array Fed Reflector (PAFR) antenna architectures for space-based sensors,” 2015 IEEE Aerospace Conference , Big Sky, MT, 2015.pp. 1-11
- J. J. Lee, "G/T and noise figure of active array antennas," in *IEEE Transactions on Antennas and Propagation*, vol. 41, no. 2, pp. 241-244, Feb. 1993, doi: 10.1109/8.214619.
- J. S. Herd and M. D. Conway, “The Evolution to Modern Phased Arrays,” in IEEE Proceedings 2016.
- *http://www.antenna-theory.com/basics/main.php*
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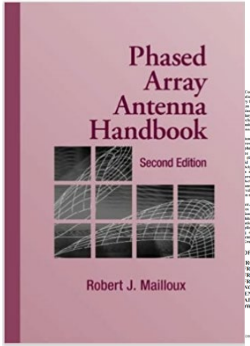


Phased Array-Fed Reflector (PAFR) Antenna Architectures for Space-Based Sensors