Ingegneria delle Telecomunicazioni

Satellite Communications

11. Beep-Beep-Beep – Antennas

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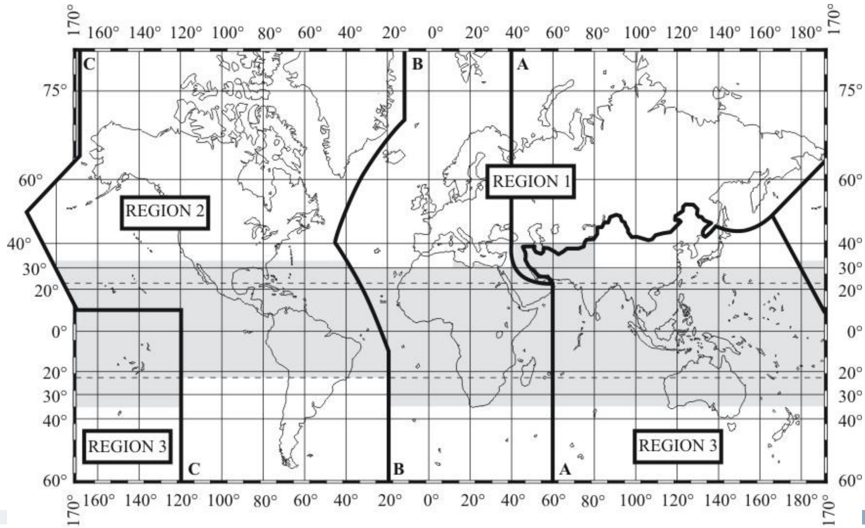
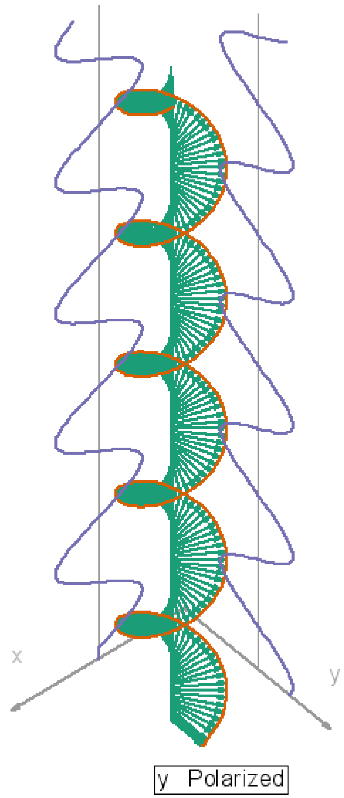
Polarization for dummies 1/3

- **Polarization orthogonality enables frequency reuse:**
    - Linearly polarized fields require polarisation alignment
    - Circularly polarized fields usually lead to more complex designs
- **Cross-polarization results in interference and needs to be minimised**
- **Polarization may vary across ITU regions for a given service**

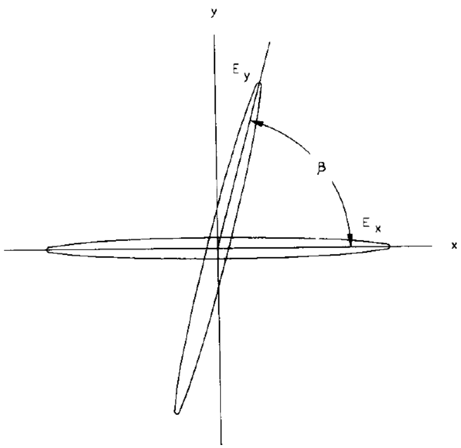




Polarization for dummies 2/3

- Any electromagnetic field may be decomposed into dual-linearly or dual-circularly polarized signals with co- and cross-polarization components

$$\boldsymbol{E} = (E_{co}\mathbf{co} + E_{cx}\mathbf{cx})e^{-jkz}$$



Linear Polarization (LP)

- *HP (x-axis)*: $\mathbf{co} = \hat{x}$, $\mathbf{cx} = \hat{y}$
- *VP (y-axis)*: $\mathbf{co} = \hat{y}$, $\mathbf{cx} = \hat{x}$

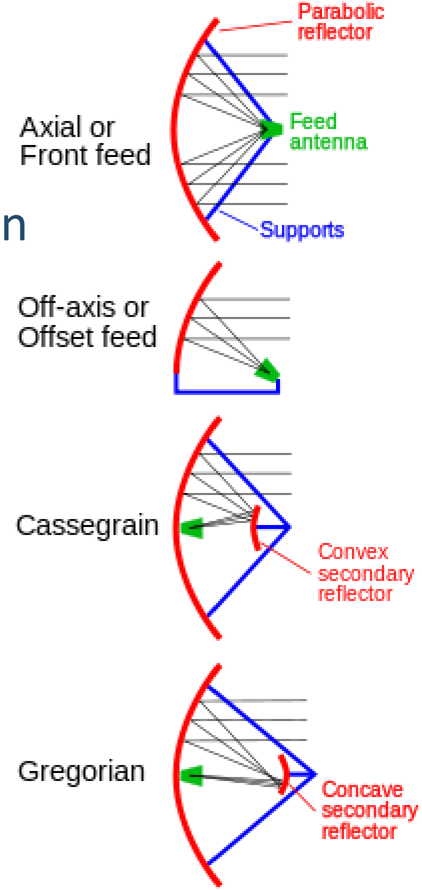
Circular Polarization (CP)

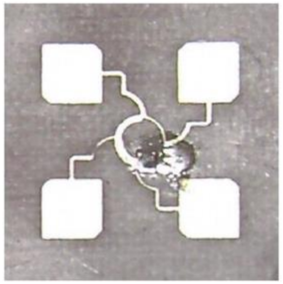
- *RHCP*: $\mathbf{co} = (\hat{x} - j\hat{y})/\sqrt{2}$, $\mathbf{cx} = (\hat{x} + j\hat{y})/\sqrt{2}$
- *LHCP*: $\mathbf{co} = (\hat{x} + j\hat{y})/\sqrt{2}$, $\mathbf{cx} = (\hat{x} - j\hat{y})/\sqrt{2}$

- Polarization mismatch losses account for differences in polarization "purity" at transmitter and receiver antenna level

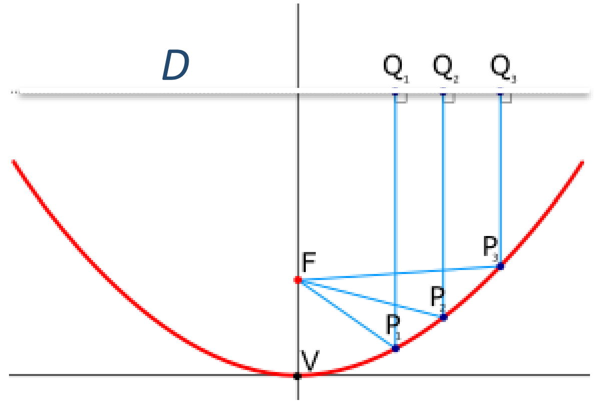
Polarization for dummies 3/3

- In composite antenna system, the polarization is usually generated at the feeding point:
  - At element level in array antennas
  - At feed level in reflector antennas
- Some techniques may be applied to reduce cross-polarization at antenna level (e.g. sequential rotation in array antennas, increased focal length in offset single and dual reflector geometries, use of a gridded/polarization selective screen)
- Polarization screens or reflective surfaces may also be used to transform LP into CP or vice versa





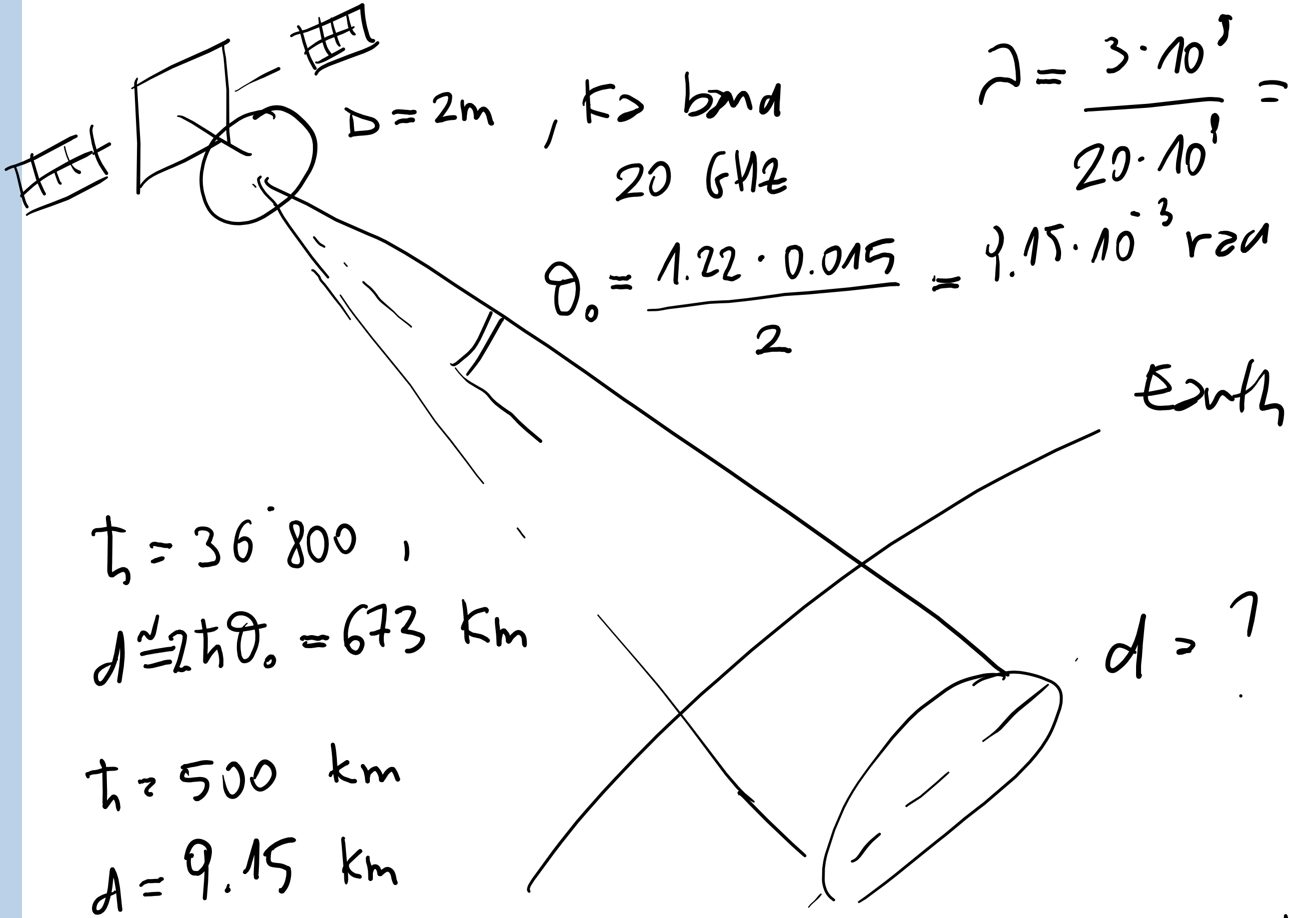
The workhorse of single-beam antennas: parabolic reflector



- Effective area: $A_e = A \cdot e_A$ where *A* is the actual area of the "mouth" of the antenna, $A = \pi (D/2)^2$, *D* the antenna diameter, and e_A =0.6÷0.7 is an efficiency parameter depending on construction
- The theoretical antenna pattern (small θ) is proportional to the Bessel function $|J_1(\pi D\theta/\lambda)|^2$ so that the *half beamwidth* can be computed considering the first zero of J_1 @ 3.832:

$$\theta_0 = 1.22\lambda / D \quad \text{(rad)} \qquad \theta_0 = 70\lambda / D \quad \text{(deg)}$$

Spot on Earth of the Parabolic Antenna



$D = 2\,m$, Ka band, 20 GHz

$$\lambda = \frac{3\cdot 10^{8}}{20\cdot 10^{9}} = 1.5\ cm$$

$$\theta_0 = \frac{1.22\cdot 0.015}{2} = 9.15\cdot 10^{-3}\ rad = 0.52^\circ$$

$h = 36\,800$,

$d \cong 2h\theta_0 = 673\ km$

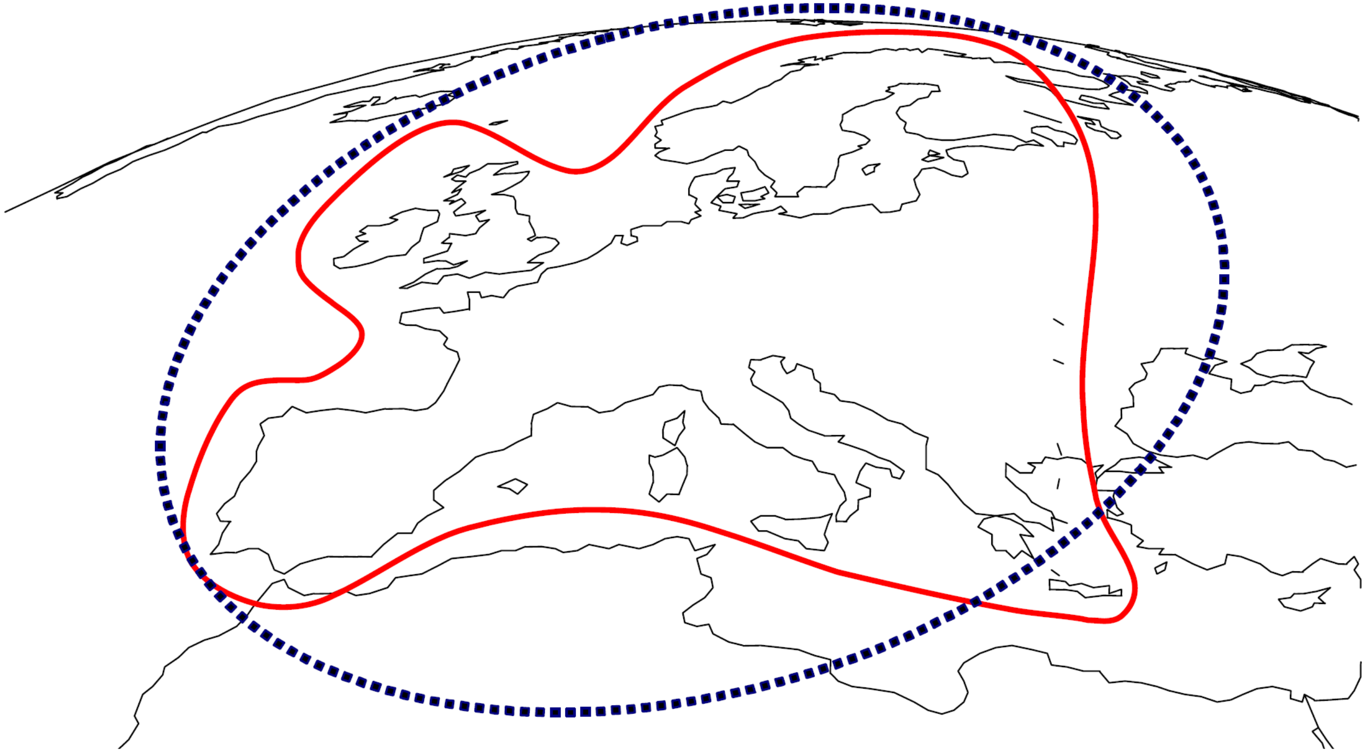
$h = 500\ km$

$d = 9.15\ km$

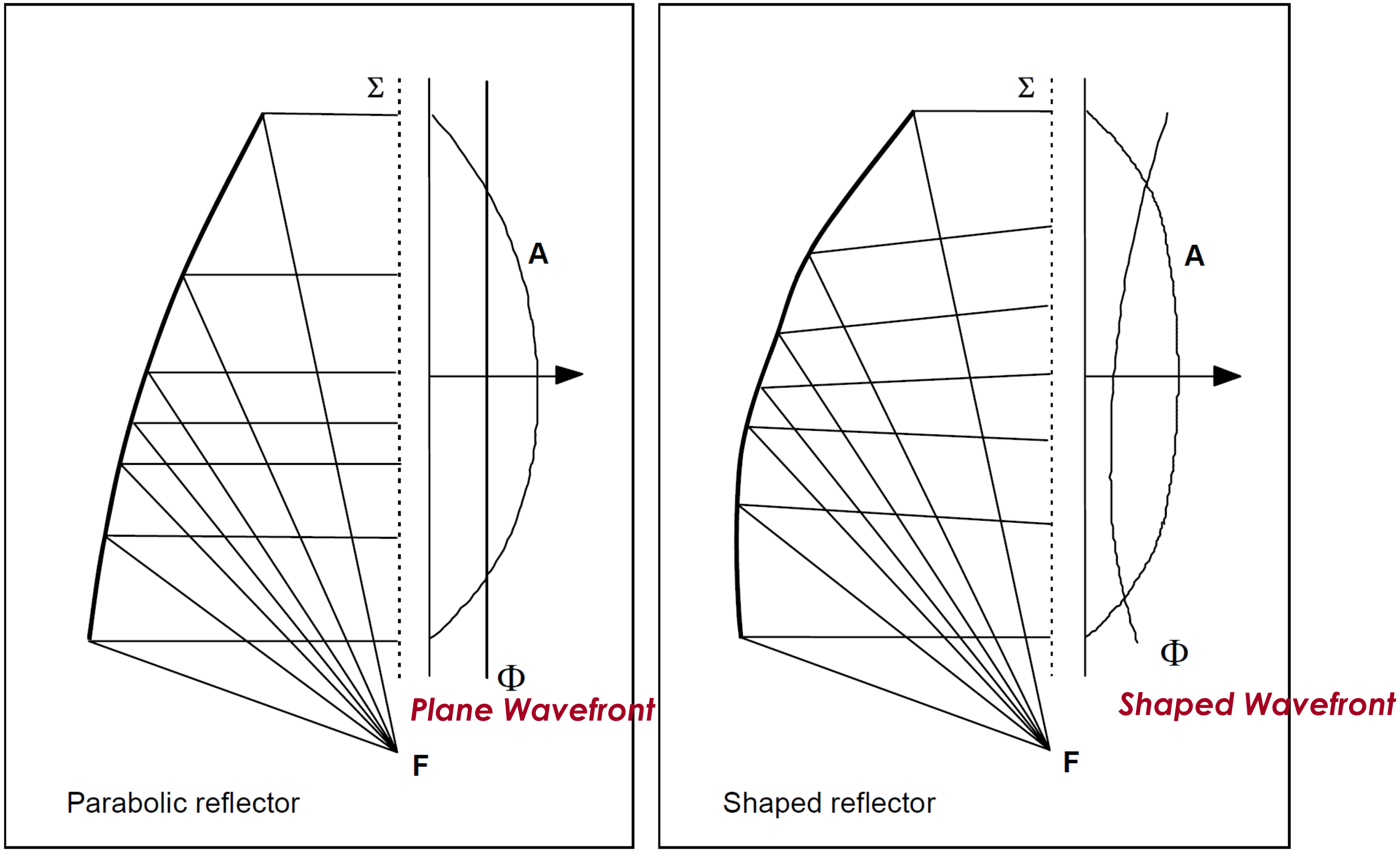
For LEO satellites, high-gain antennas are an issue!!

Shaped parabolic reflector

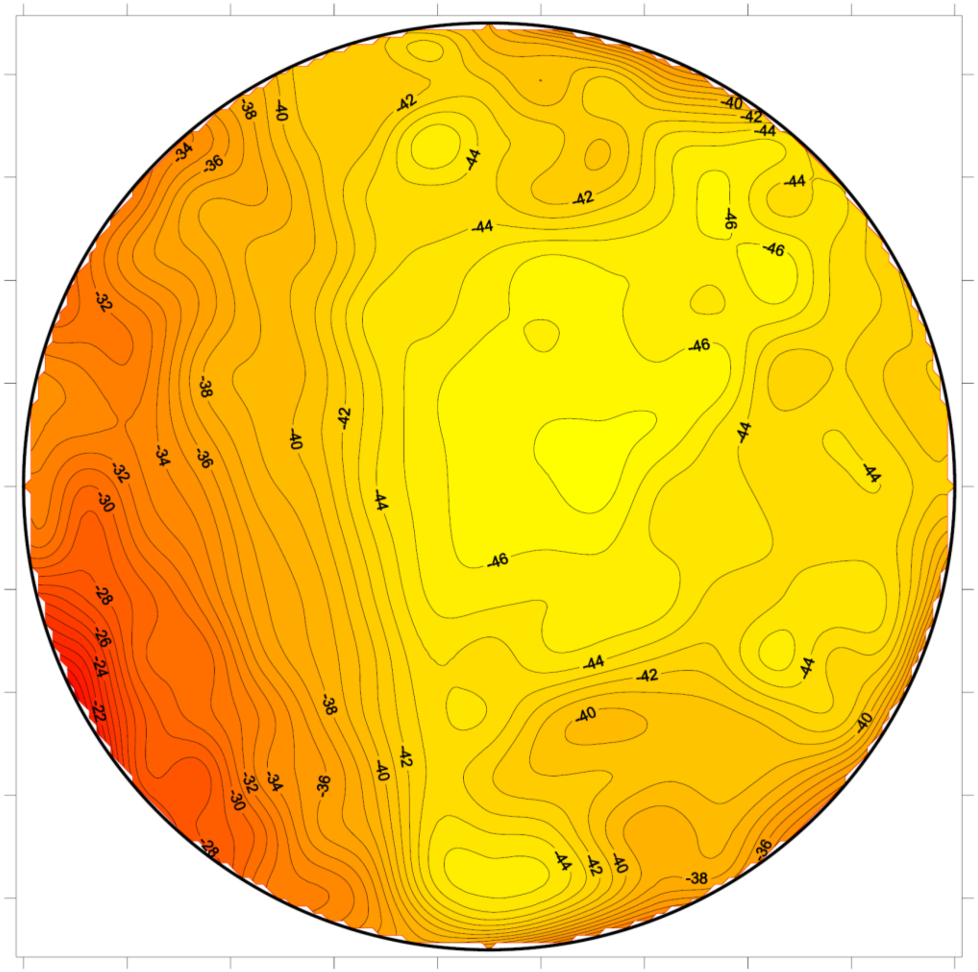
- Can be numerically optimized to give a desired contour on the Earth



Shaping the surface

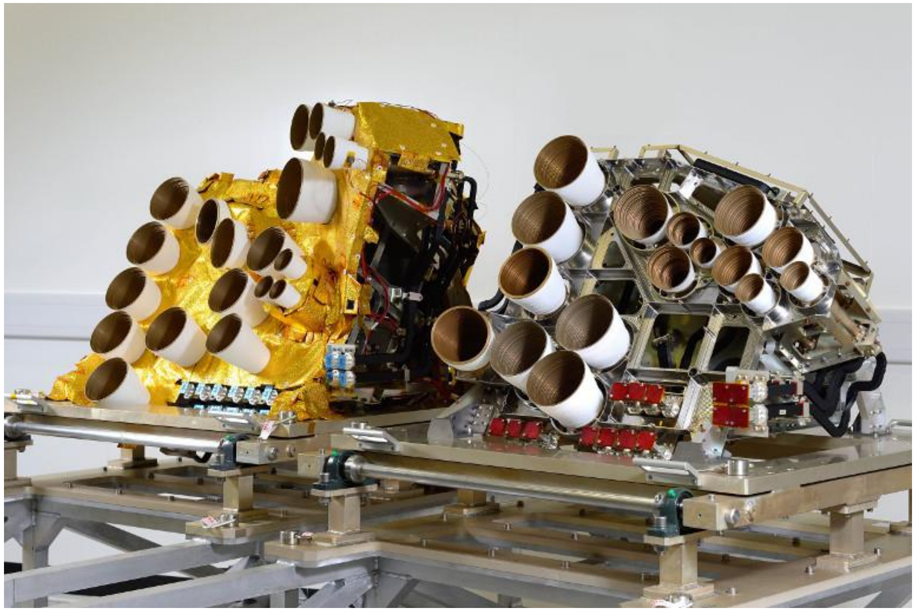


Shaping the surface



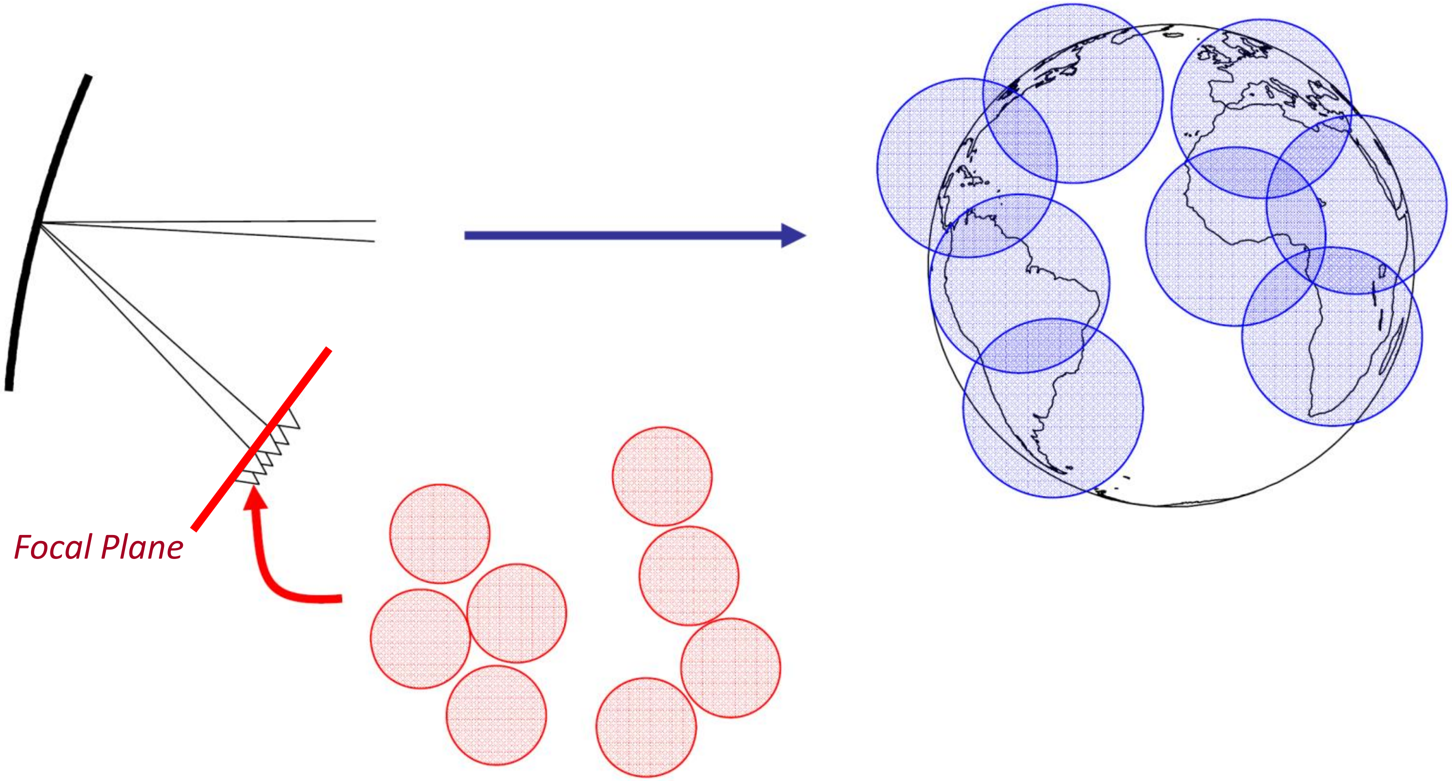
Multibeam, Multifeed Reflector Antennas

Satellite



End-User

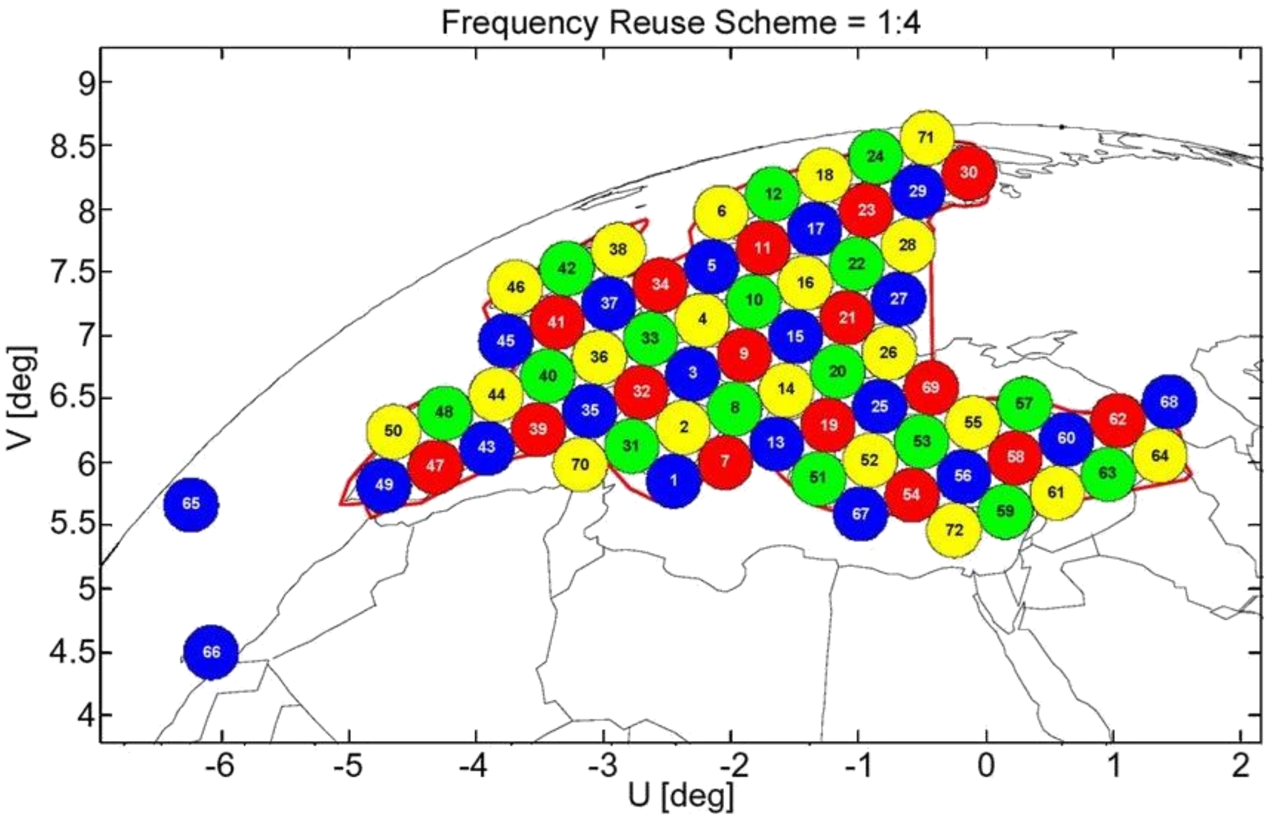
MutliFeed, Multi Beam Reflector Antenna



- The layout of feeds in the reflector focal plane is the mirror image of the desired coverage.

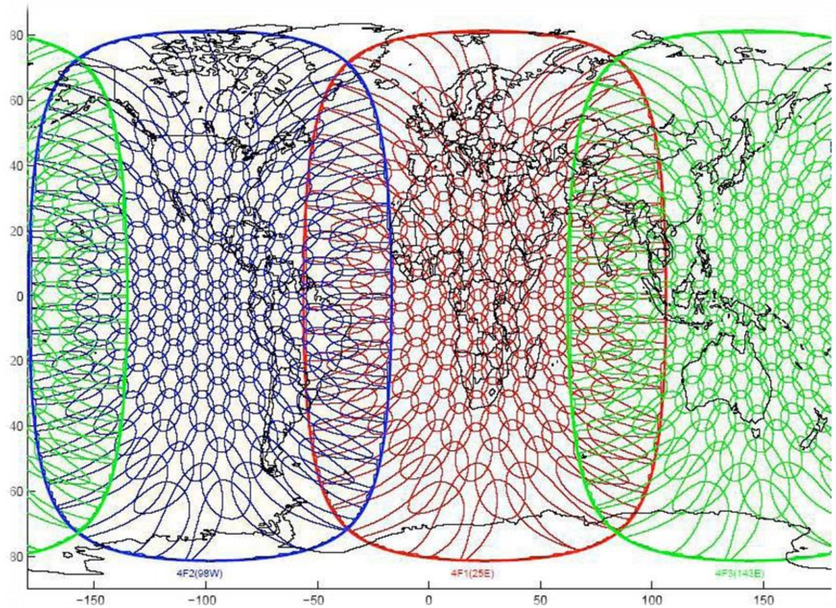
Why multibeam?

- **Multibeam antenna has two purposes**
  - Since the beams are narrow, the gain is high, and the link budget is very good
  - We can make spatial frequency/ polarization reuse vey much like what is done in a terrestrial cellular network, and increase the area efficiency of the network



Multi-Beam, Multi-Feed Reflector Antennas

- **The low gain antennas used for user terminals require highly directive multiple beam space segment antennas**
    - For example, the Inmarsat BGAN service (3G) is provided by the Inmarsat-4 fleet, each satellite having a 9 m reflector

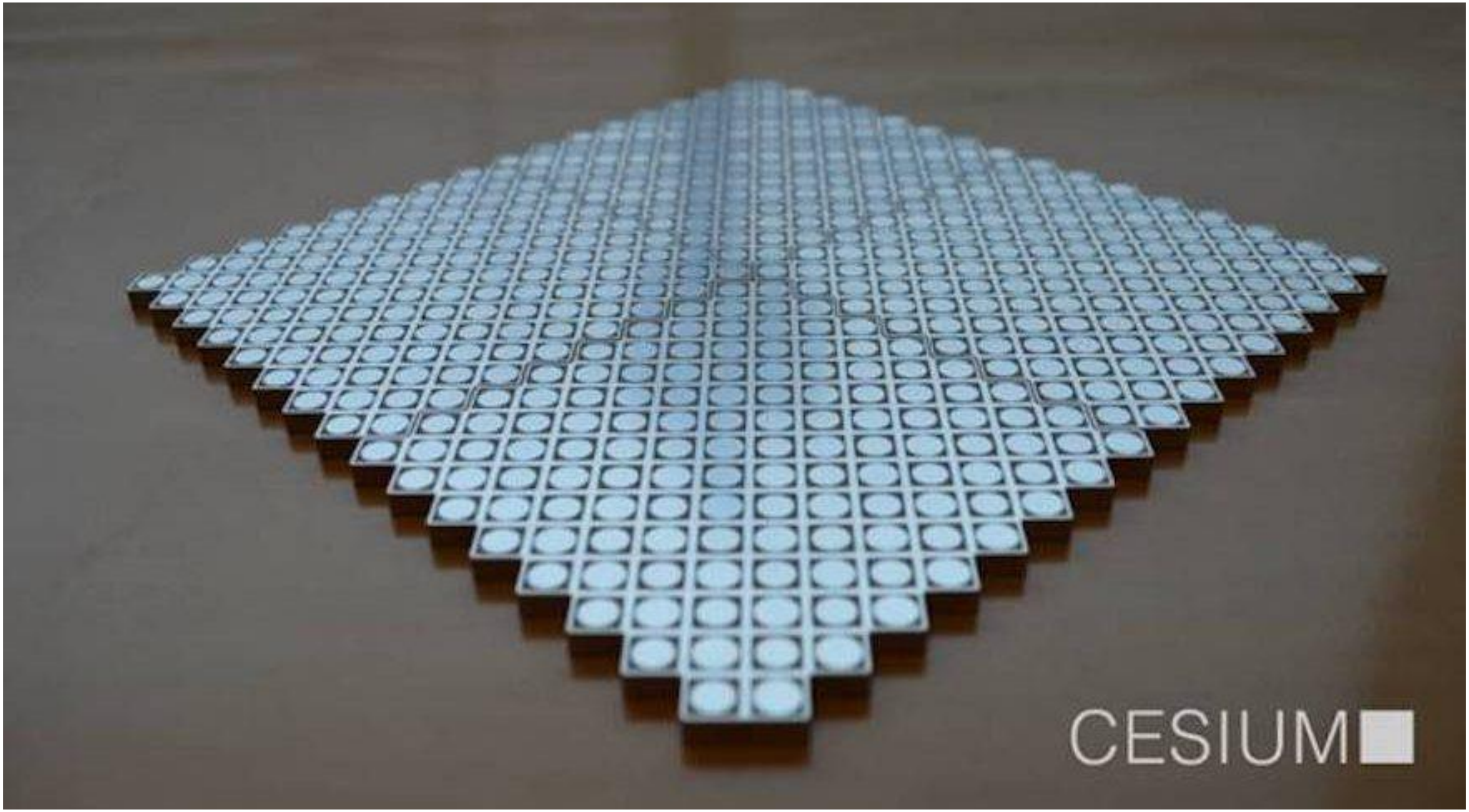


Mechanically Steerable Antennas

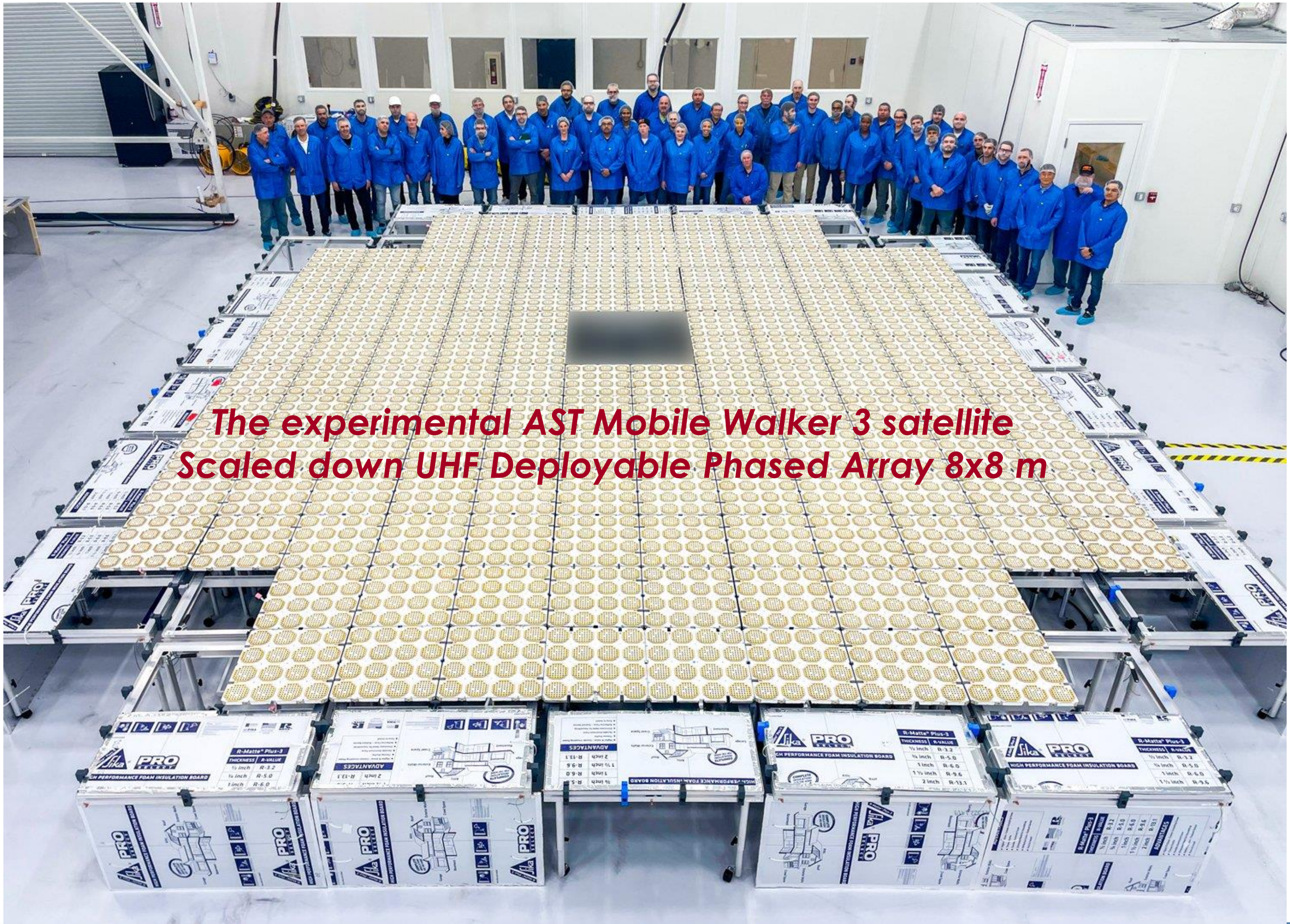
Mechanically Steerable Antennas with Radome

Electronically Steerable Antennas

Steerable Antennas



AST Mobile Antenna



AST SpaceMobile Achieves Space-Based 5G Cellular Broadband Connectivity From Everyday Smartphones, Another Historic World First

September 19, 2023

- *AST SpaceMobile's groundbreaking space-based 5G cellular broadband capabilities and new data rate of 14 Mbps follows closely on the heels of successful 4G testing with AT&T and Vodafone*
- *This historic achievement was reached using the BlueWalker 3 test satellite in collaboration with partners Vodafone, AT&T, and Nokia, and further shows promise for filling coverage gaps with 4G and 5G broadband connectivity from space around the planet*
- *The same patented technologies support AST SpaceMobile's commercial satellites, the first five of which the company currently plans to launch in Q1 2024*

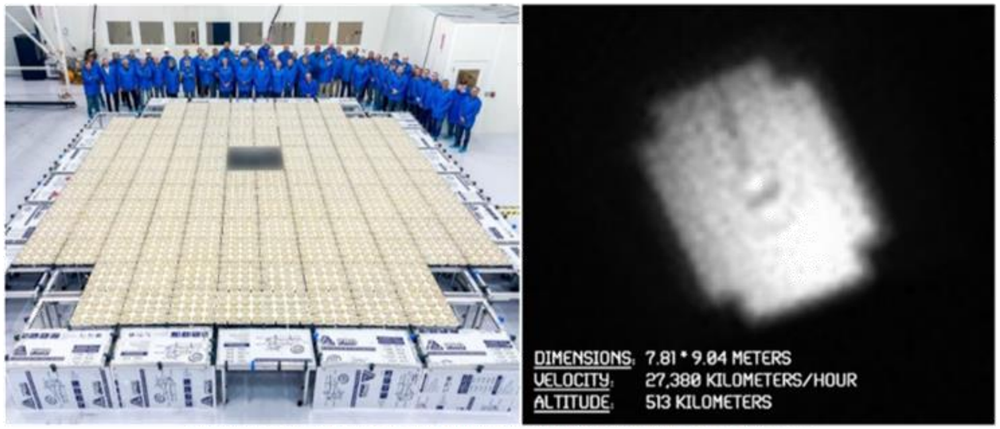
MIDLAND, TX – September 19, 2023 – AST SpaceMobile, Inc. ("AST SpaceMobile") (NASDAQ: ASTS), the company building the first and only space-based cellular broadband network accessible directly by standard mobile phones, today announced another unprecedented leap in telecommunications by successfully making the first-ever 5G connection for voice and data between an everyday, unmodified smartphone and a satellite in space.

Company engineers demonstrated space-based 5G connectivity by placing a call from Maui, Hawaii, USA, to a Vodafone engineer in Madrid, Spain, using AT&T spectrum and AST SpaceMobile's BlueWalker 3 test satellite — the largest-ever commercial communications array deployed in low Earth orbit. Fifth-generation or 5G mobile networking is the fastest, most efficient, highest-throughput, lowest-latency, and flexible wireless standard ever released by the 3GPP consortium.

The 5G call was placed on September 8, 2023, from an unmodified Samsung Galaxy S22 smartphone located near Hana, HI, in a wireless dead zone. 5G connectivity testing was completed with our partners Vodafone, AT&T and Nokia. In a separate test, the company broke its previous space-based cellular broadband data session record by achieving a download rate of approximately 14 Mbps.

These historic accomplishments follow AST SpaceMobile's April announcement that the company had completed the first-ever space-based voice calls using everyday unmodified smartphones. In June, AST SpaceMobile announced that the satellite reached initial download speeds above 10 Mbps. The company's comprehensive testing program with its partners has continued since June, including additional voice calls, 4G video calls and now 5G cellular broadband connections. These speeds, beyond supporting basic voice and text, also enable browsing the internet, downloading files, using messaging apps, streaming video, and more on everyday smartphones.

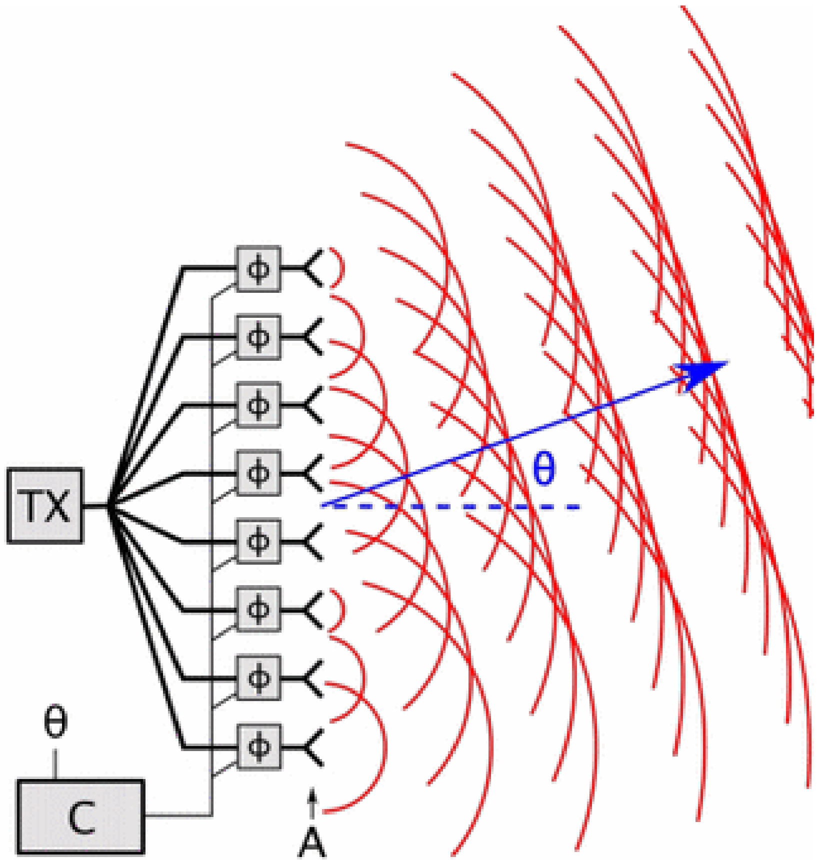
"Once again, we have achieved a significant technological advancement that represents a paradigm shift in access to information. Since the launch of BlueWalker 3, we have achieved full compatibility with phones made by all major manufacturers and support for 2G, 4G LTE, and now 5G," said Abel Avellan, Chairman and Chief Executive Officer of AST SpaceMobile. "Making the first successful 5G cellular broadband connections from space directly to mobile phones is yet another significant advancement in telecommunications AST SpaceMobile has pioneered. We are more confident than ever that space-based cellular broadband can help transform internet connectivity across the globe by filling in gaps and connecting the unconnected."



BlueWalker 3 on the ground at our Midland, Texas facility prior to launch, and in space

Linear (phased) Array

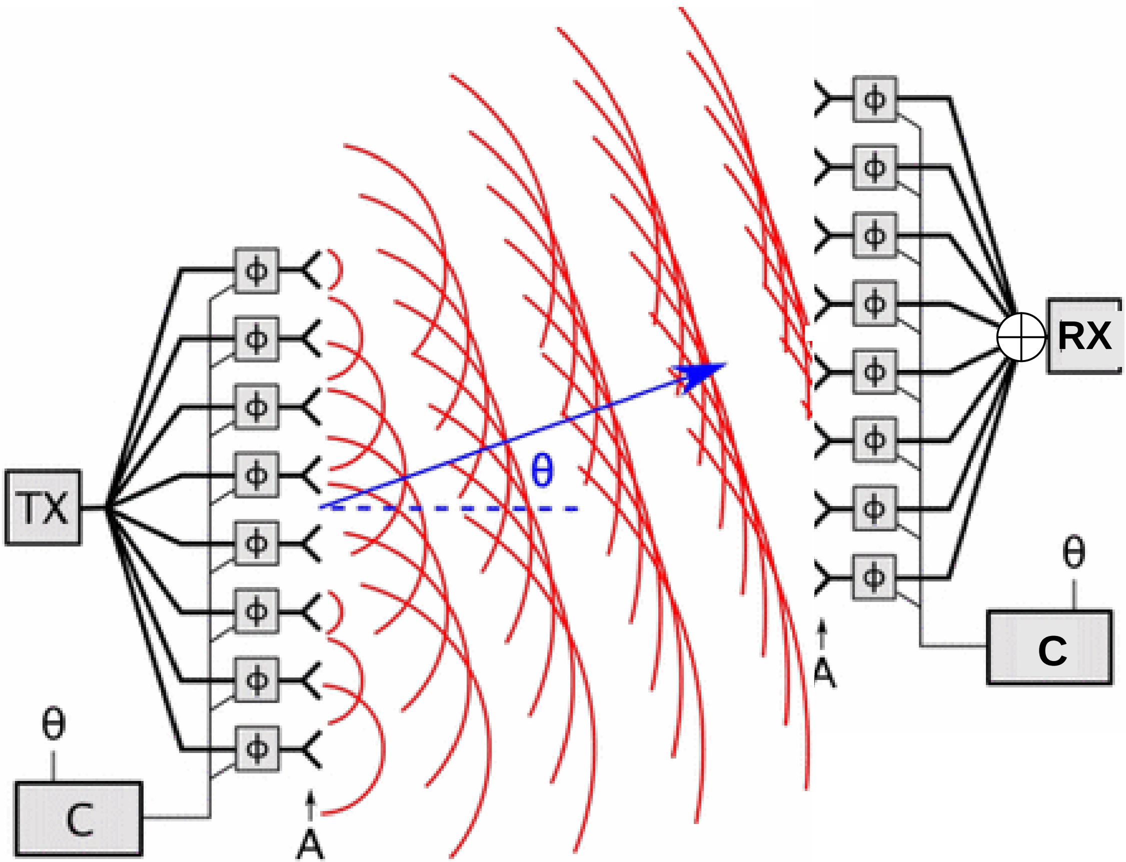
- *Array* **A** of *N* equi-spaced radiating elements dsitributed on a line at distance *d*, possibly fed via phase shifters cotrolled by a controller **C** to get a beam shape oriented in a desired direction θ
- By (Electronically) changing the phase shifts, the pointing direction $\boldsymbol{\theta}$ is changed



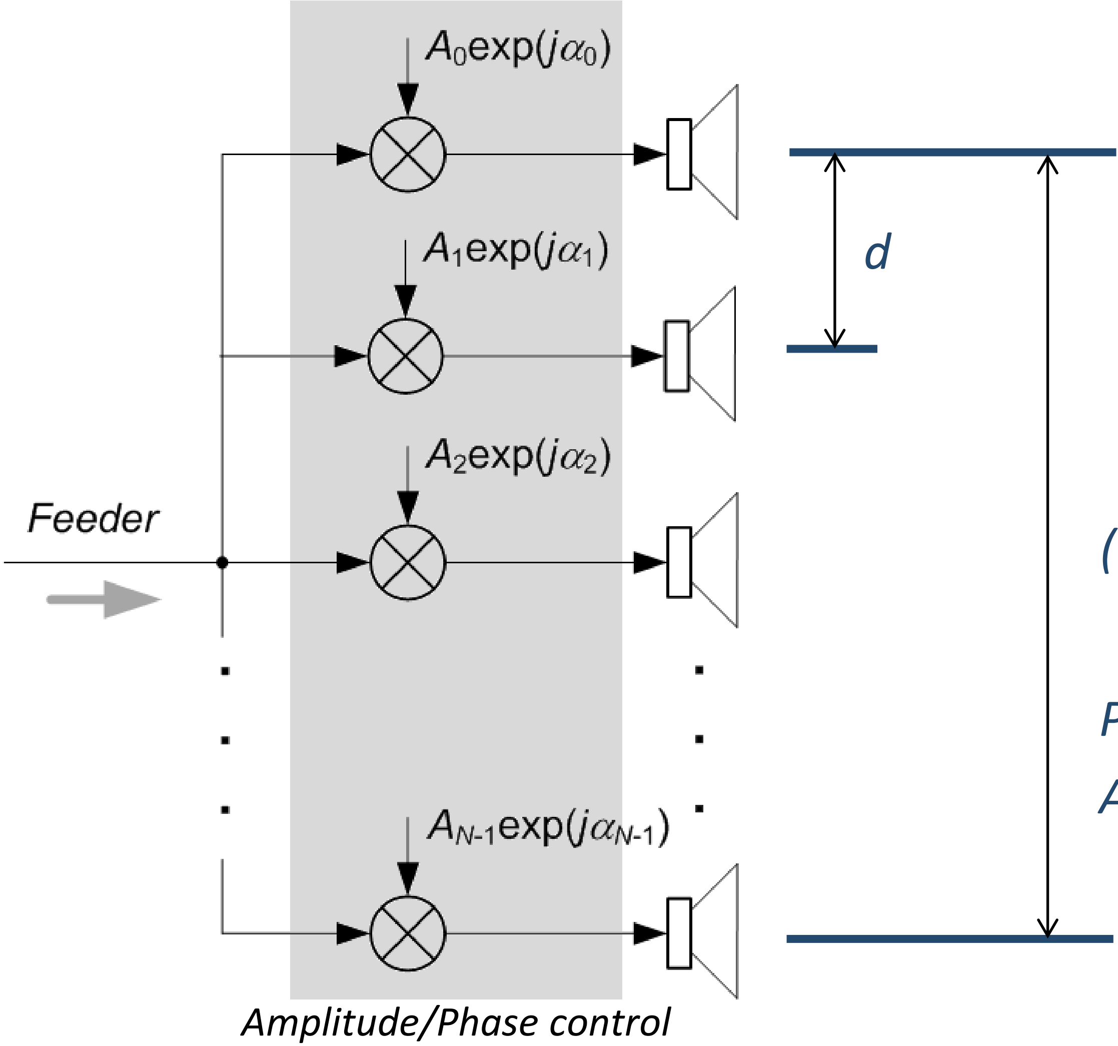
Multiple-Element Antenna System: Linear Phased Array

- The effect is *reciprocal*: with the same phase shift we get directivity along θ during reception as well

- The TX array needs in general one (HP) amplifier per radiating element, while the RX array has one LNA per element



Generalized Linear Phased Array with Tapering



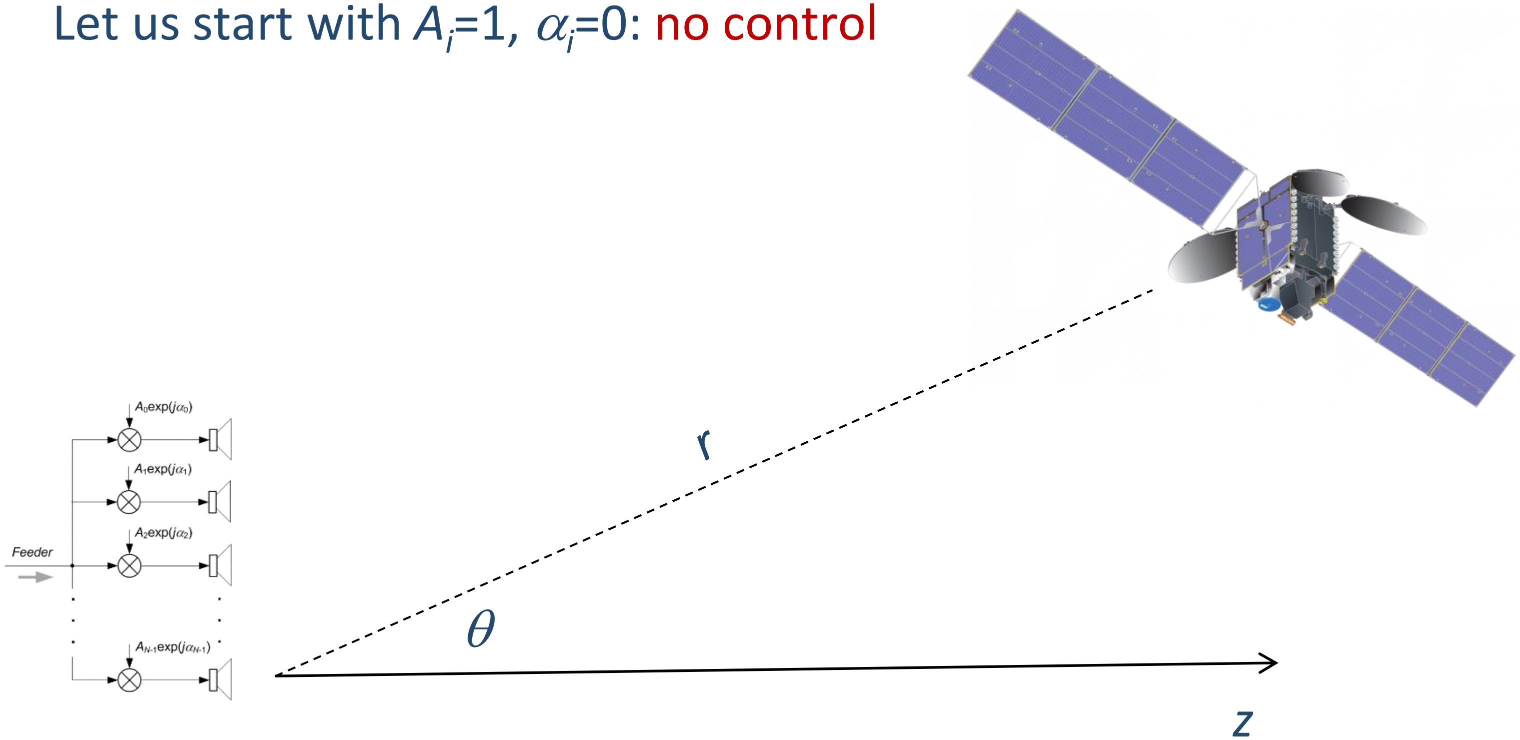
(N-1)d=L

Phased-Array :

$A_0=A_1=\ldots=A_{N-1}=1$

Linear Array 1/7

Let us start with A_i=1, α_i=0: no control



An overlap of the waves radiated by each element is received; in the far field, the distance *r* from each element to the receiver is practically the same (therefore the received intensity is the same for each element), but ...

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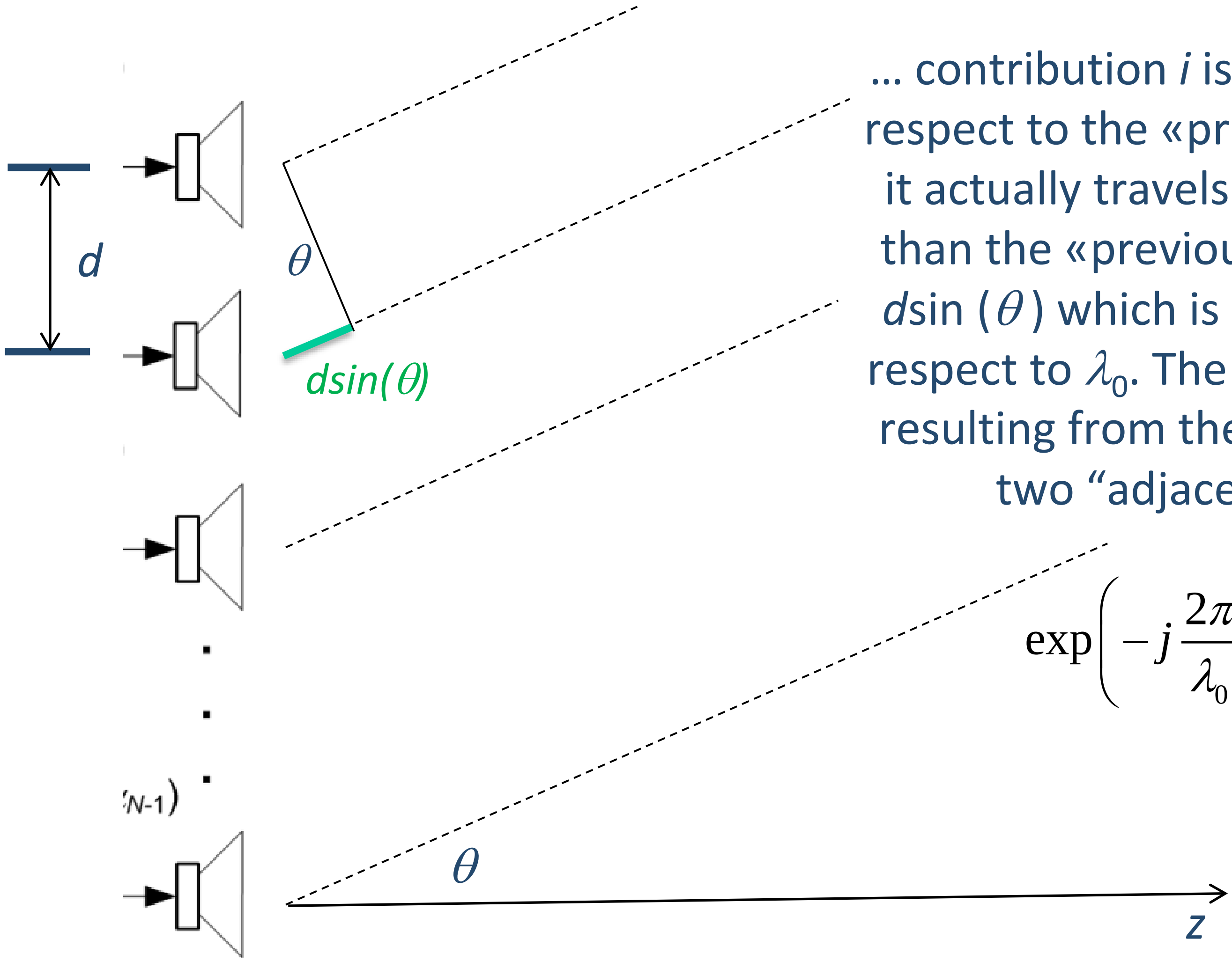
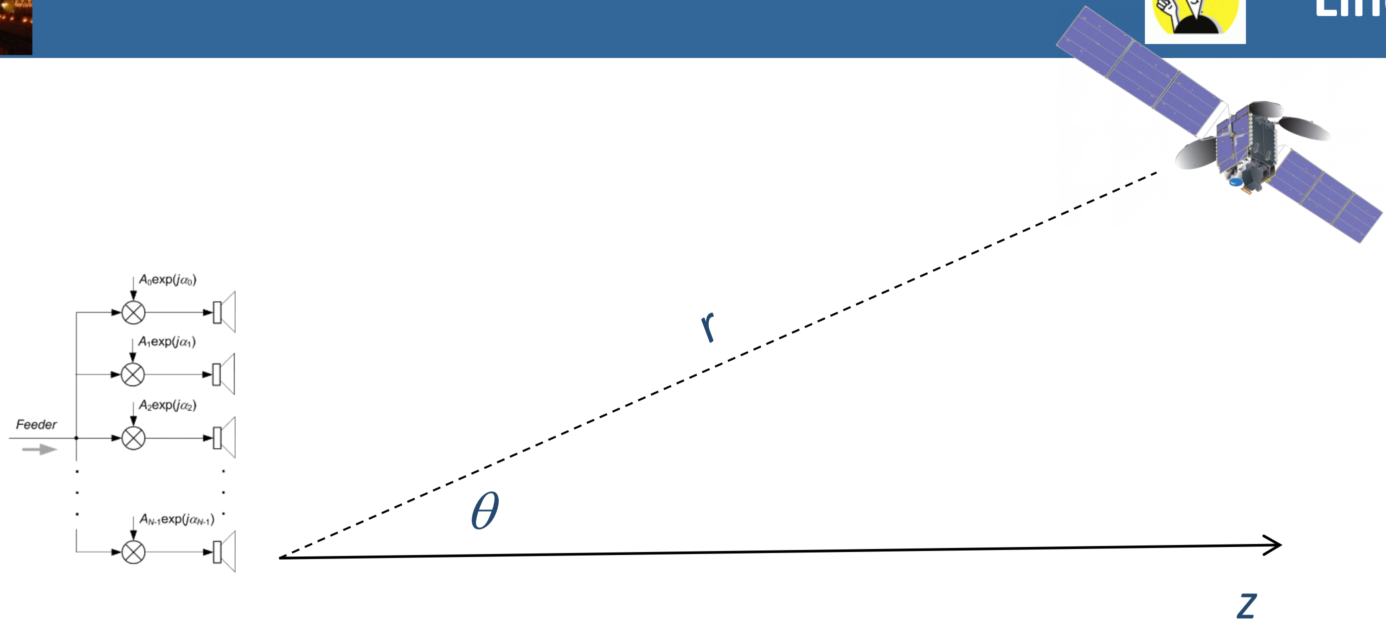
Linear Array 2/7



… contribution *i* is phase-shifted with respect to the «previous» *i-1* because it actually travels a greater distance than the «previous» by the quantity $d\sin(\theta)$ which is **not** negligible with respect to λ_0. The relative phase shift resulting from the different paths of two "adjacent" waves is:

$$\exp\left(-j\frac{2\pi}{\lambda_0}d\sin(\theta)\right)$$

Linear Array 3/7



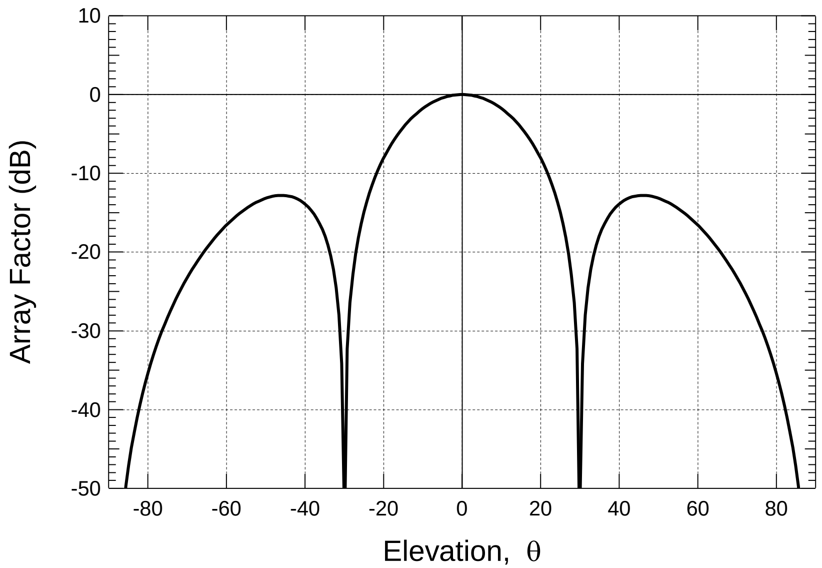
In summary, the total received signal along θ is proportional to

$$\sum_{i=0}^{N-1}\exp\left(-j2\pi i\,\frac{d\sin(\theta)}{\lambda_0}\right)=\frac{1-\exp\left(-j2\pi N\,\frac{d\sin(\theta)}{\lambda_0}\right)}{1-\exp\left(-j2\pi\,\frac{d\sin(\theta)}{\lambda_0}\right)}=\exp\left(-j\pi(N-1)\frac{d\sin(\theta)}{\lambda_0}\right)\frac{\sin\left(\pi N\,\frac{d\sin(\theta)}{\lambda_0}\right)}{\sin\left(\pi\,\frac{d\sin(\theta)}{\lambda_0}\right)}$$

Linear Array 4/7

→ the radiation pattern of the elementary radiating element (all elements assumed equal) is changed by the so-called *normalized array factor*

$$F(\theta) = \left| \frac{\sin\left(\pi N \dfrac{d \sin(\theta)}{\lambda_0}\right)}{N \sin\left(\pi \dfrac{d \sin(\theta)}{\lambda_0}\right)} \right|^2 \qquad F(0) = 1$$

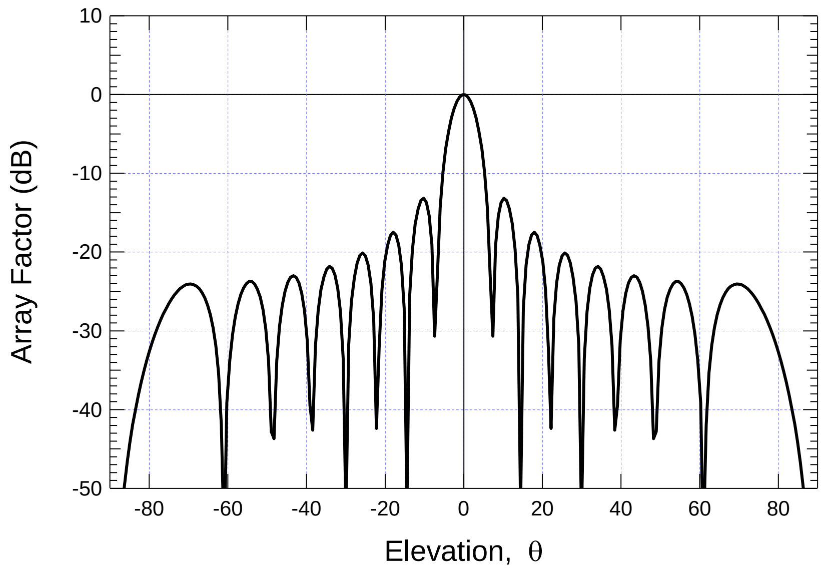


$N = 8 \, , \, d = \lambda_0 / 4$

Linear Array 5/7

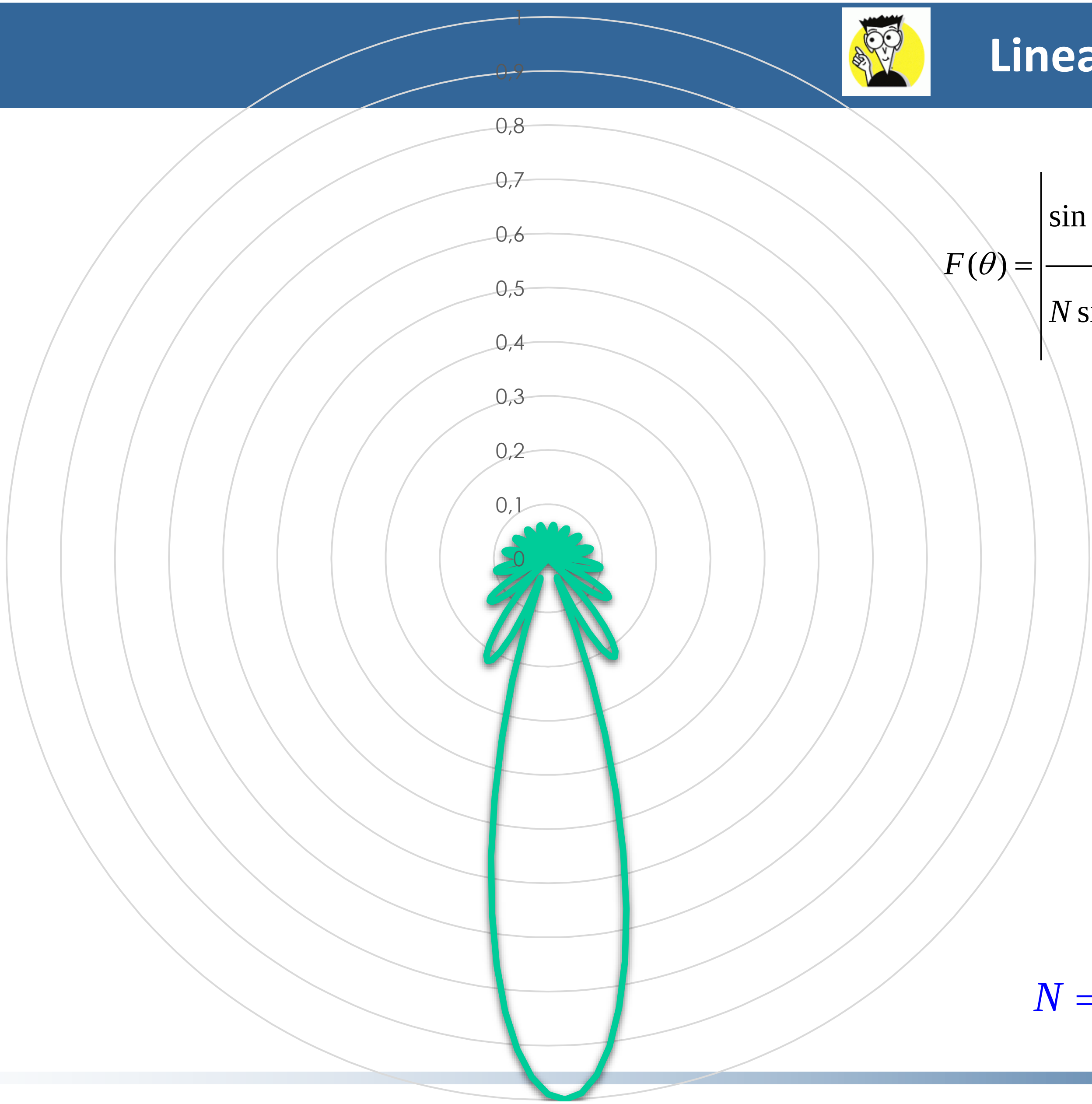
→ the radiation pattern of the elementary radiating element (all elements assumed equal) is changed by the so-called *normalized array factor*

$$F(\theta) = \left| \frac{\sin\left(\pi N \dfrac{d \sin(\theta)}{\lambda_0}\right)}{N \sin\left(\pi \dfrac{d \sin(\theta)}{\lambda_0}\right)} \right|^2 \qquad F(0) = 1$$



$N = 16\,,\ d = \lambda_0 / 2$

Linear Array 6/7



$$F(\theta) = \left| \frac{\sin\left(N\pi \frac{d \sin(\theta)}{\lambda_0} \right)}{N \sin\left(\pi \frac{d \sin(\theta)}{\lambda_0} \right)} \right|^2$$

$$N = 16 \, , \, d = \lambda_0 / 2$$

Linear Array 7/7

The Array Factor is

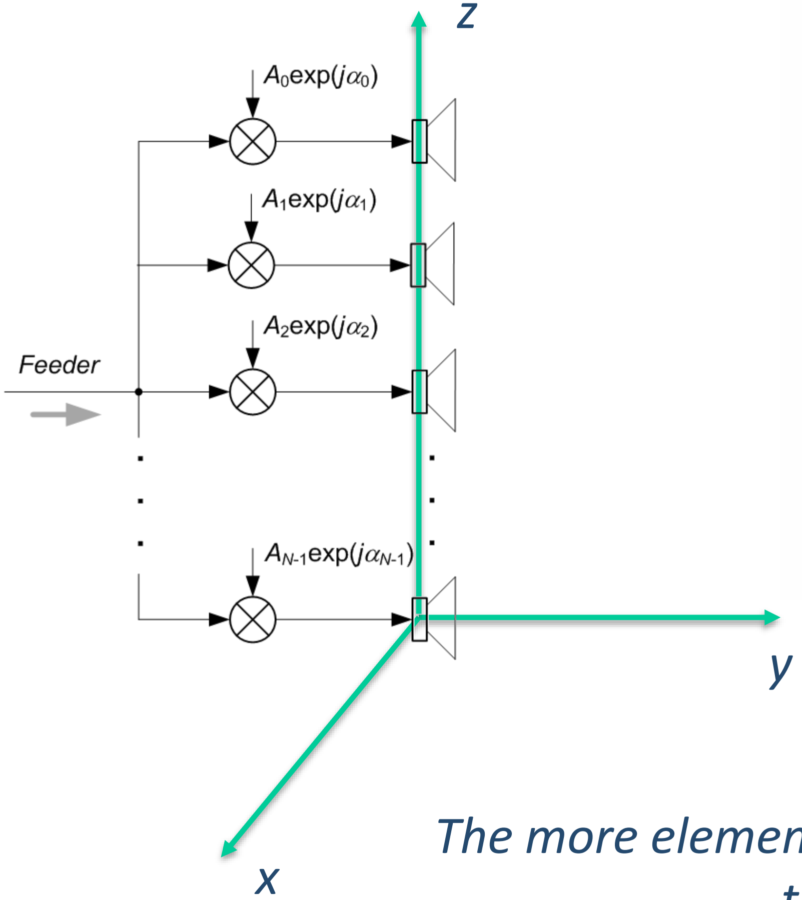
$$F(\theta) = \left| \frac{\sin\left(\pi N \frac{d \sin(\theta)}{\lambda_0}\right)}{N \sin\left(\pi \frac{d \sin(\theta)}{\lambda_0}\right)} \right|^2$$

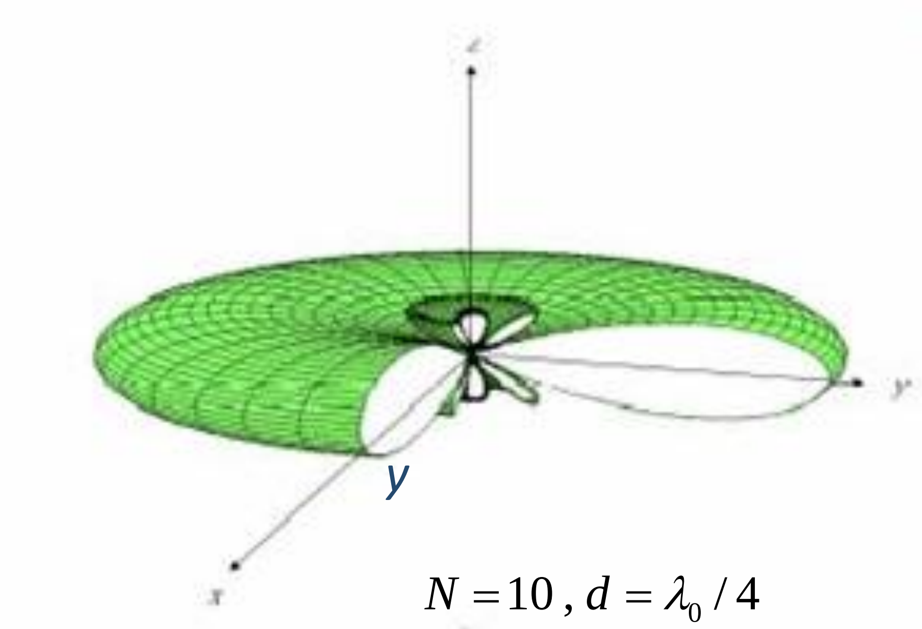
with an elevation angle θ within ±90 degrees. The main beam (lobe) is always at θ=0, there might be additional beams, the so-called *grating lobes* at

$$\theta_m = \pm \sin^{-1}\left(m \frac{\lambda_0}{d} \right) \qquad (m \text{ integer})$$

That are actually present only iff $d>\lambda_0$

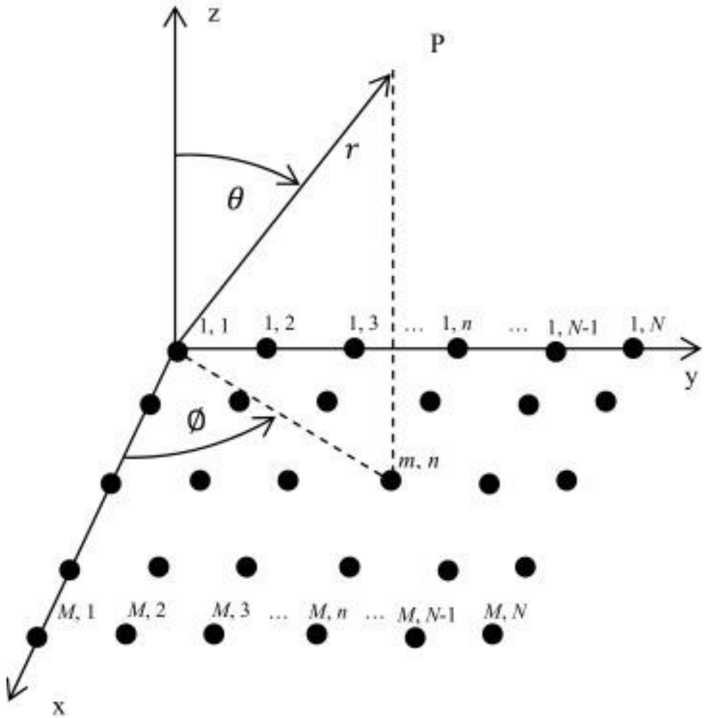
Directivity !





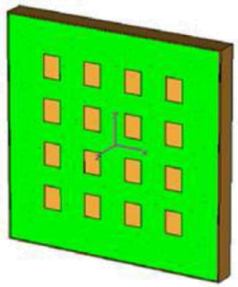
The more elements we use, the narrower is the beam !

Planar Array 1/2

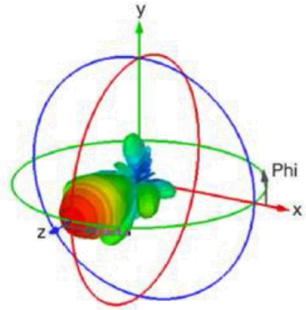


$$F(\theta)=\left|\frac{\sin\left(\pi N\dfrac{d\sin(\theta)\cos(\phi)}{\lambda_0}\right)}{N\sin\left(\pi\dfrac{d\sin(\theta)\cos(\phi)}{\lambda_0}\right)}\right|^2\left|\frac{\sin\left(\pi M\dfrac{d\sin(\theta)\sin(\phi)}{\lambda_0}\right)}{M\sin\left(\pi\dfrac{d\sin(\theta)\sin(\phi)}{\lambda_0}\right)}\right|^2$$

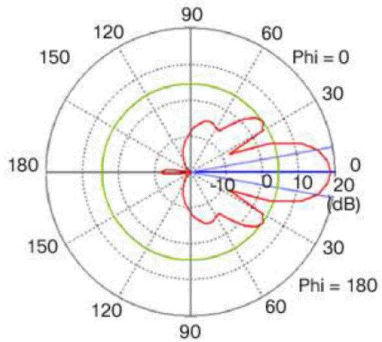
Planar Array 2/2



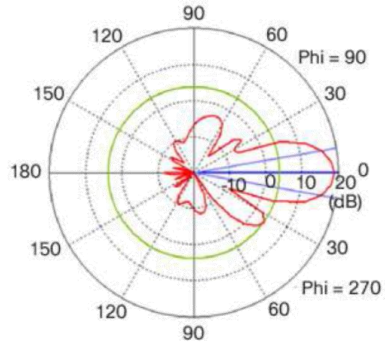
(a) 4x4 Patch Array Antenna



(b) 4x4 Patch Array 3D Radiation Pattern



(c) 4x4 Patch Array Azimuth Plane Pattern



(d) 4x4 Patch Array Elevation Plane Pattern

$$F(\theta) = \frac{1}{N^2} \frac{\sin^2\left(\pi N \dfrac{d \sin(\theta)\cos(\phi)}{\lambda_0}\right)}{\sin^2\left(\pi \dfrac{d \sin(\theta)\cos(\phi)}{\lambda_0}\right)} \frac{1}{M^2} \frac{\sin^2\left(\pi M \dfrac{d \sin(\theta)\sin(\phi)}{\lambda_0}\right)}{\sin^2\left(\pi \dfrac{d \sin(\theta)\sin(\phi)}{\lambda_0}\right)}$$

Phased Array (linear array with phase control)

Let's now reconsider the phase shifts α_i , disregarding the tapering (no amplitude variation across elements). The total received signal is

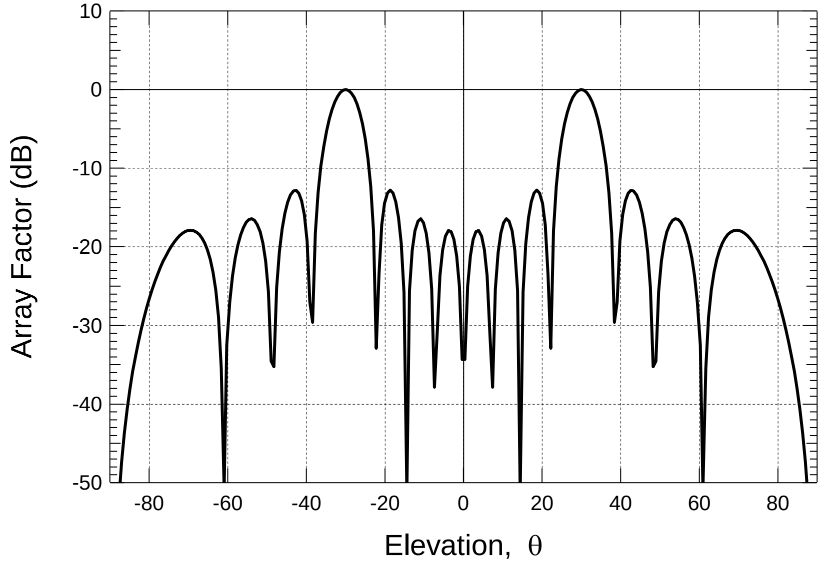
$$\sum_{i=0}^{N-1} \exp\left[-j\left(2\pi i \frac{d\sin(\theta)}{\lambda_0} - \alpha_i\right)\right]$$

We can change the direction of pointing of the main beam just setting the phase shifts as

$$\alpha_i = 2\pi i \frac{d\sin(\theta_0)}{\lambda_0}$$

The set of coefficients α_i is called the STEERING VECTOR

$$N = 8\,, d = \lambda_0 / 4\,, \theta_0 = \pi / 6$$



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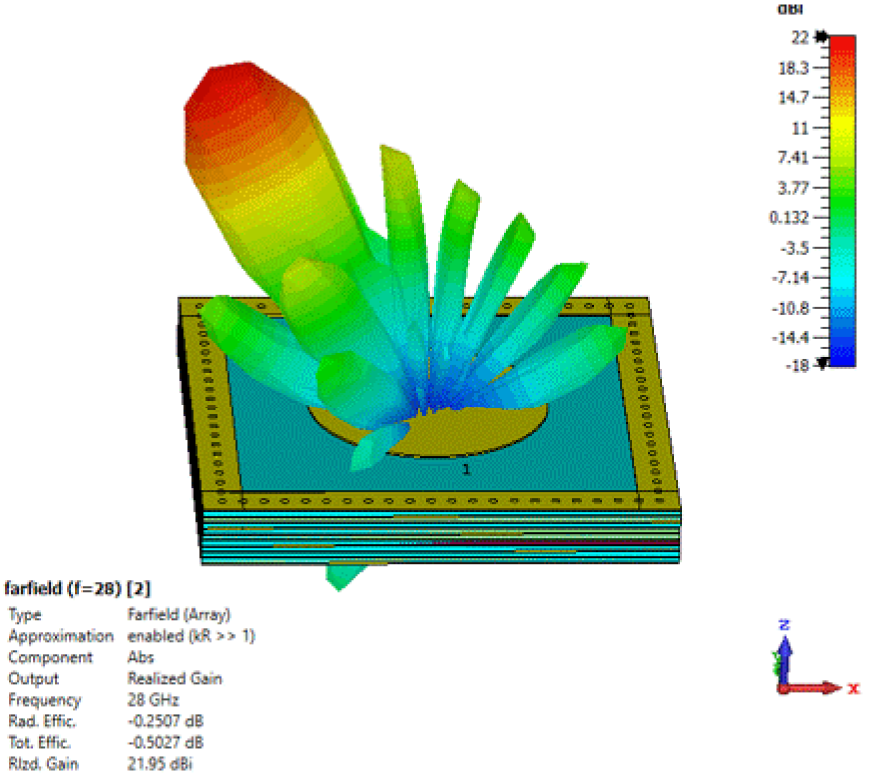
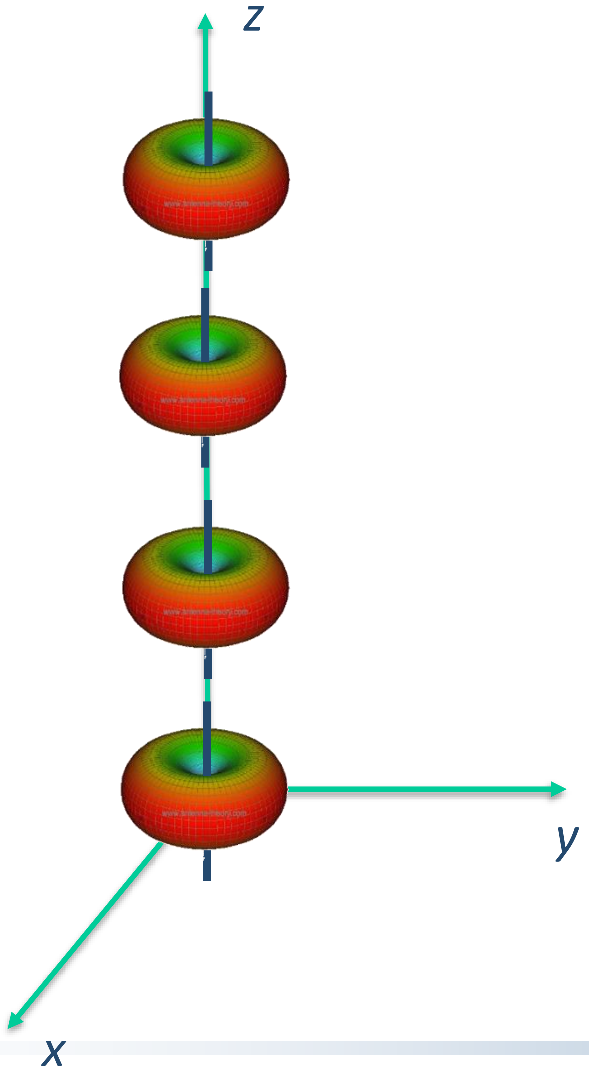
Electronically-Steerable Antenna

With *digital phase shifters*, the value of α_i can be set and continually varied upon digital control so as to steer the main beam of the array where wanted/needed: DIGITAL BEAMFORMING (DBF) /ELECTRONICAL STEERING



Actual Radiation Pattern 1/2

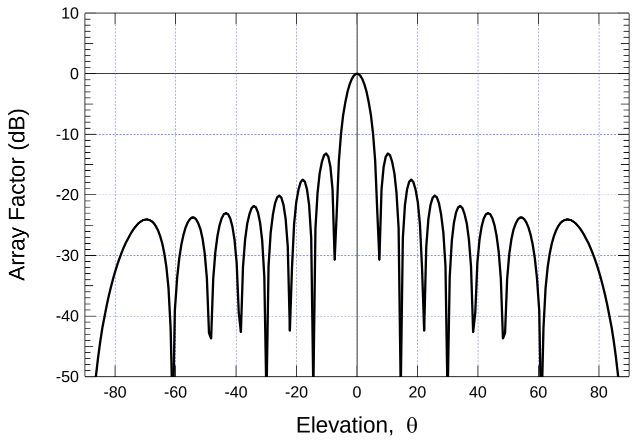


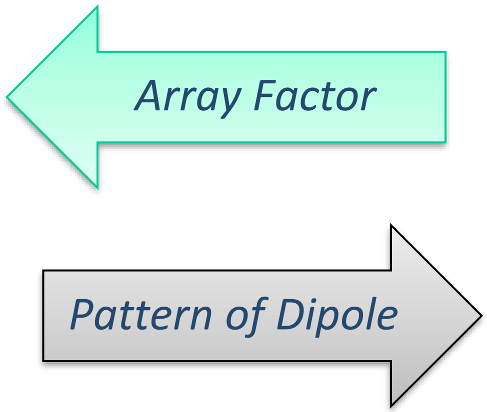
- The elements are *not* omnidirectional – the array factor has to be applied to the radiation pattern of each element – like this example with $\lambda_0/2$ dipoles…

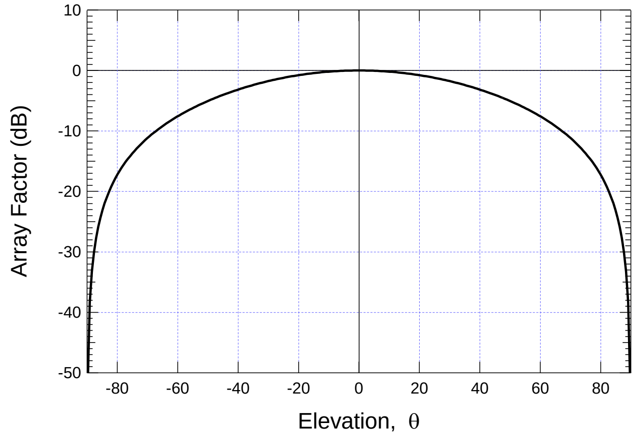
$$G(\theta)=\left|\frac{\sin\left(\pi N\frac{d\sin(\theta)}{\lambda_0}\right)}{N\sin\left(\pi\frac{d\sin(\theta)}{\lambda_0}\right)}\cdot\frac{\cos\left(\frac{\pi}{2}\sin(\theta)\right)}{\cos(\theta)}\right|^2$$

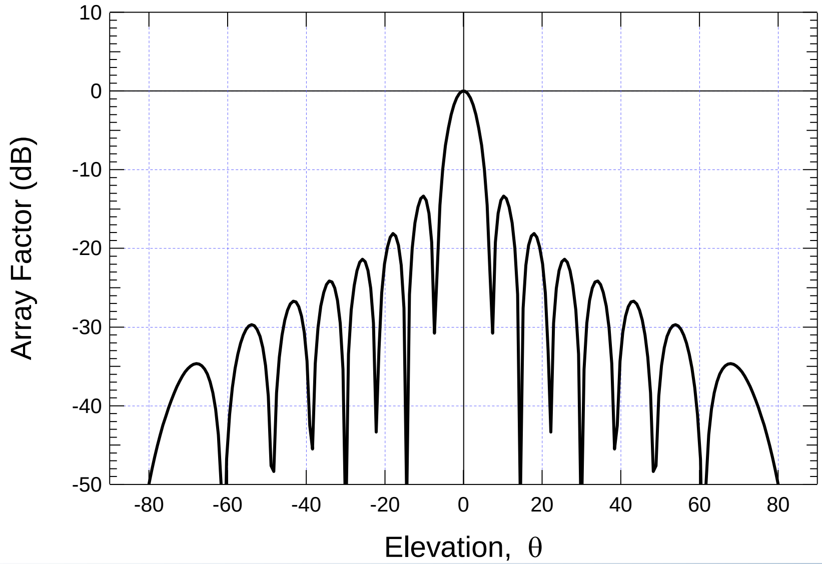
array factor | single- element rad. pattern

Actual Radiation Pattern 2/2





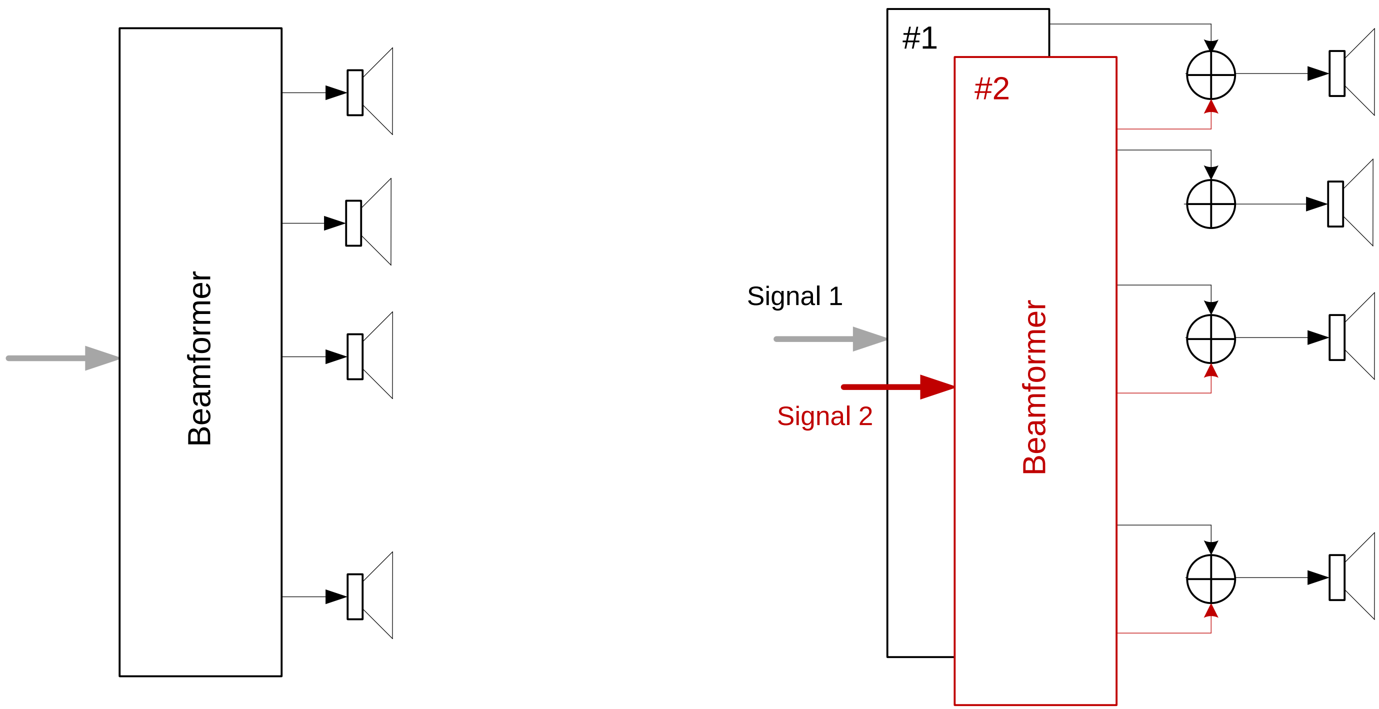




Resulting composite pattern of the antenna array

Beamforming Network (Matrix)

One signal, one beam *Two signals, two beams*



- Can be generalized to *M* signals: different signals can be “routed” to different beams in different directions by applying *M* different sets of beamforming coefficients (phase shifts) – the set of *M* steering vectors is also called the *beamforming matrix*
- The multibeam array can also be designed as a feeder element for a reflector antenna