Fundamentals of Phased Arrays

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Overview of the presentation

- Introduction
- Types of arrays
- Application of Phased arrays
- Linear and Planar Arrays
- Radiation patterns scanning
- Array design and Grating lobes
- Array distributions
- Embrace example

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Phased Array Antennas

introduction

- Phased array is a directive antenna made with individual radiating sources (several units to thousands of elements).
- Radiating elements might be: dipoles, open-ended waveguides, slotted waveguides, microstrip antennas, helices, spirals etc.
- The shape and direction of pattern is determined by relative phases amplitudes applied to each radiating element.
- A phased array antenna offers the possibility to steer the beam by means of electronic control (a dedicated computer is required).

Different types of phased arrays

The collection of radiators can be on any of the following different type of surfaces, such as:

- **LINEAR ARRAY:**
  Elements arranged on a straight line in one dimension

- **PLANAR ARRAY:**
  Elements arranged on a plane in two dimensions (rectangular, square or circular aperture)

- **CONFORMAL ARRAY:**
  Elements are distributed on a non planar surface

Applications of Phased Arrays

- Ground based multi-function radar for military use

- Airborne radar for surveillance (RBE2)

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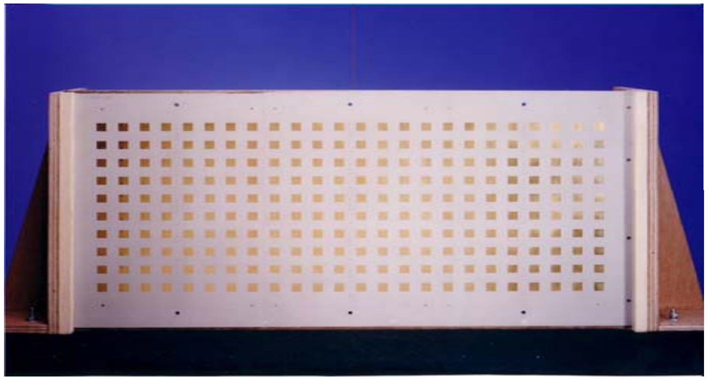
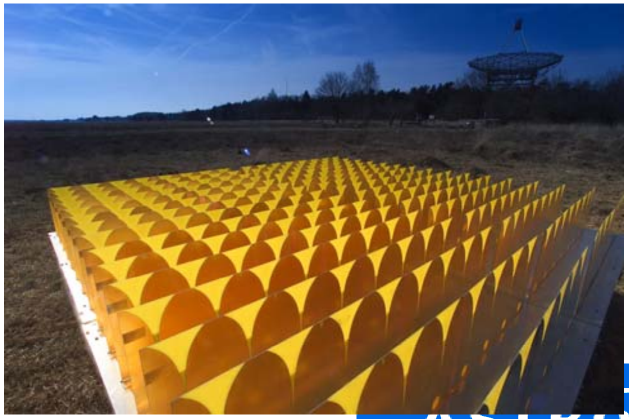
Application continued

- Spaceborne SAR and communications for remote sensing



- Recently for radio astronomy



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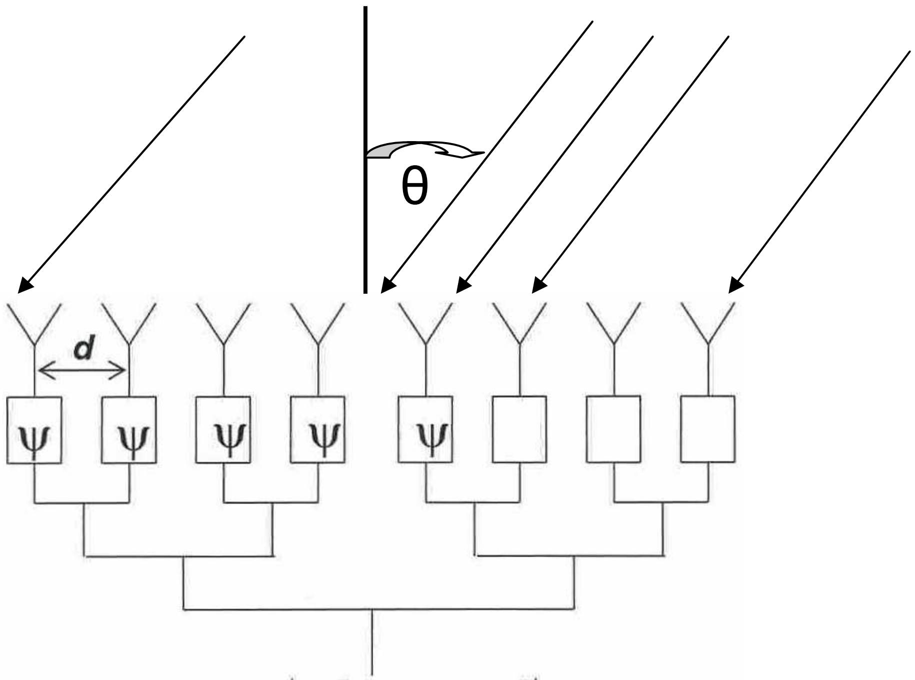
Linear array radiation pattern

A linear array is made of N elements uniformly fed,
spaced by a distance d

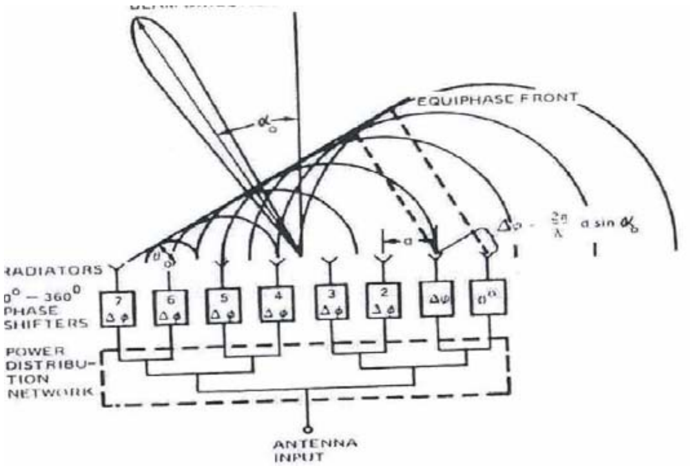


- Phase shift between adjacent sources:
  $\Psi = 2 \cdot \pi \cdot (d/\lambda) \cdot \sin\theta$
  (θ = angle of incidence)

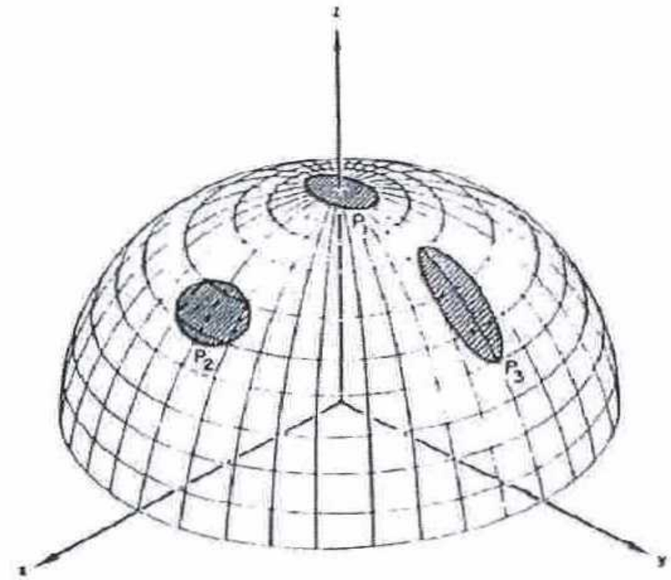
$$|Ea(\theta)| = \left| \frac{\sin\left[N\pi\left(\frac{d}{\lambda}\right) \cdot \sin(\theta)\right]}{\sin\left[\pi\left(\frac{d}{\lambda}\right) \cdot \sin(\theta)\right]} \right|$$

$$Ga(\theta) := \frac{(|Ea(\theta)|)^2}{N^2}$$

For scanning the beam



thetas := 0.0 d := 0.5



$$E(\theta) := \sum_{i} \left[A_i \cdot \exp\left[j \cdot 2 \cdot \pi \cdot d \cdot i \cdot \left(\sin\left(\frac{\theta \cdot \pi}{180.0} \right) - \sin\left(\text{thetas} \cdot \frac{\pi}{180.0} \right) \right) \right] \right]$$

Array Factor

Typical scanning angle	$\pm 60^0$
Typical gain losses	$G(a) = G(0°) \cos a$
Half power beamwidth	$\theta_{3dB}(a) = \theta_{3dB}(a) / \cos(a)$

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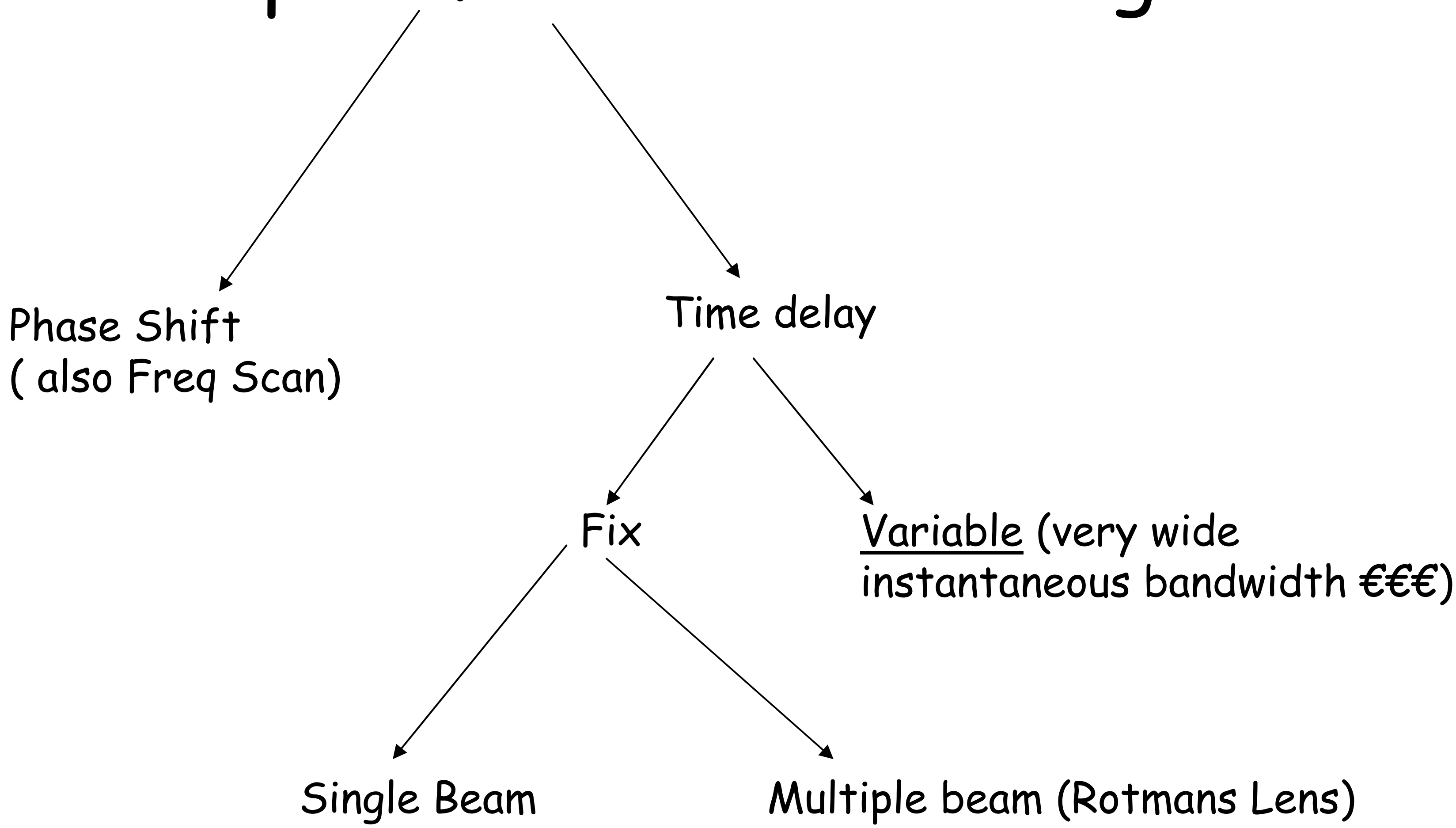
Principles for beam scanning



OR combination of phase and time delay

3db Beamwidth and scanned beam for a linear array

- Radiation Pattern Characteristics

e.g. Radiation pattern for a linear array of N elements with $d/\lambda = 0.5$:

- half power beamwidth: $\Theta_{3dB} = 102°/N$ Or $(\Theta_{3dB}(\theta) = 0.88/(d/\lambda)$ in radians

$$\Theta_{3dB}(\theta) = \Theta_{3dB}(0)/Cos(\theta)$$

- First side lobe 13.2 dB below the main lobe
- <u>when directive elements are used</u>, the resultant pattern is the product of the array pattern $Ga(\Theta)$by the individual source pattern $Ge(\Theta)$.

$$G(\Theta) = Ge(\Theta) \times Ga(\Theta)$$

$Ge(\Theta)$ = element factor
$Ga(\Theta)$ = array factor

$$\text{Gain } G = G(\Theta) \times \cos(\Theta)$$

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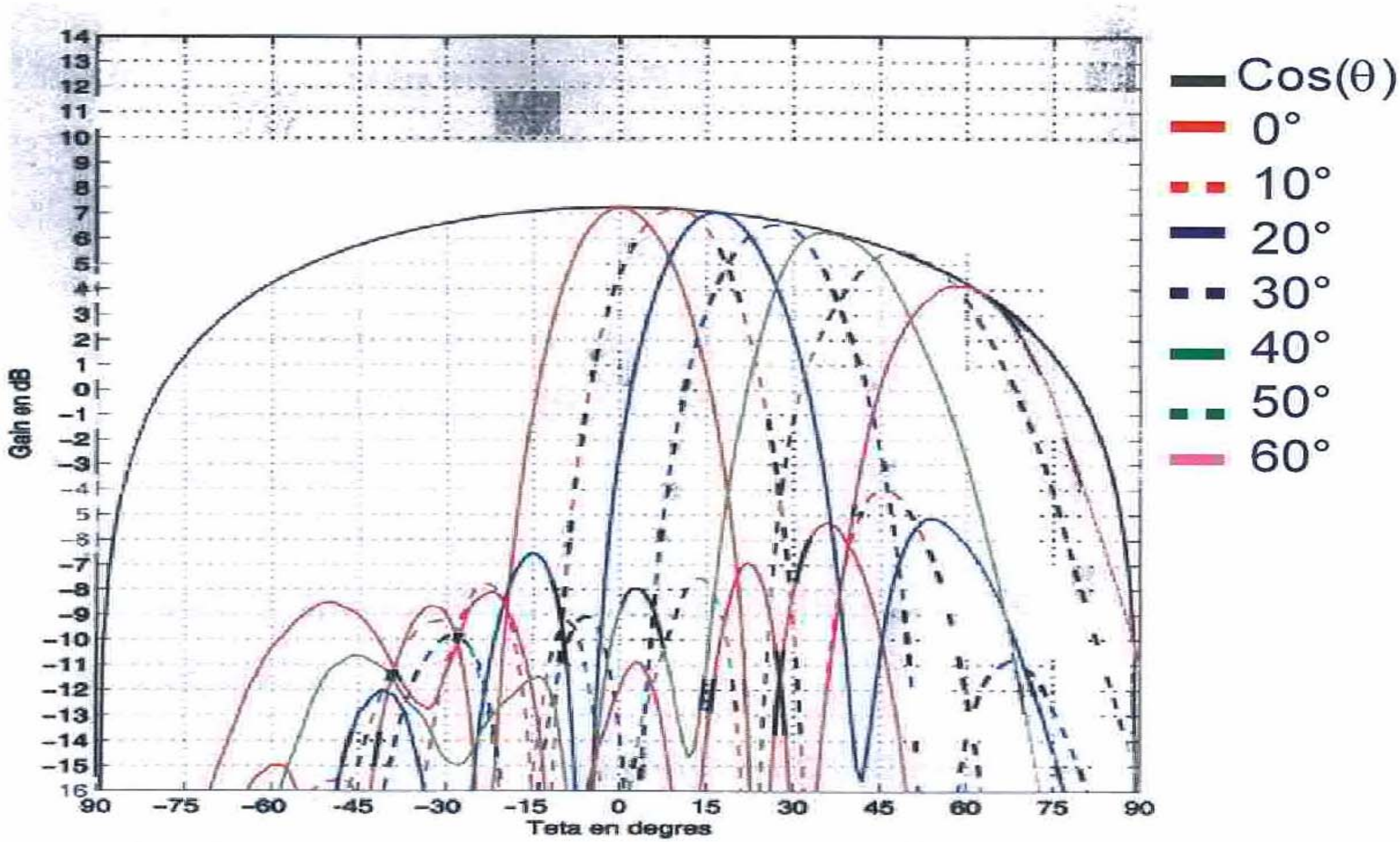
Gain as a function of scan angle



Linear array radiation pattern

- **GRATING LOBES:**
  - |Ea (θ)| is maximum whenever sin θ = ± nλ/d
  - Main lobe at sin θ = O

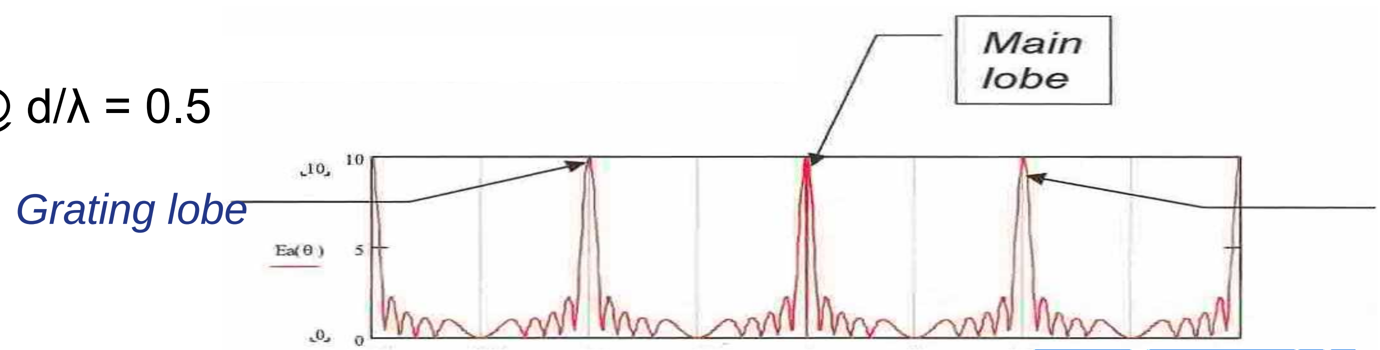
Other maxima are grating lobes:

- Grating lobes are undesirable and must be avoided
- they appear for n = ±1, ± 2, etc...
- for d/2 = 0.5 - sin θ >1 - no (real) grating lobes
- if d/λ = 1 grating lobes appear at θ = ± 90°

To prevent grating lobe, the element spacing d must satisfy:

$$d/\lambda \leq 1/(1+\sin\theta_{max})$$

Pattern for n=10 @ d/λ = 0.5



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To re-cap - the avoidance of the grading lobe condition:

To prevent grating lobe, the element spacing d must satisfy:

$$d/\lambda \leq 1/(1+\sin\theta_{max})$$

- Some new definition have been introduced recently:
  - Dense Array if $d/\lambda < 0.5$
  - Sparse Array if $d/\lambda > 0.5$
    - Personal opinion is that there is no need for a new definition as the above condition explains everything.
    - To avoid GL 'completely', we must keep $d/\lambda \leq 0.5$ for ALL frequency
    - Sparse array already has a different meaning in array antenna design terminology (thinned arrays, density tapered array etc)
- The conditions hold for planar geometry also

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Planar Array radiation pattern

• The radiation pattern of a two dimensional planar array can be written as the product of radiation pattern in the two planes which contain the principal axes of the antenna:

$G(\theta a, \theta e) = G1(\theta a) \times G2(\theta e)$ (array separability: f(x,y) = f(x) * f(y)

• Normalised radiation pattern of a uniformly illuminated rectangular array:

$$G(\theta e, \theta a) = \frac{\sin^2\left[N\pi\left(\frac{d}{\lambda}\right)\sin\theta a\right]}{N^2\sin^2\left[\pi\left(\frac{d}{\lambda}\right)\sin\theta a\right]} * \frac{\sin^2\left[M\pi\left(\frac{d}{\lambda}\right)\sin\theta e\right]}{M^2\sin^2\left[\pi\left(\frac{d}{\lambda}\right)\sin e\right]}$$

N = No of elements in θa dimension with d spacing
M = No of elements in θe dimension with d spacing

Comments:

- Equations used for modelling arrays but no account of mutual coupling is included
- In the design phase mutual coupling must be included otherwise radiation patterns will degrade and will have a poor match.

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Array distributions

- To design an array with lower sidelobes we have many different types of array distributions available to us. e.g.

- Uniform – simplest with first sidelobe level at about -13 dB
- Dolph - Tchebyschev – all equal sidelobes at any level
- Modified Sin x/x distribution - 1st sidelobe is specified (Taylor one-parameter distributions
- Taylor n-bar distribution (specified no of equal sidelobes)
- Taylor circular Aperture (2 – D arrays)
- there are many others….. (See Hansen – Phased array Antennas, Wiley)

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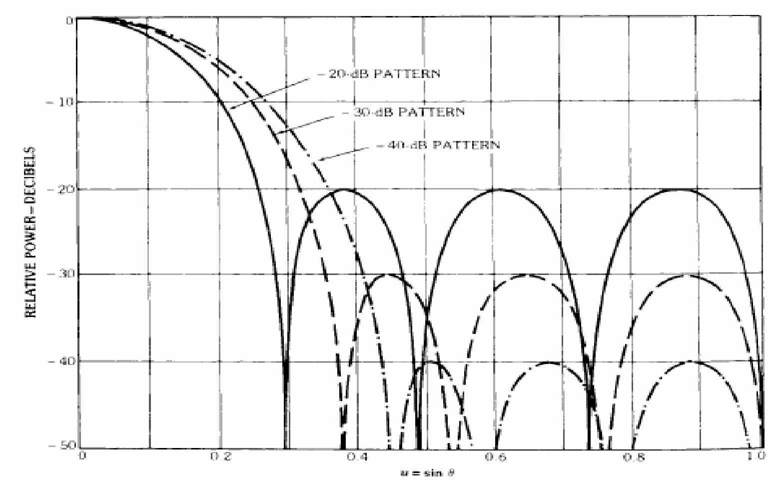
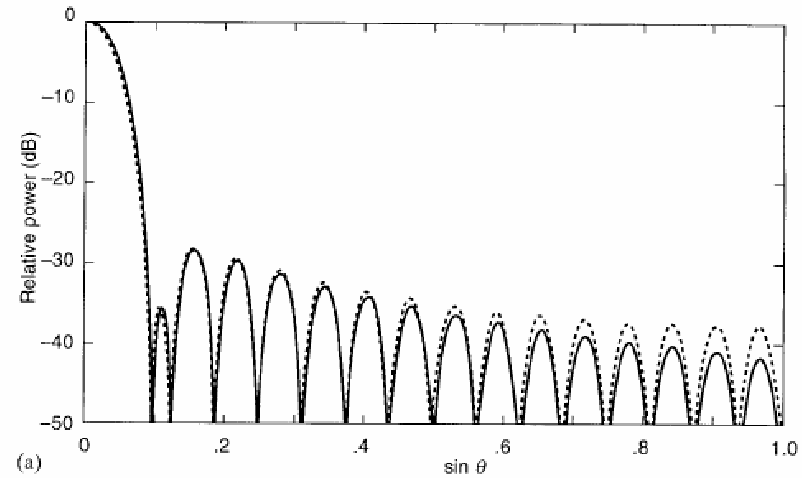
Examples of different distributions



Example of Dolph-Tchebyscheff
@sidelobe level of -20, -30 and – 40DB



Example of Nbar Taylor distribution
@ n bar =2 , -40db

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So exactly(≈) how do we design a phased array? (1)

We will consider the case for Embrace design

- Start with the size (or $\Theta_{3dB}(\theta)$ requirements or gain
  - We require approx 1m x 1m tile (or in λs) and many hundreds of tiles
    - » (as we had done before for ThEA)
  - The size also gives us an idea for the analysis of the phased array (finite or infinite)
- How do we fill this aperture?
  - We need scan requirements
    - » Astronomer normally say 'all the way down to horizon' i.e. ±90 deg.
- Consider the frequency range of operation
  - Highest and lowest frequency
    - » (For Embrace we chose about 1550MHz to 400MHz)
  - Determine spacing such that scan requirements are met at the frequency of operation
- It is these parameter you have to optimise for - *Normally !!!*

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So exactly(≈) how do we design a phased array? (2)

- For Embrace we also had to optimise for cost!
  - For cost optimisation, we sometimes over design or under design slightly, (negotiate the performance)
  - As Embrace is a 'demonstrator' – there was no need to stick to the numbers produced on frequency and scan req't so rigidly.
  -
    - (Scan up to 90 deg and up to Neutral Hydrogen frequency – 1421MHz)
    - $\lambda/2$ at 1421 MHz = 21/2 = 10.5 cm i.e. _about_ 9 el x 9 el
    - We chose 8 el x 8 el which gives 12.5 cm spacing in 1metre.
    - 12.5 cm spacing gives scan of up to between 40 and 45 degrees at 1421 MHz
    - We considered this acceptable. (Dense, Sparse, closely packed ??? etc.)
- Sometimes there are additional parameters which also needs to be considered for optimisation.
  - Weight (Not considered here)

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Analysis

- Once you have approximate dimensions, you need to analyse with correct software
- Determine exactly what you want out from the software e.g. for a phased array, designed on an infinite array basis, one needs the VSWR (reflection coefficient) v Scan and Frequency.
- Use only the verified the software. (or write your own but verify extensively.)

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Comments:

- Must not 'overdesign' too much otherwise it will be costly
- Significant cost reduction will come from a proper design
- Continue to make 'sanity' checks at each level
- Let's see how we have used these comments for Embrace design

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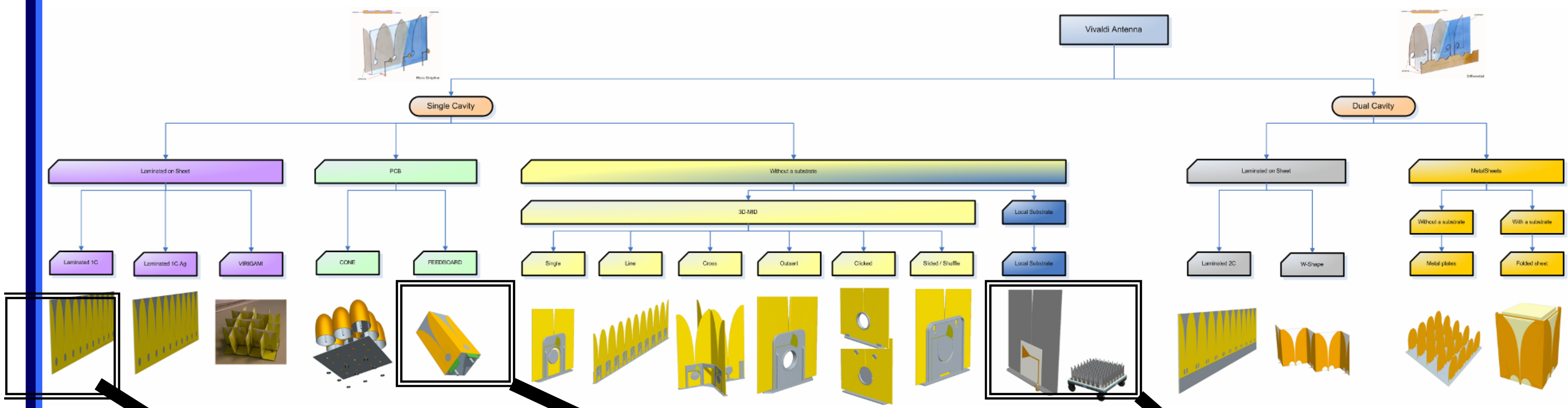
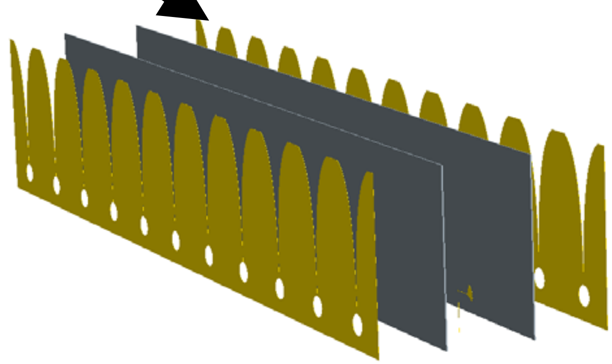
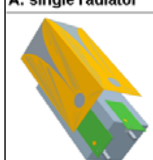
Antenna concepts





4: Feed board single cavity

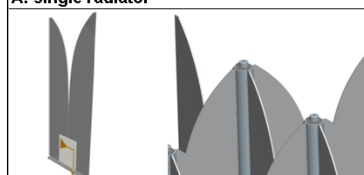
A: single radiator



weight	note	Ranking
33,3333	add ground stripline	5
33,3333		4
33,3333		5

6: AL Viva single cavity

A: single radiator



weight	Note	Ranking
33,3333	stripline feed added	5
33,3333		5
33,3333		4

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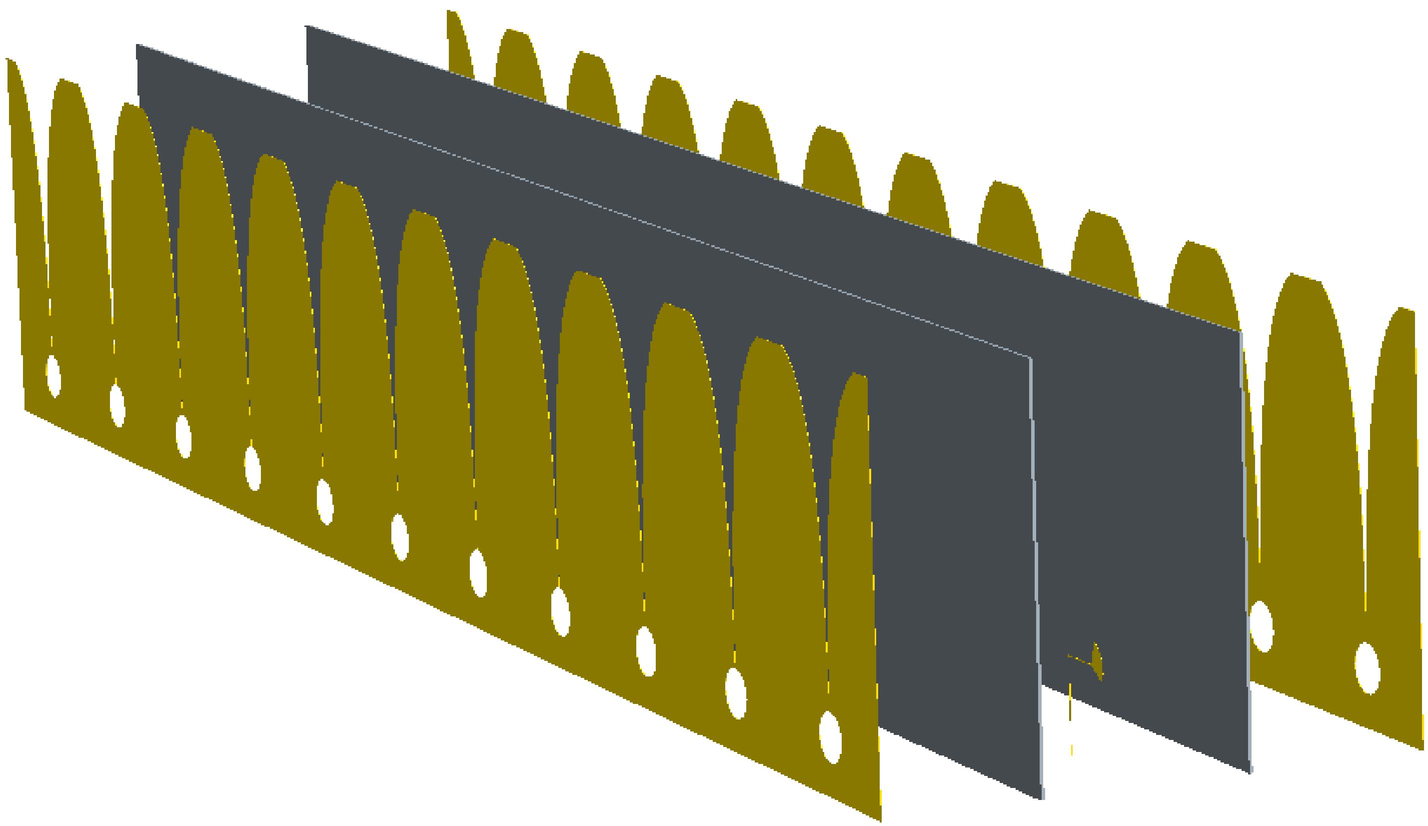
Baseline design of the radiators

- Design Vivaldi with a stripline feed configuration
- Similar design to THEA – safe approach



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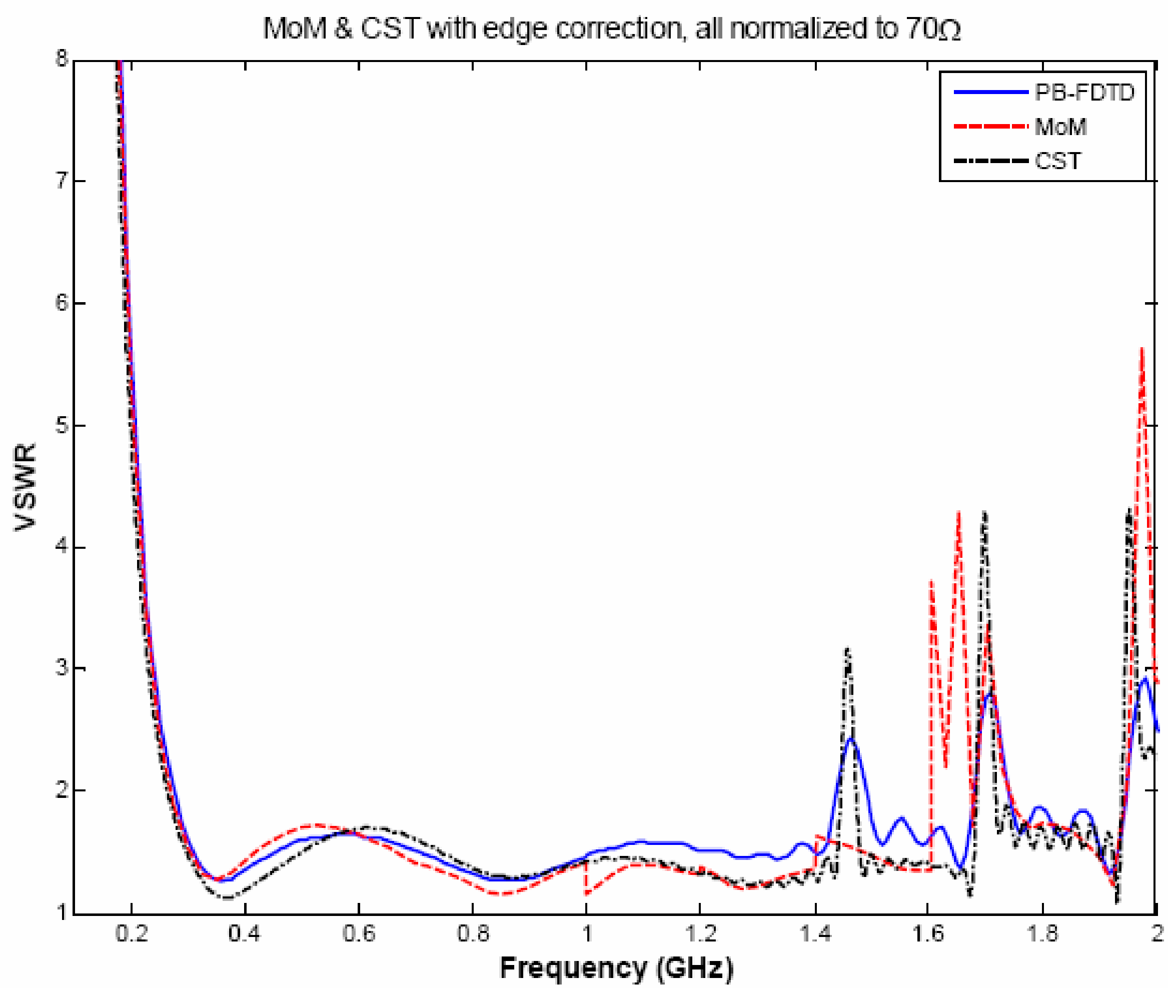
Verification of Simulation software



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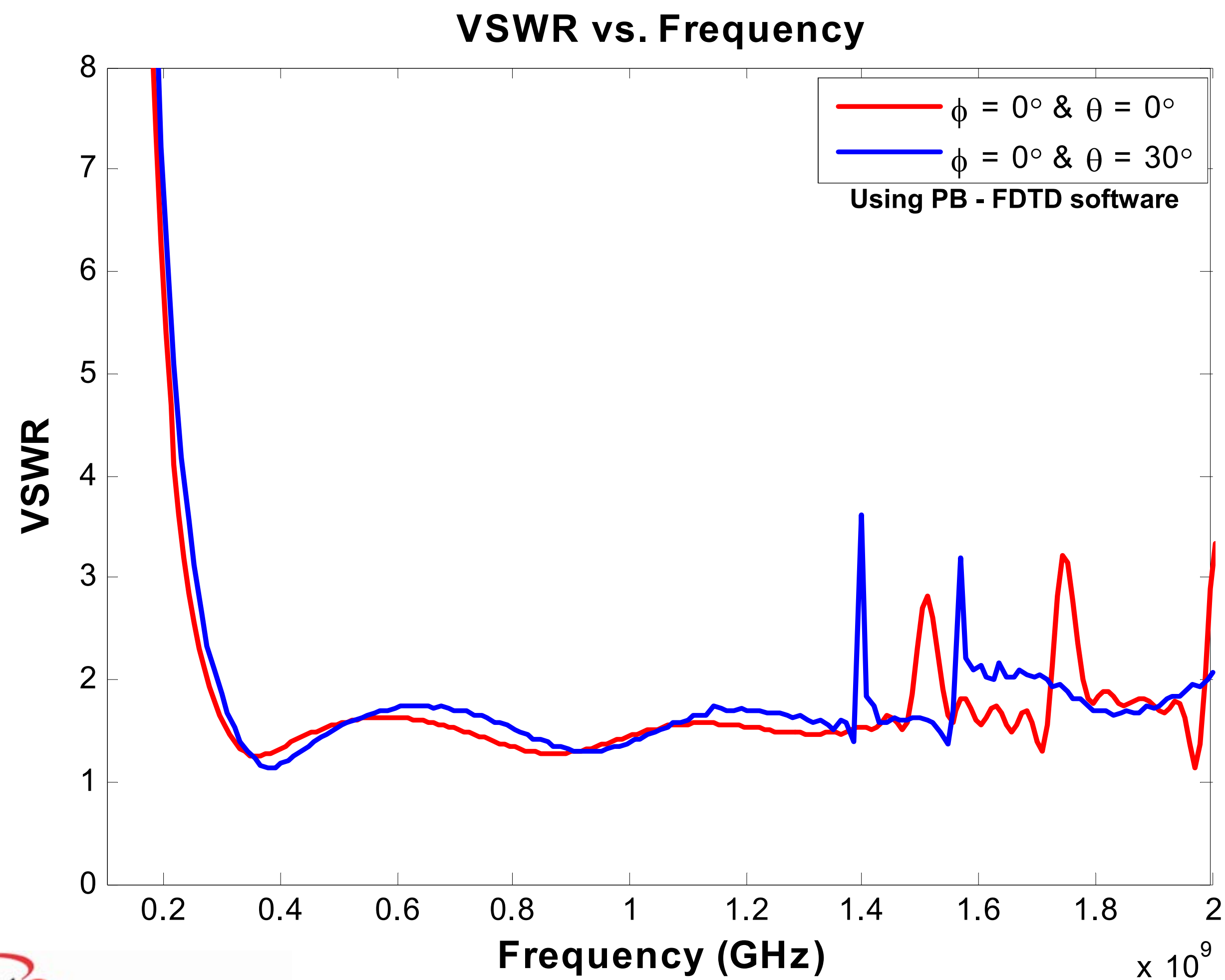
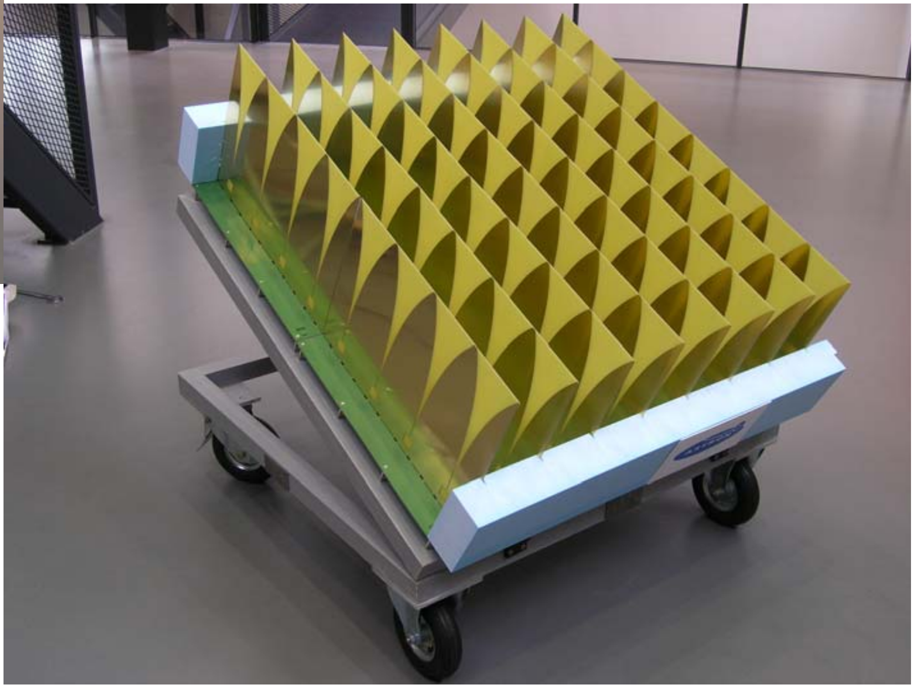
Simulated performance for Vivaldi with Stripline feed (Embrace)



Actual tile



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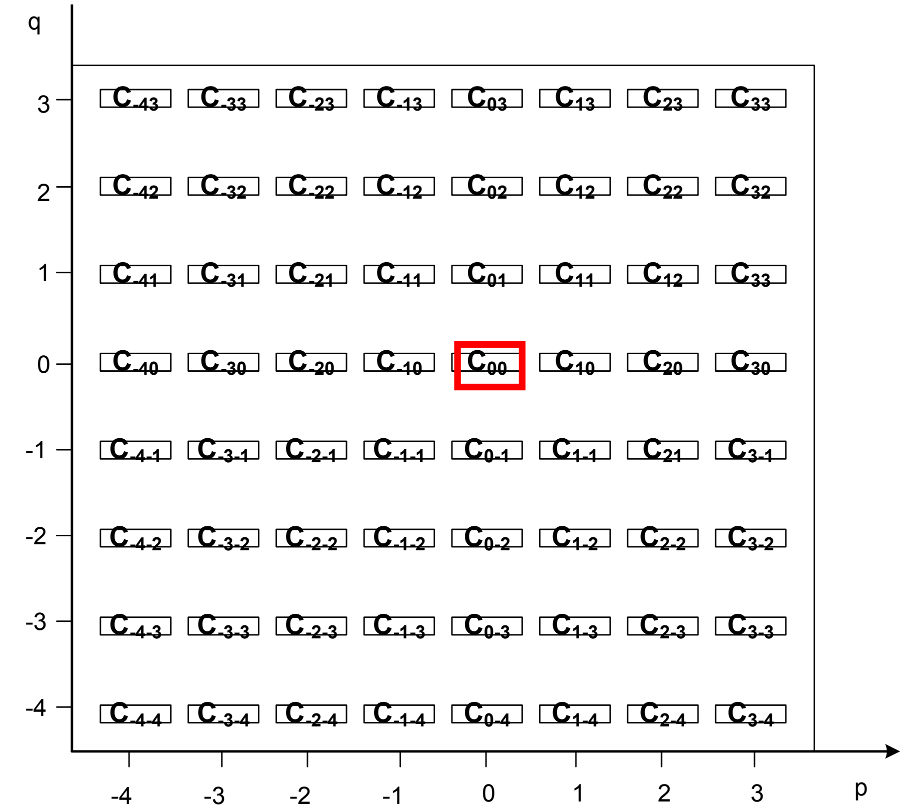
Measured 8 x 8 Array

$$\Gamma_{ACT} = \sum_{p=-\infty}^{\infty} \sum_{q=-\infty}^{\infty} C_{00,pq} \exp\{-j(k\sin\theta\cos\phi pDx)\} \times \{-j(k\sin\theta\cos\phi qDy)\}$$



0.3 GHz, λ x λ
1.2 GHz, 4λ x 4λ

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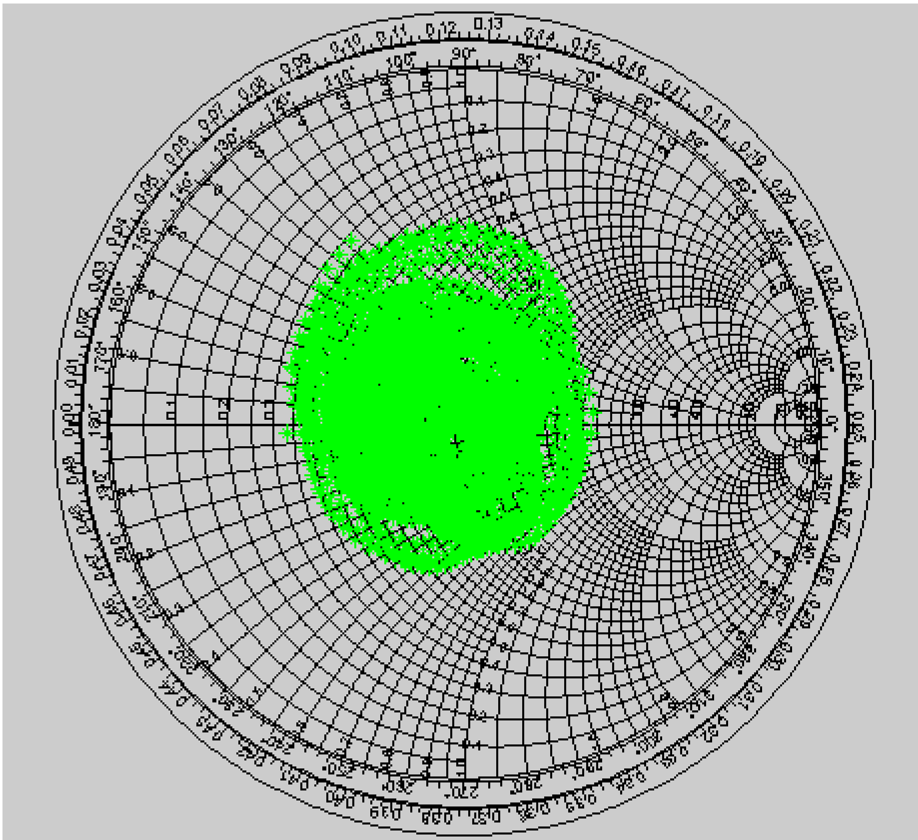
Smith Chart



Normalised to feed line impedance: 70 ohms

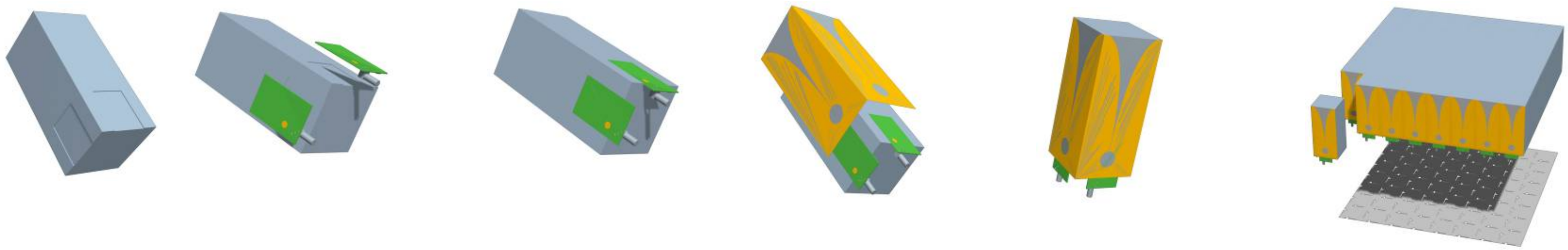
0.3 – 1.4 GHz

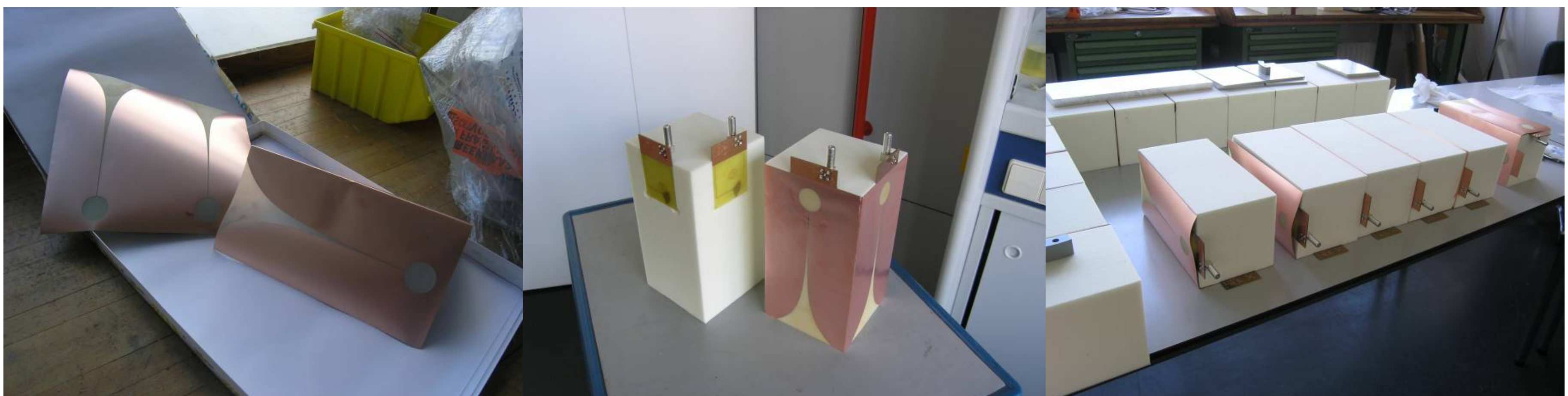
H-Plane 0° - 45°

E-Plane 0° - 45°

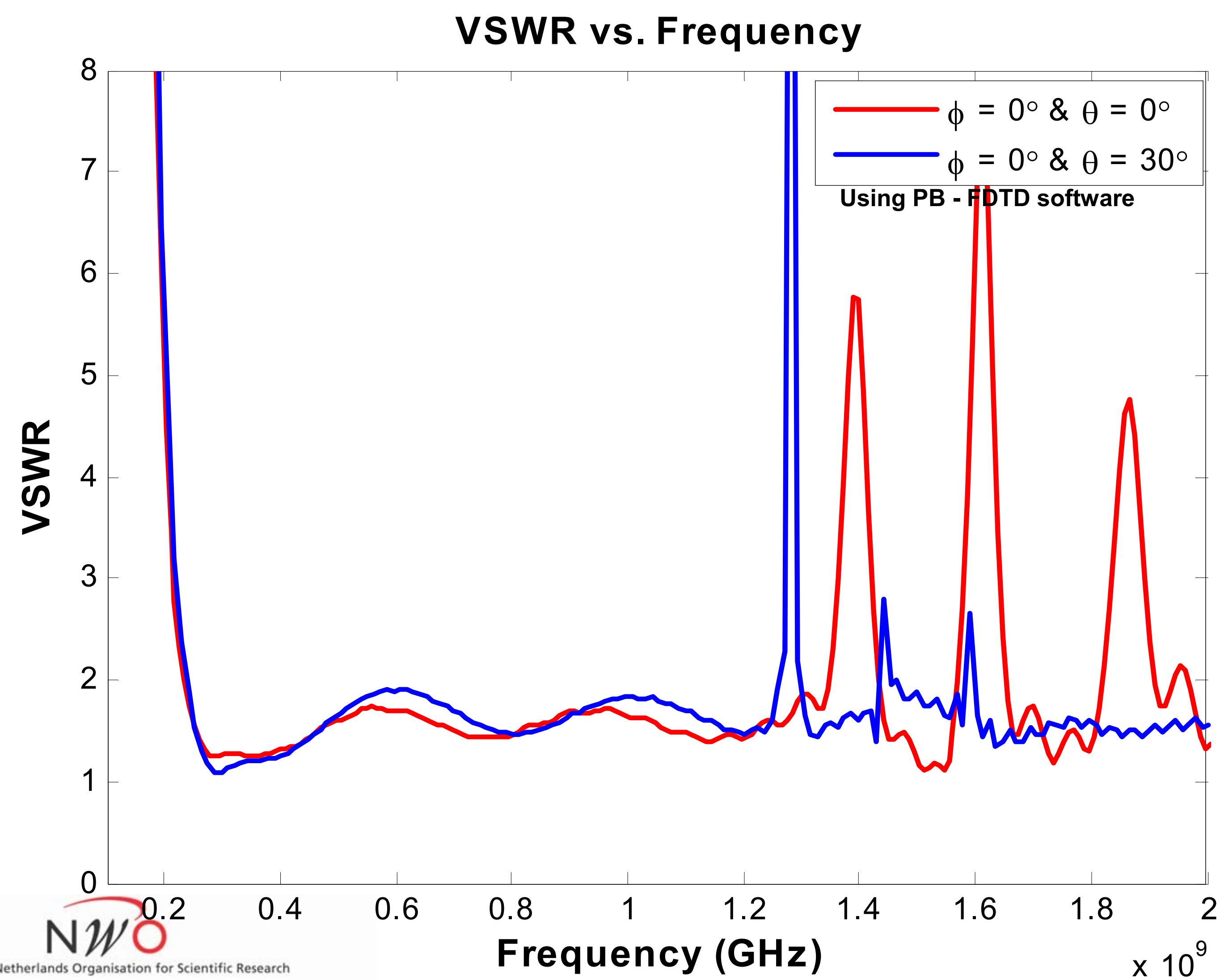
Migration to Low cost and Dual polarisation

- Single sided Vivaldis and a microstrip feed
- Simple construction and low cost





Simulated performance for Vivaldi with Microstripline feed



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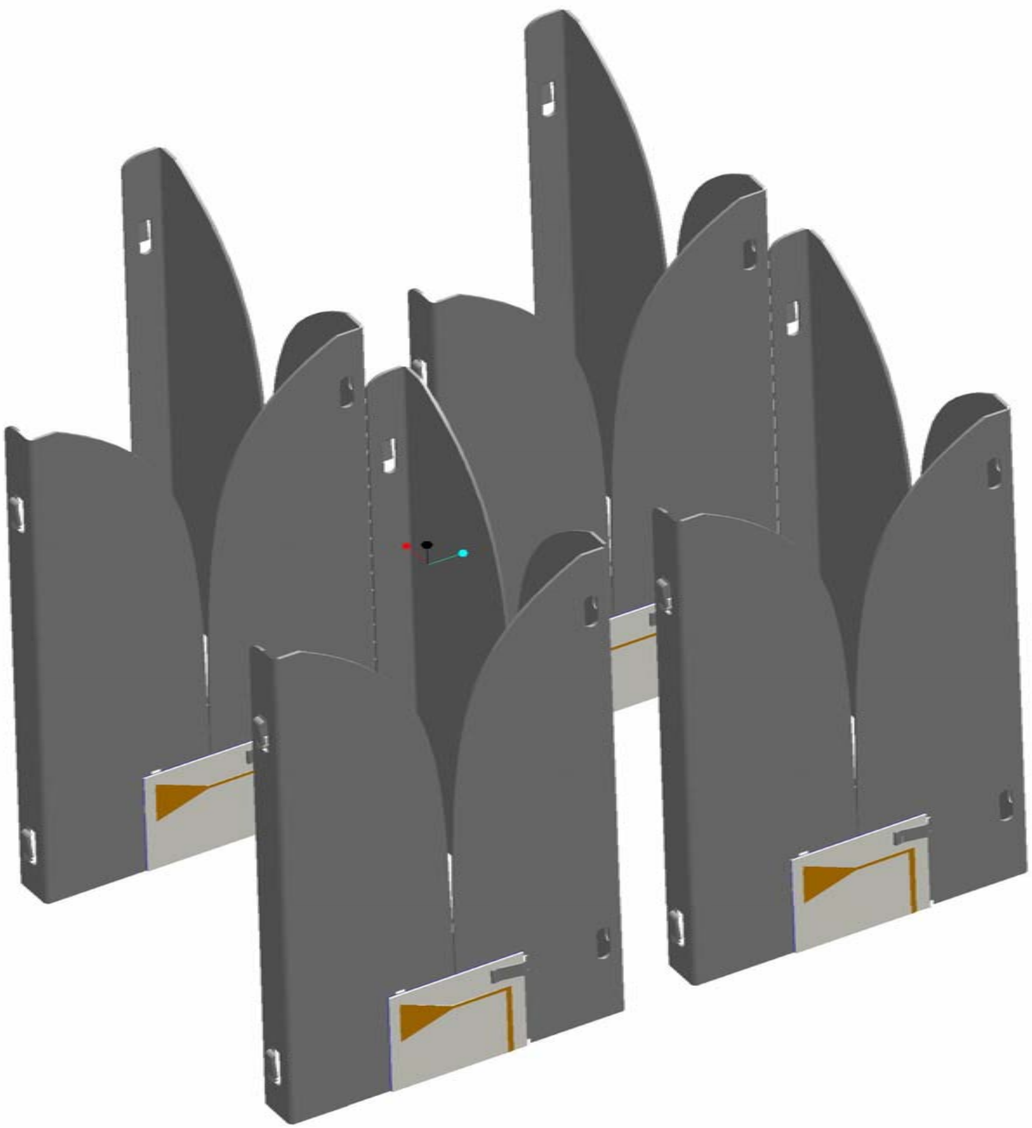
Chosen antenna type from all the possible options



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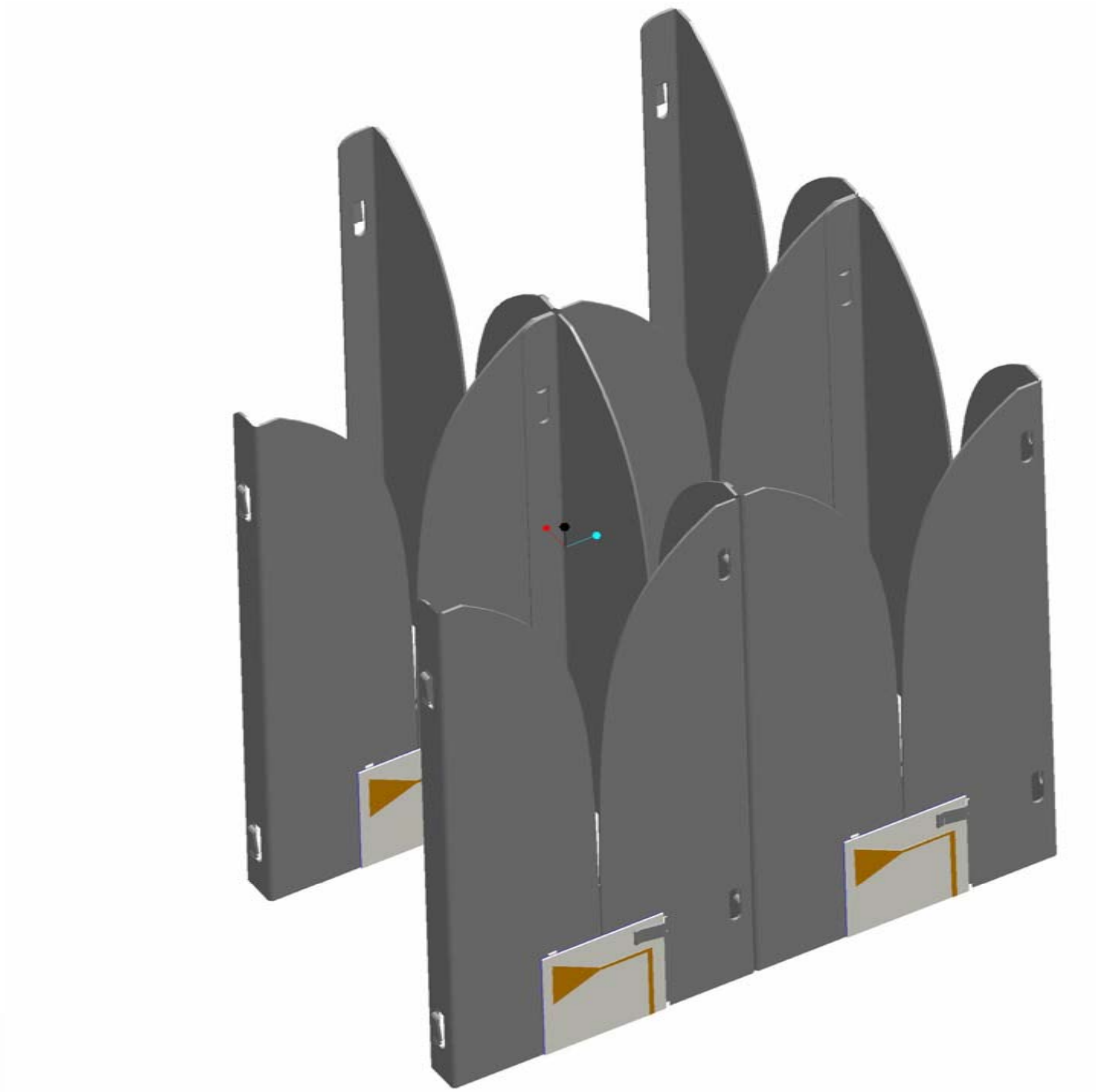
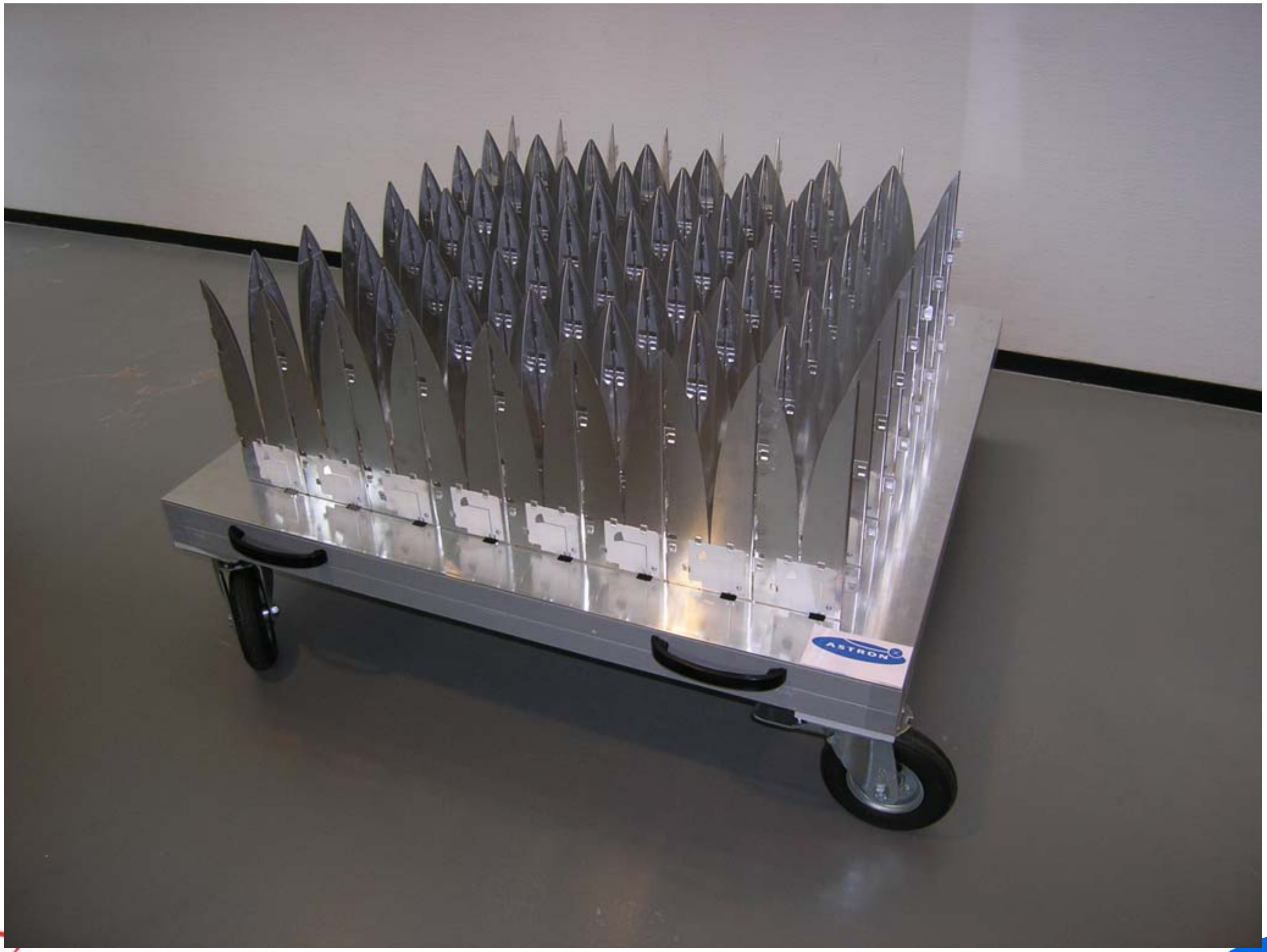
Possible practical design of Vivaldis



Embrace Tile



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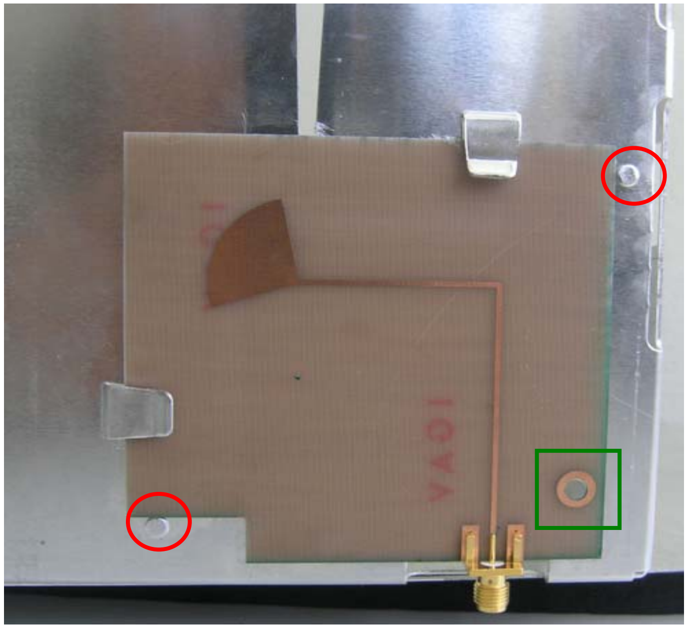
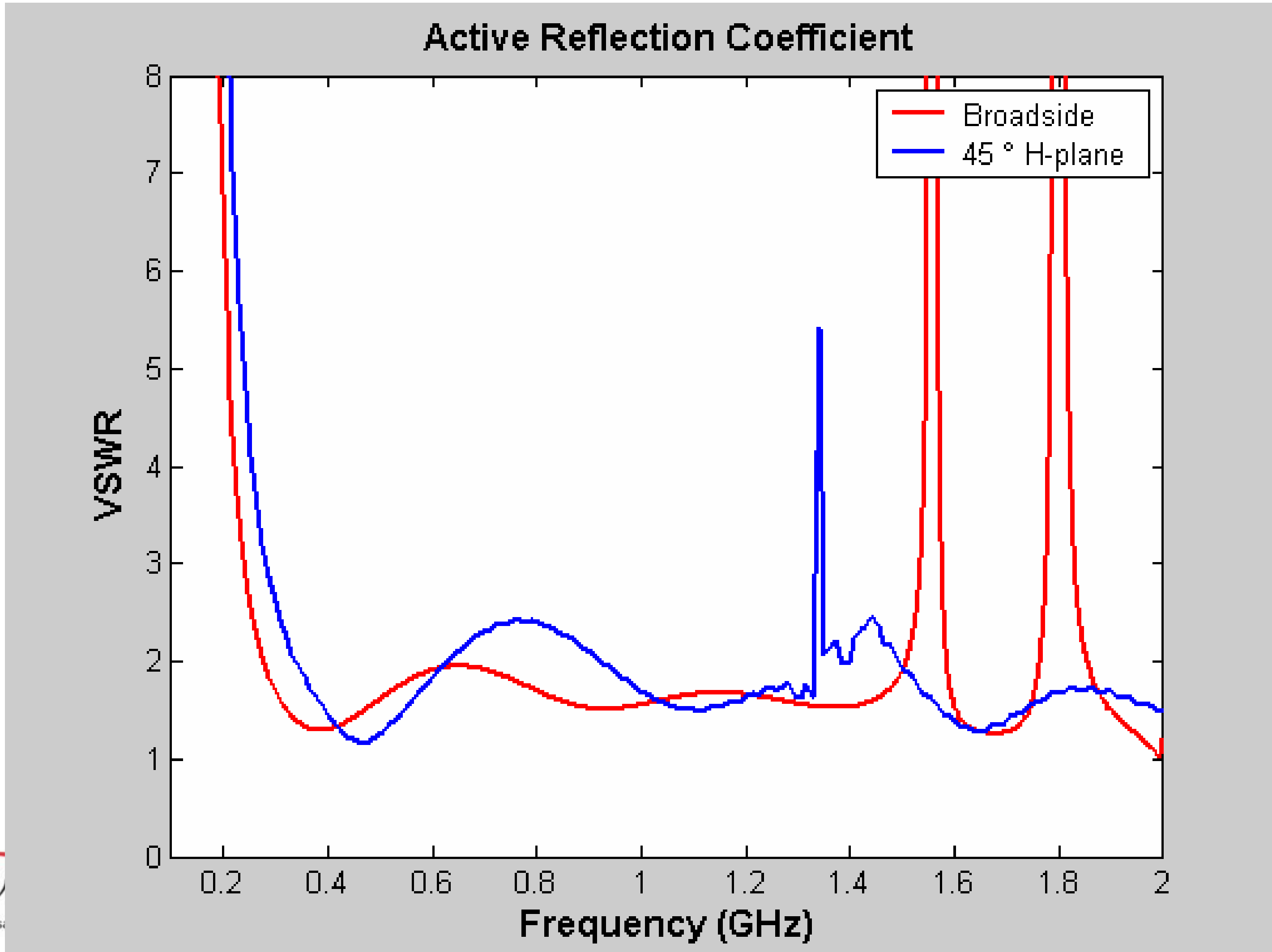
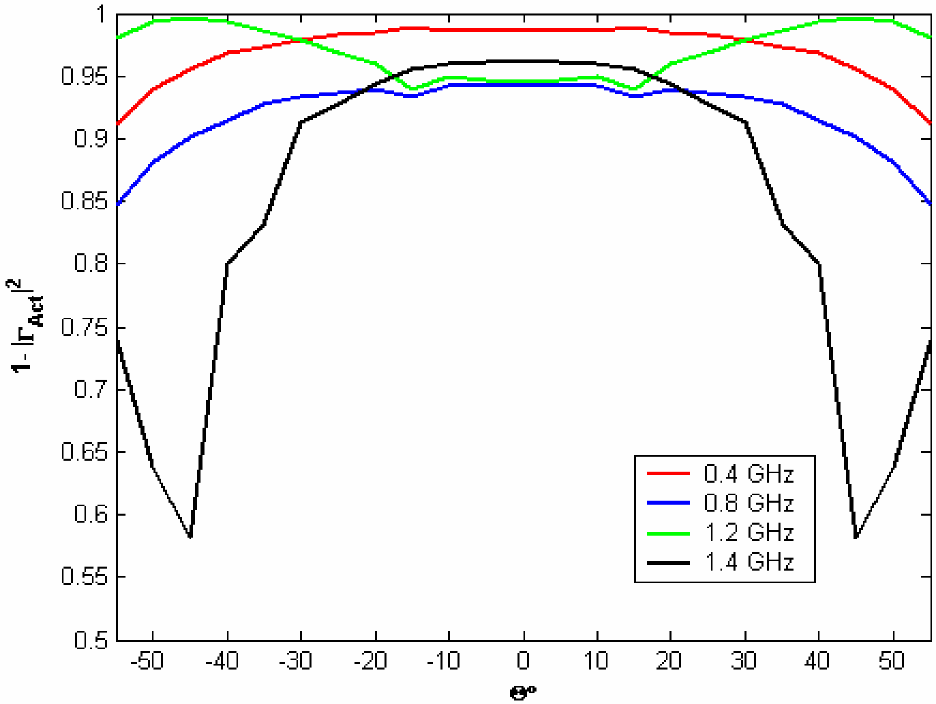


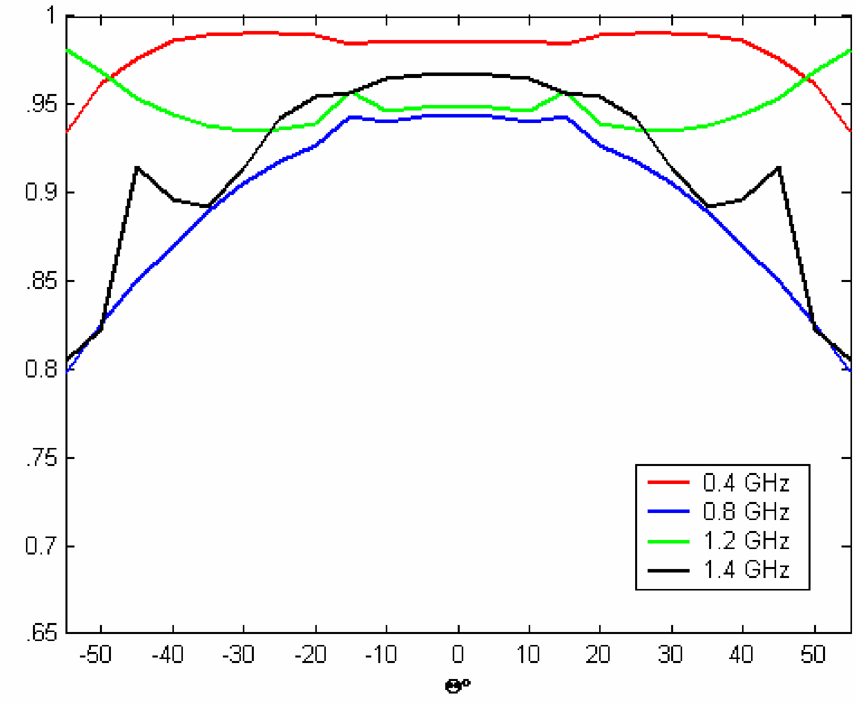
Aluminium Radiator with microstrip feed



Element pattern as a function of frequency (for Embrace Vivaldi antennas)

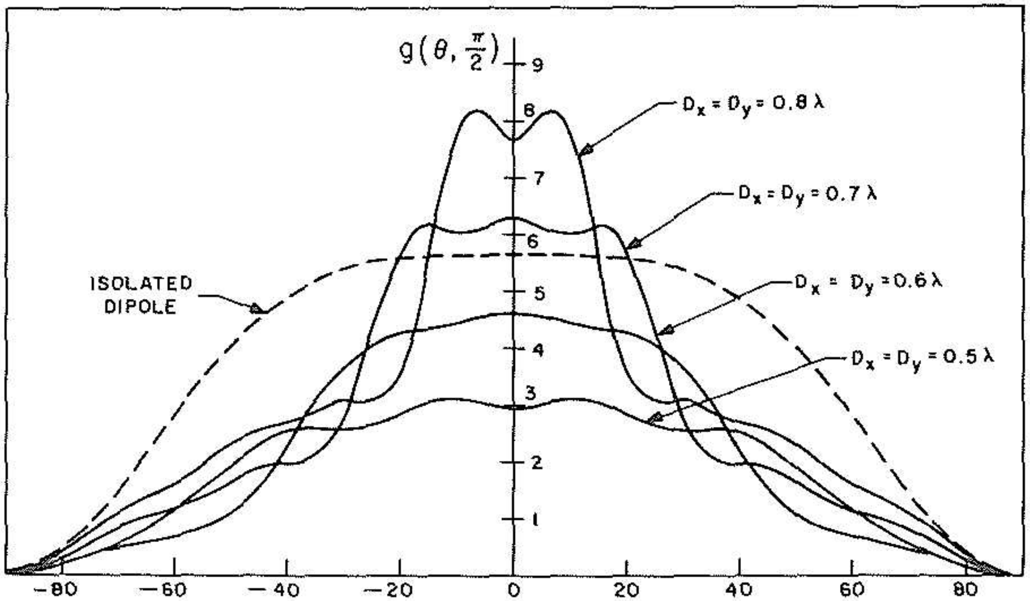


E-Plane



H-Plane

Element pattern as a function of spacing



H plane element pattern for a centre element of a 7 x 9 element λ/2 dipole array

- Larger the spacing, smaller the allowed scanned region before the GL appears
- Scanned blindness appears just before the emergence of the GL
- Spacing not only restricts the scanned region but also narrows the element pattern
- before the analysis, the basic design process must be understood

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References

- Hansen R. C., ‘Phased Array Antennas’, Wiley
- Mailloux R., ‘Phased Array Antennas Handbook’, Artech House
- Brookner, E. ‘Practical Phased Array Antenna Systems’, Artech House

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Thank you