Advanced Antenna Systems for 21st Century Satellite Communications Payloads

by

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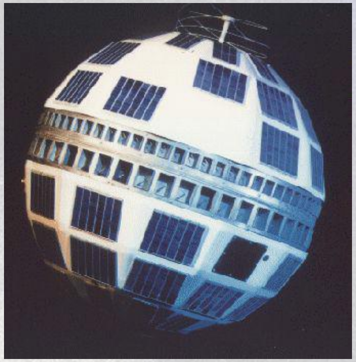
AGENDA

- Introduction to Satellite Communications
- Phased Arrays
- Contoured Beam Antennas
- Multi-beam & Multi-Band Antennas
- Reconfigurable Beam Antennas
- Hybrid Antennas
- PIM & Multipaction
- Conclusions



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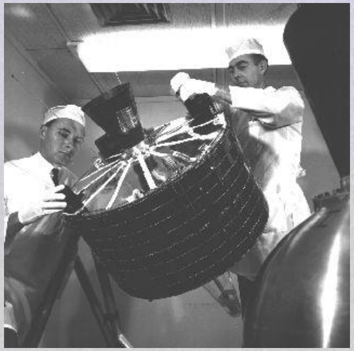

SYNCOM 2

*S. Rao, L. Shafai, & S. Sharma, "Handbook of Reflector Antennas and Feed Systems", Vol. 3, Artech House Publishers, June 2013
** S. Rao, "Advanced Antenna Technologies for Satellite Communications Payloads", IEEE Trans. AP, Special Issue, Apr 2015

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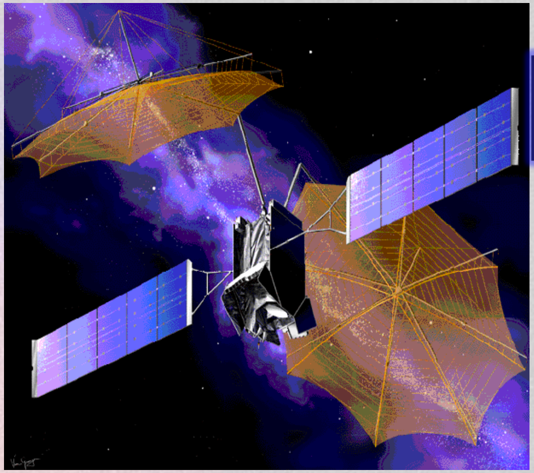
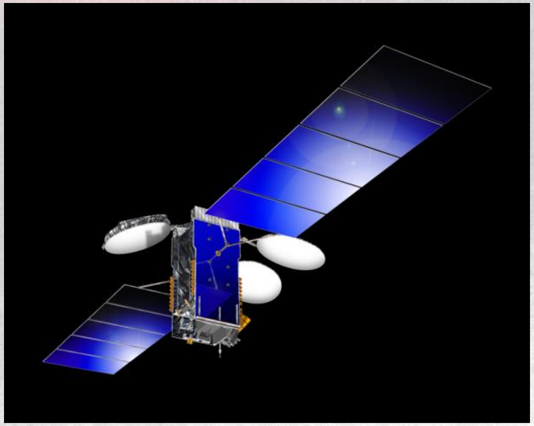
Introduction to SATCOM Antennas: Definition of Satellite Communications

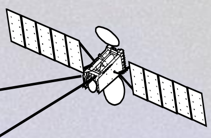


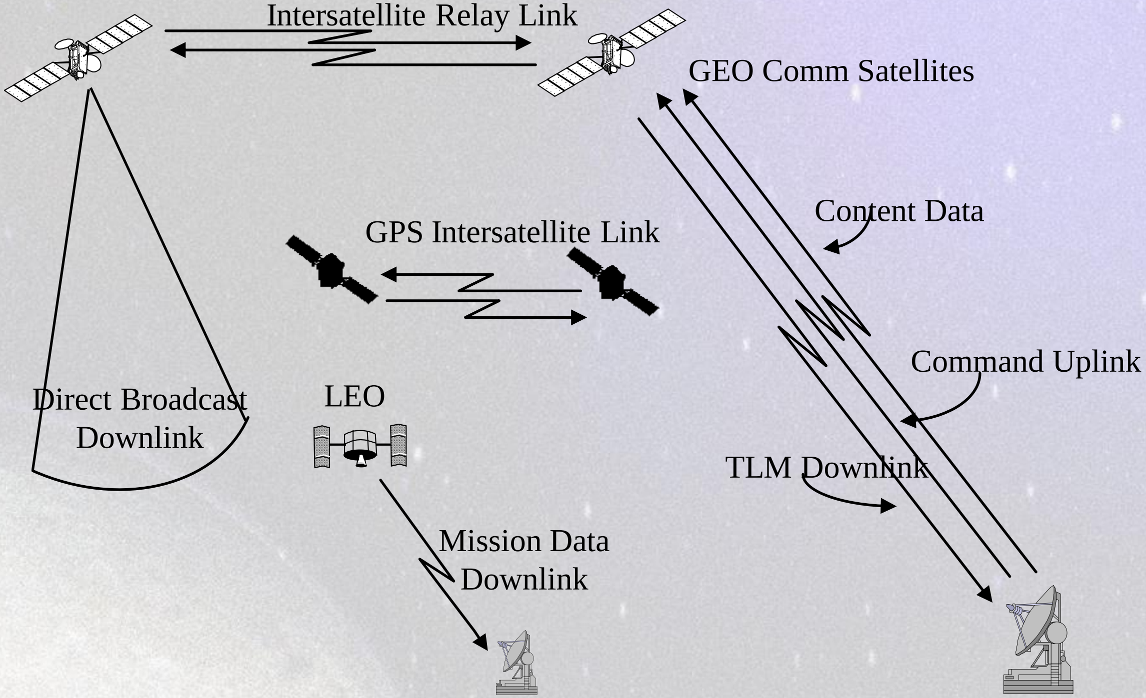
3 or 4 satellites for global GEO coverage



17.4^0

- Earth Radius = 6832 kms
- Satellite Altitude = 35786 kms
- Subtended Angle = +/- 8.7^0





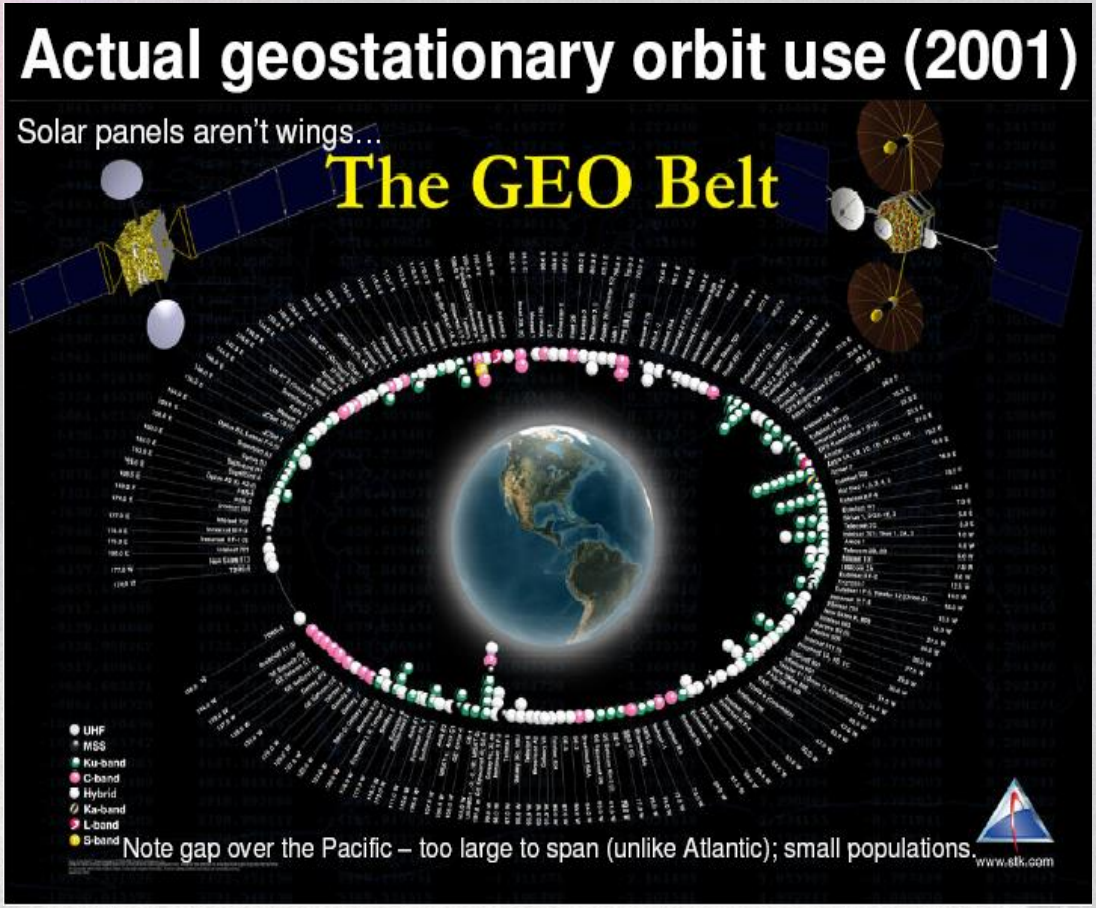
Key Considerations

- Thermal
- High Power, PIM
- ESD
- X-pol, Bandwidth

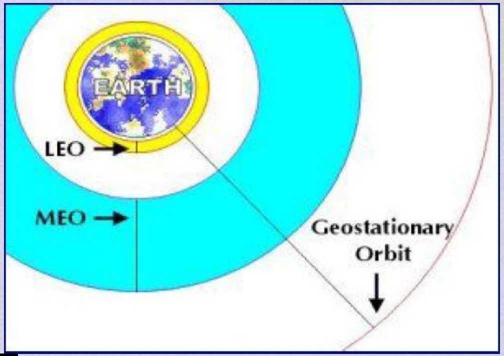
$$SNR = EIRP + G/T + 228.6 + S_L - 10\log_{10}(B_w)$$
$$= G_T + P_i + G_R - T + 228.6 + S_L - 10\log_{10}(B_W)$$

*** Antenna design critical to satellite payload**

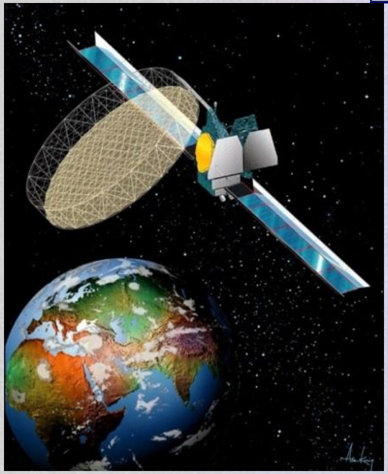
GEO Satellites

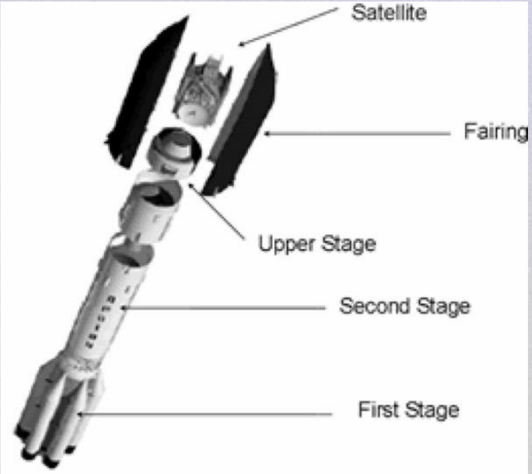


Designated Satellite Services (ITU)



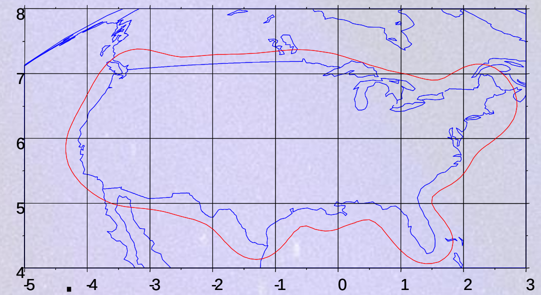
- Aeronautical Mobile Satellite Service (AMSS)
- Aeronautical Radio Determination Satellite Services (ARDSS)
- Amateur Satellite Service
- **Broadcasting Satellite Service (BSS)**
- Earth-Exploration Satellite Service (EESS)
- **Fixed Satellite Service (FSS)**
- **Inter-Satellite Service (ISS)**
- Land Mobile Satellite Service (LMSS)
- Maritime Mobile Satellite Service (MMSS)
- Meteorological Satellite Services
- **Mobile Satellite Service (MSS)**
- Radio Determination Satellite Services (RDSS)
- Space Operations Service
- Space Research Service
- Standard Frequency and Time Signal Satellite Service
- **Personal Communication Services (PCS)**





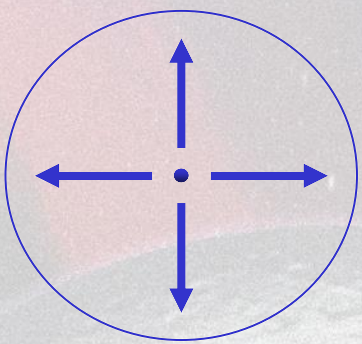
Antenna design depends on satellite service and coverage

Antenna Directivity, Gain, Polarization

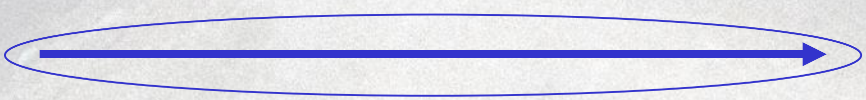


- **Isotropic radiator**
  - A point source that radiates equally in all directions
- **Directivity**
  - A measure in dB of an antenna's ability to transmit or receive energy in a given direction compared to an isotropic radiator.

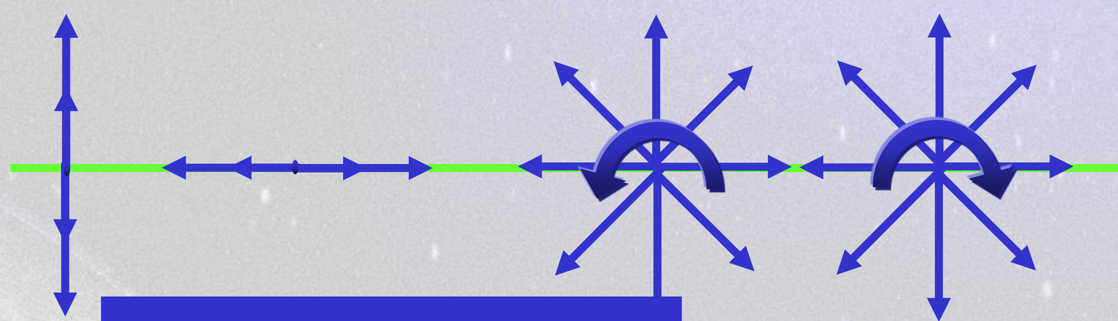
Isotropic Radiator



Directive Antenna



Vertical **Horizontal** **Left Hand Circular** **Right Hand Circular**



- **OMTs (symmetric, asymmetric)**
- **Polarizers**

- **Gain**

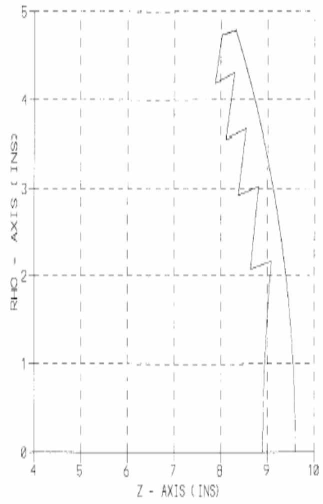
  = Directivity – Antenna Losses

Spacecraft Antenna Types

- High Gain Antennas (30 dBi to 70 dBi)
  - Reflector Antennas (widely used)
  - Lens Antennas (hardly used)
    - * Dielectric Lenses: ESD issues
    - * Waveguide Lenses: Narrow Bandwidth
  - Array Antennas (occasionally used)

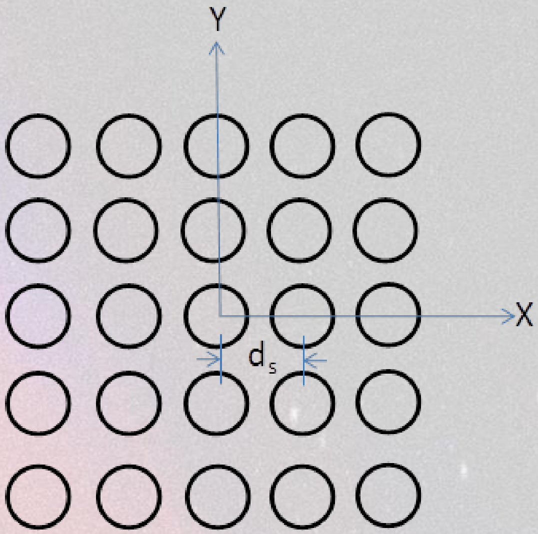
- Medium Gain Antennas (15 dBi to 25 dBi)
  - Global coverage horns

- Low Gain Antennas (0 dBi to 12 dBi)
  - Biconical Antennas
  - Waveguides
  - Horn Antennas



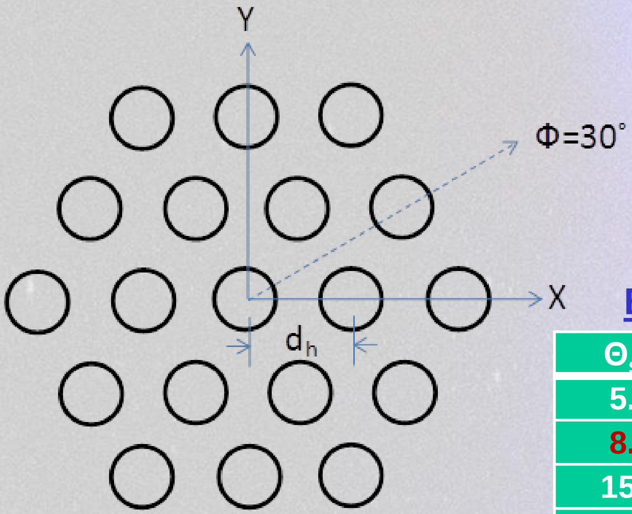
Radiation of satellite antennas is highly dependent on spacecraft structure, antenna suite, & mutual coupling effects. RF analyses and tests need to be carried out to validate the designs.

Phased Array Antennas: Lattice



(a)

Square Lattice



(b)

Hexagonal Lattice

$$\frac{d_s}{\lambda_h} \leq \frac{1}{sin\theta_{sm} + sin\theta_G}$$

- Ease of implementation
- Better scan loss

$$\frac{d_h}{\lambda_h} \leq \frac{1.1547}{sin\theta_{sm}+sin\theta_G}$$

- Fewer number of elements (15% less)
- More scan loss

- Flexibility
- Low-Profile
- Lower Efficiency
- Higher Cost

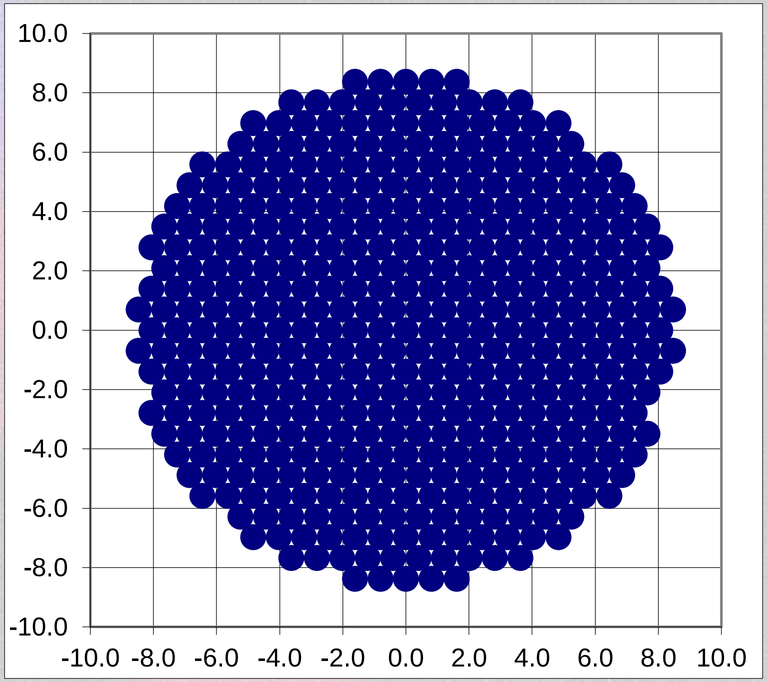
Elem Spacing Vs Scan Angle

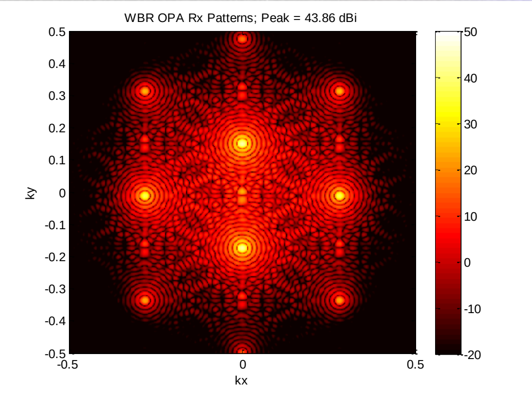
Θ_{sm}	Θ_G	d_s/λ	d_h/λ
5.0	6.0	5.22	6.02
8.7	9.7	3.13	3.61
15.0	16.0	1.87	2.16
30.0	32.0	0.97	1.12
45.0	47.0	0.70	0.80
60.0	65.0	0.56	0.66
70.0	75.0	0.52	0.61
80.0	85.0	0.50	0.58

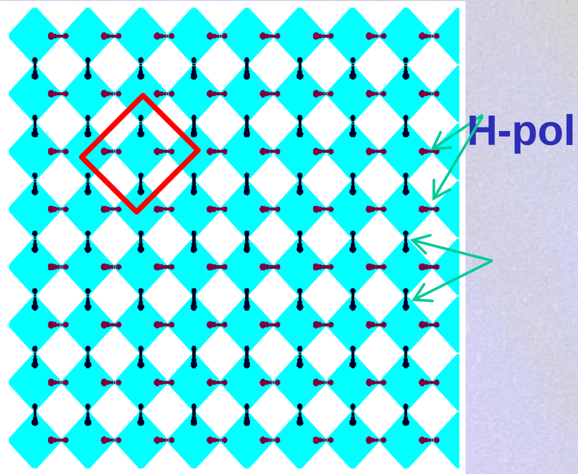
SQUARE ↑ (column d_s/λ) HEX ↑ (column d_h/λ)

- Choose element spacing based on highest frequency & max scan angle
- Choose element design based on bandwidth, polarization, & scan reqts
- Prepare detailed loss budget (amp/phase errors, quantization, element loss, thermal, impl margin etc.)
- Evaluate array gain at lowest frequency
- Evaluate array front-end losses based on highest freq

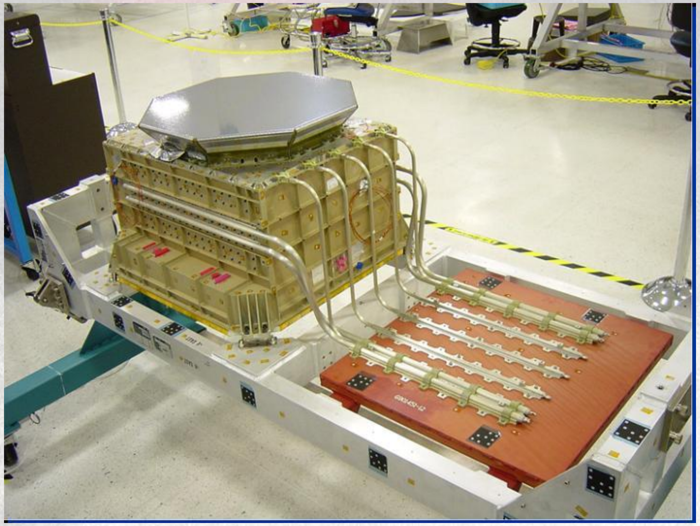
Phased Arrays with Flexible Beams

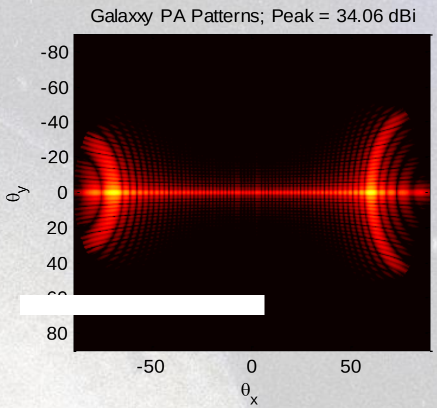


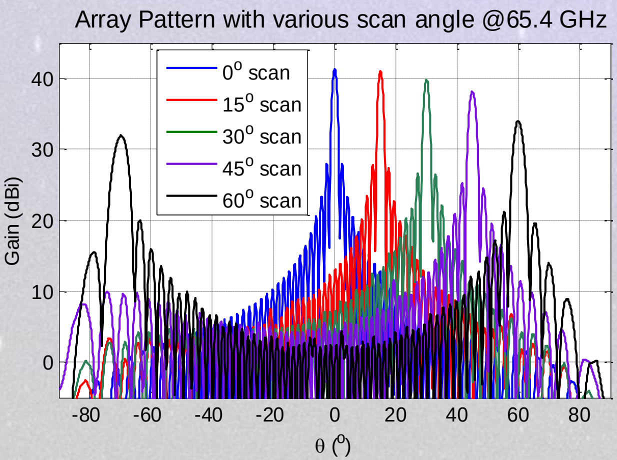




- Scan blindness
- Scan loss
- Bandwidth
- Grating lobes
- Thermal design & control







Array Design

- Number of Elements: $N = 10^{0.1(D_A - D_e)}$
- D_e is the element gain at bore-sight
- Array Directivity:

$$D_A = G_p + L_S + SL + T_L + I_m$$

Peak Gain (over cov.) → G_p

Insertion Loss → L_S

ScanLoss (elem.Patt roll-off) → SL

Taper Loss (about 90%) → T_L

Impl. Margin → I_m

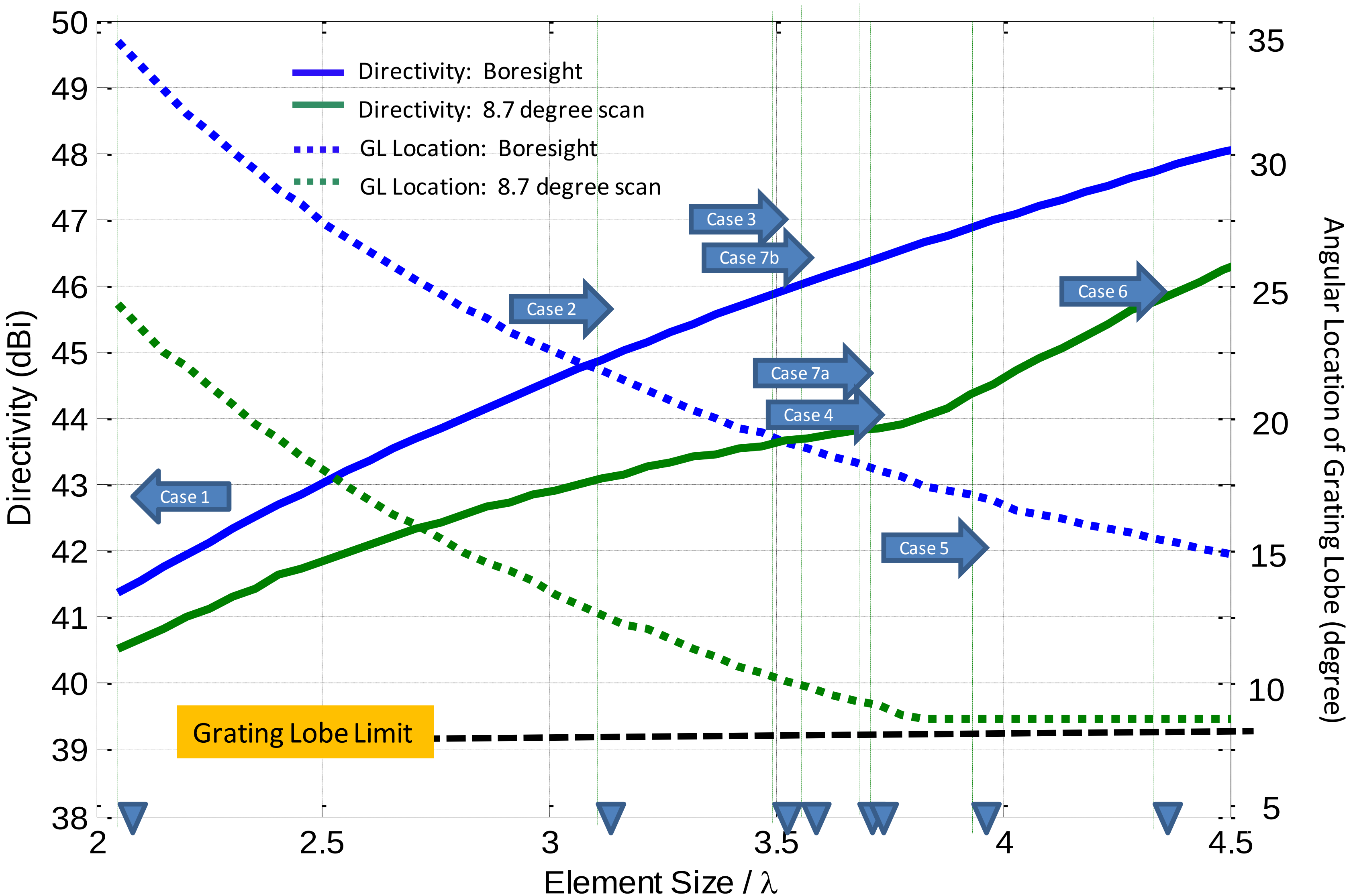
Key considerations

- Scan Angle
- Array lattice
- Bandwidth
- Scan blindness
- Polarization
- Sidelobes

Scan Angle (degrees)	Element Spacing in λ at Highest Freq. *		Number of Elements for 1000 λ**2 at Highest Freq	
	Square Lattice	Hexagonal Lattice	Square Lattice	Hexagonal Lattice
80	0.50	0.58	4000	3464
70	**0.52**	**0.60**	**3698**	**3208**
60	**0.55**	**0.64**	**3306**	**2863**
50	**0.61**	**0.70**	**2687**	**2327**
40	0.71	0.82	1984	1718
30	0.88	1.02	1291	1118
20	1.19	1.37	706	611

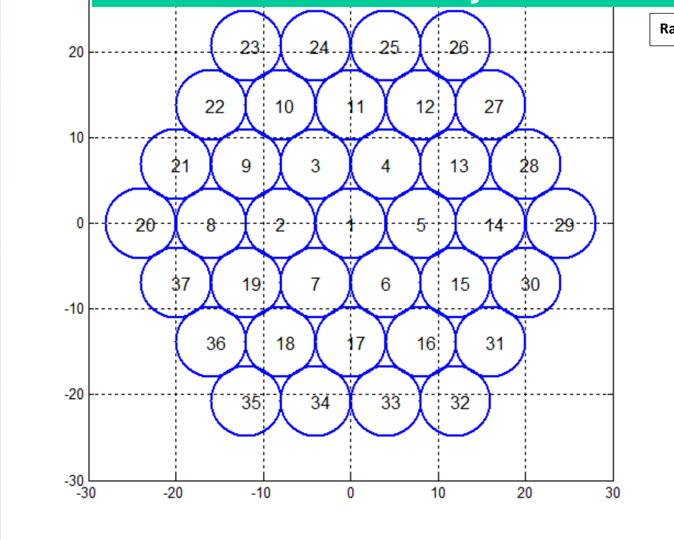
*** Assumes closest grating lobe location as 10 deg. larger than the maximum scan angle**

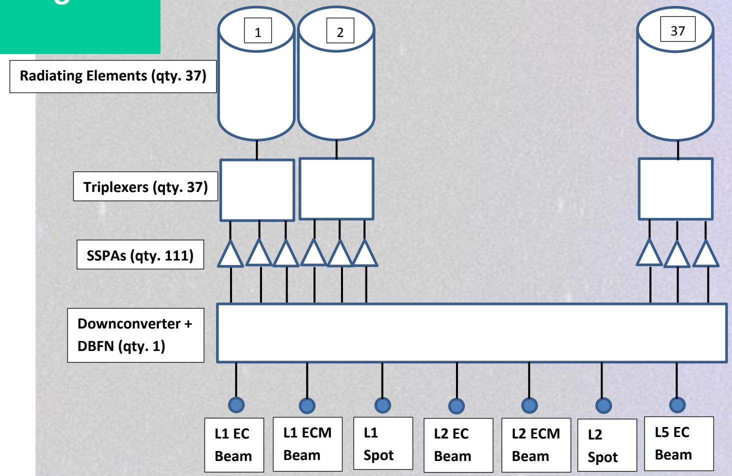
Element Spacing vs Grating Lobes



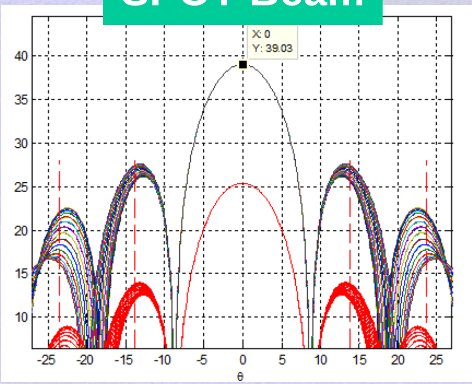
L-Band Reconfigurable Array for GPS Next

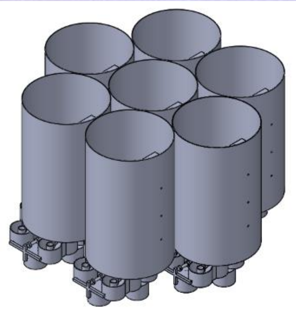
37-Element Array Geometry with Hexagonal Grid Layout

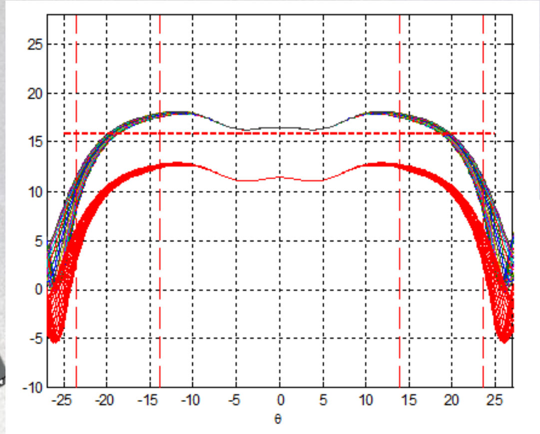




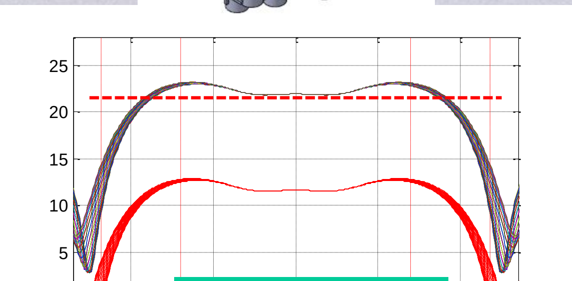
SPOT Beam



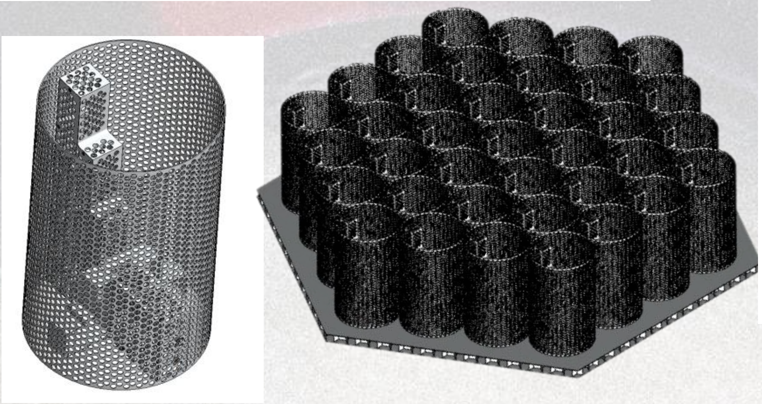




EC Beam

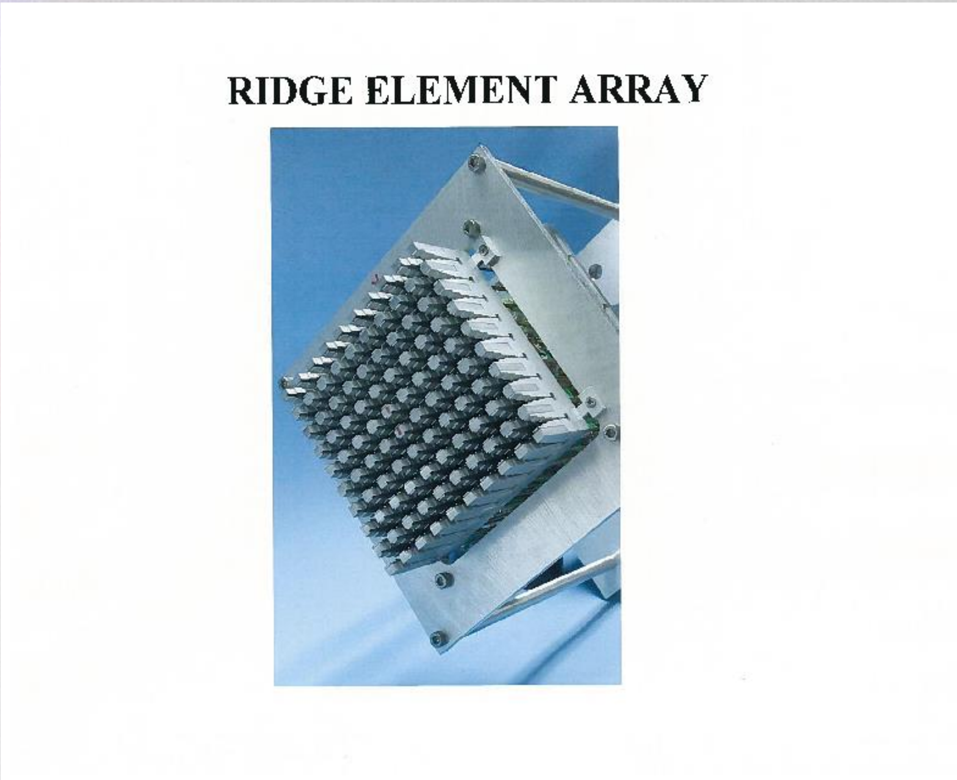


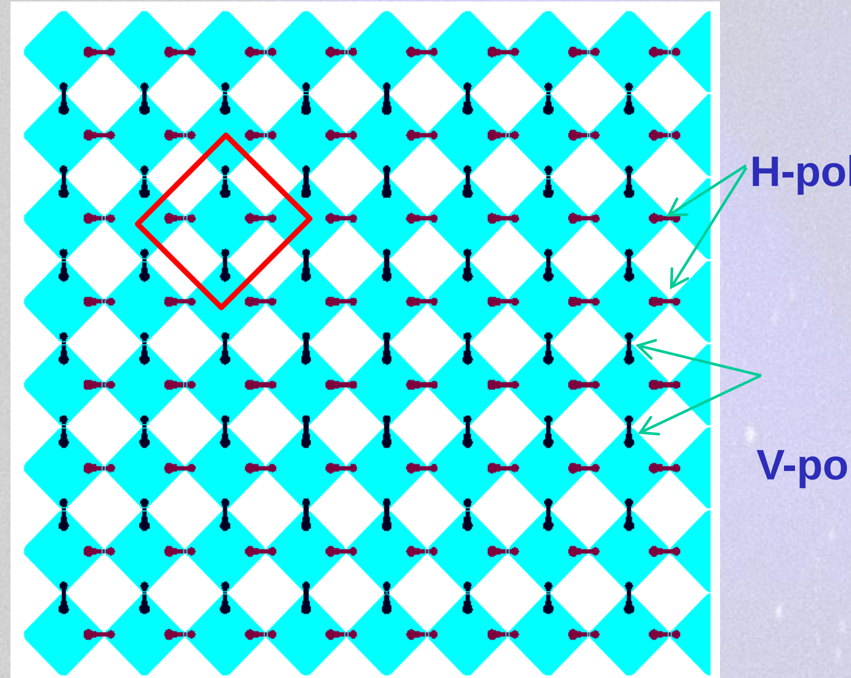
EC-M Beam

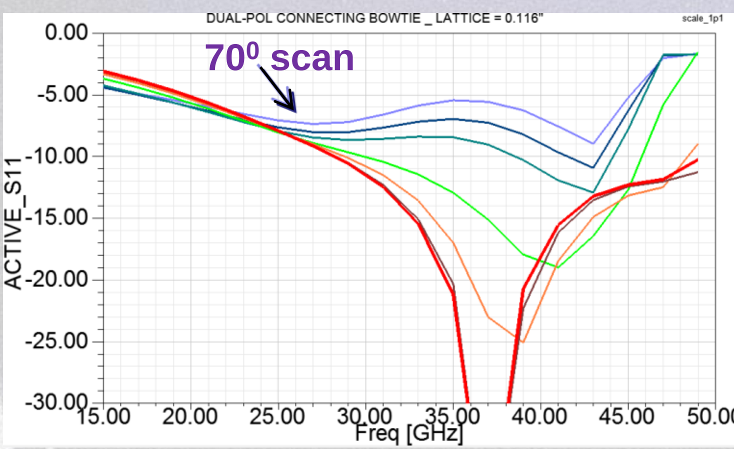


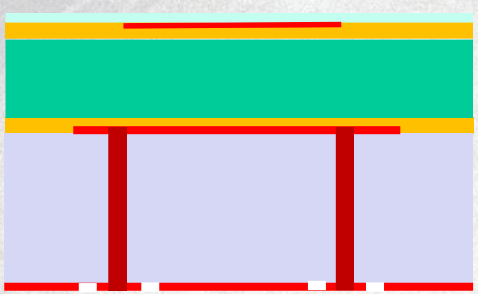
STAIR Element & Array

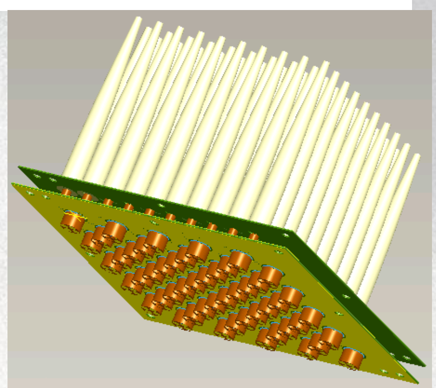
Wide-Band Arrays (Multi-Octave Bandwidths)







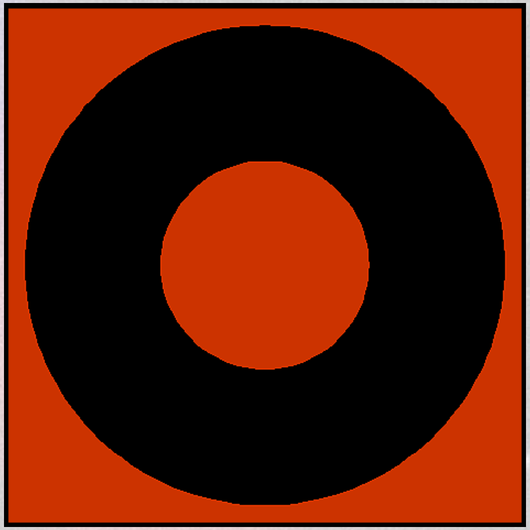




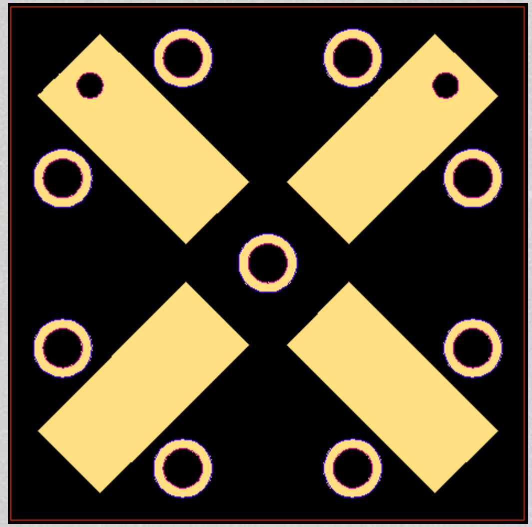
Stacked-Patch Array

Low-Profile Wide-Scan Arrays

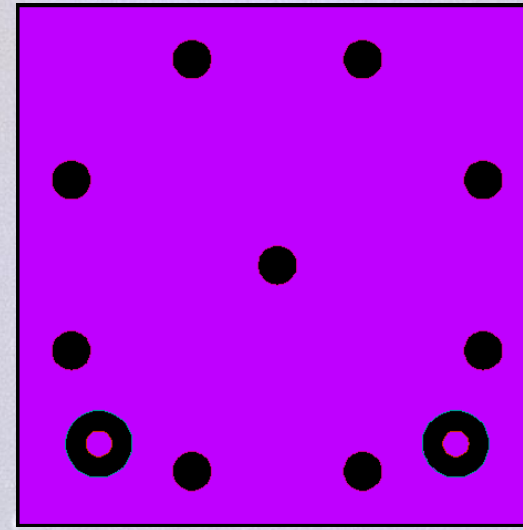
LAYER1



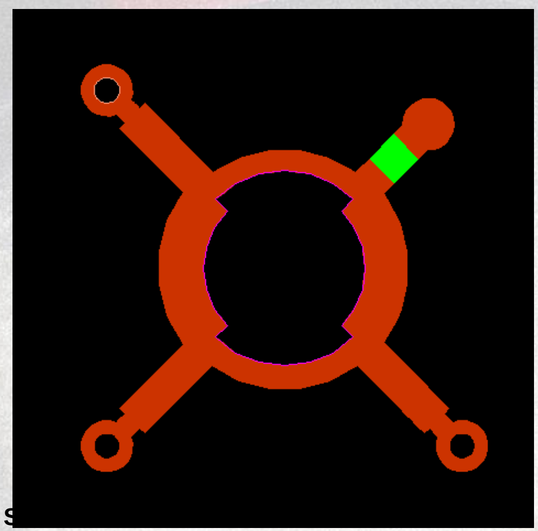
LAYER2



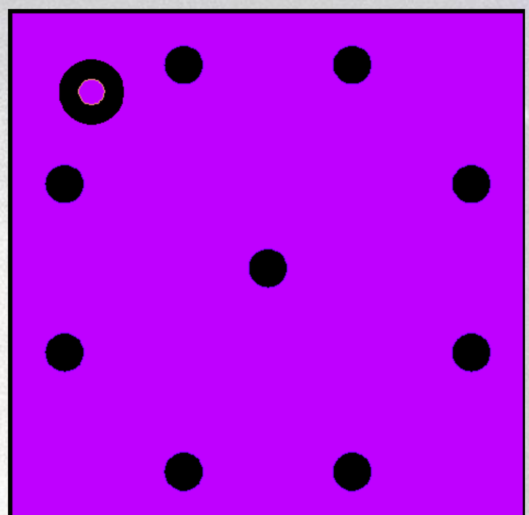
LAYER3



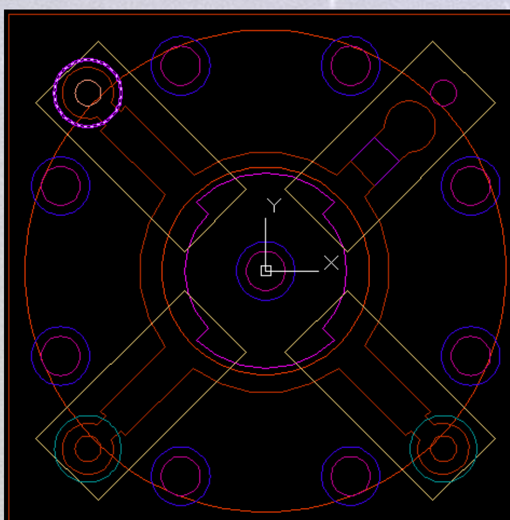
LAYER4



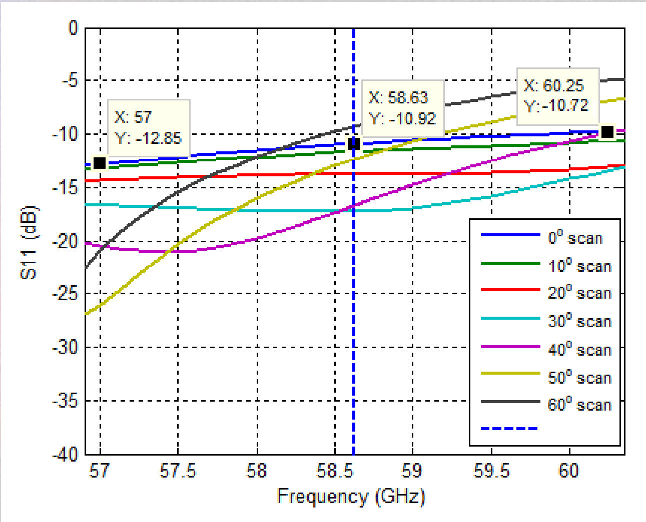
LAYER5

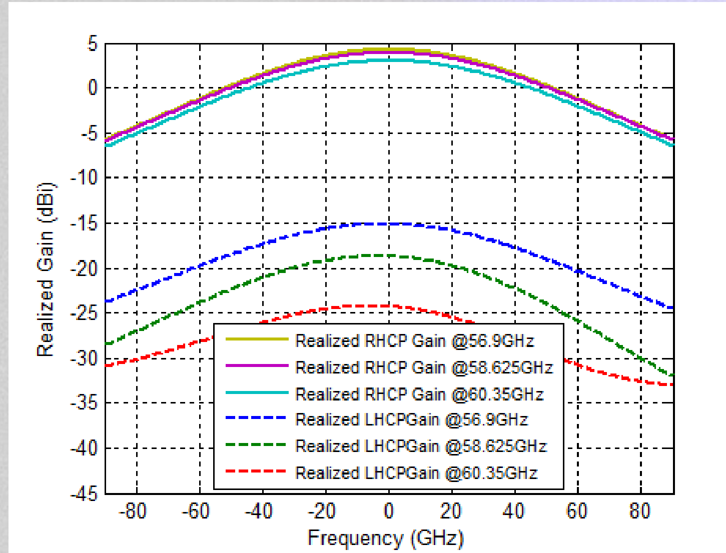


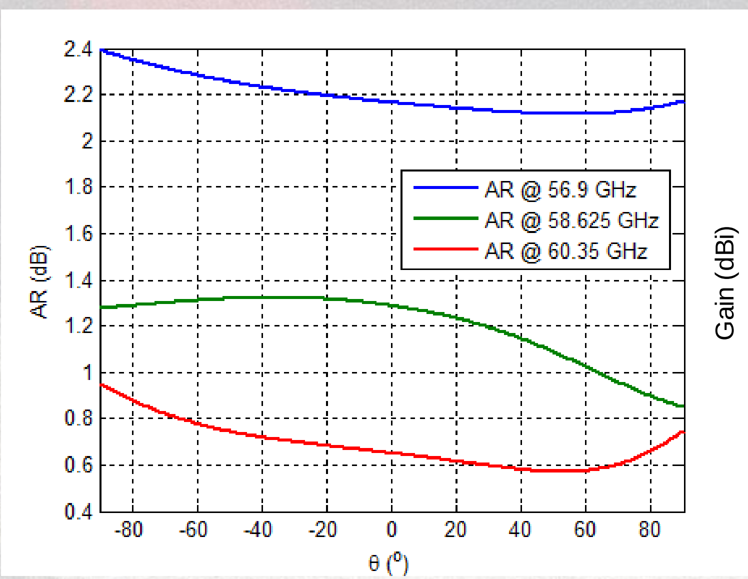
LAYERS 1-5

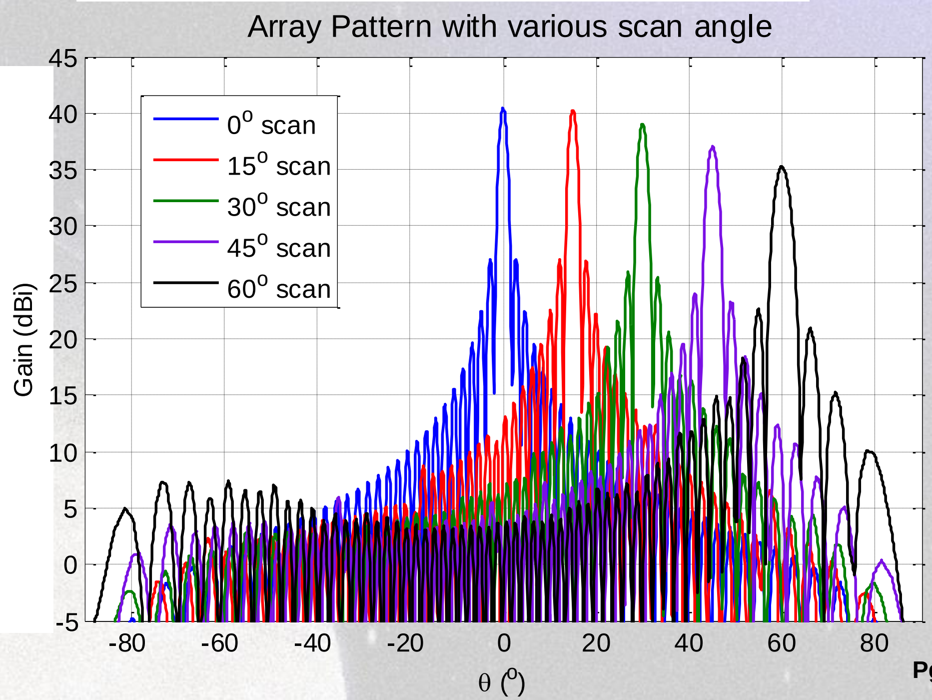


Low-Profile Wide-Scan Phased Array Performance

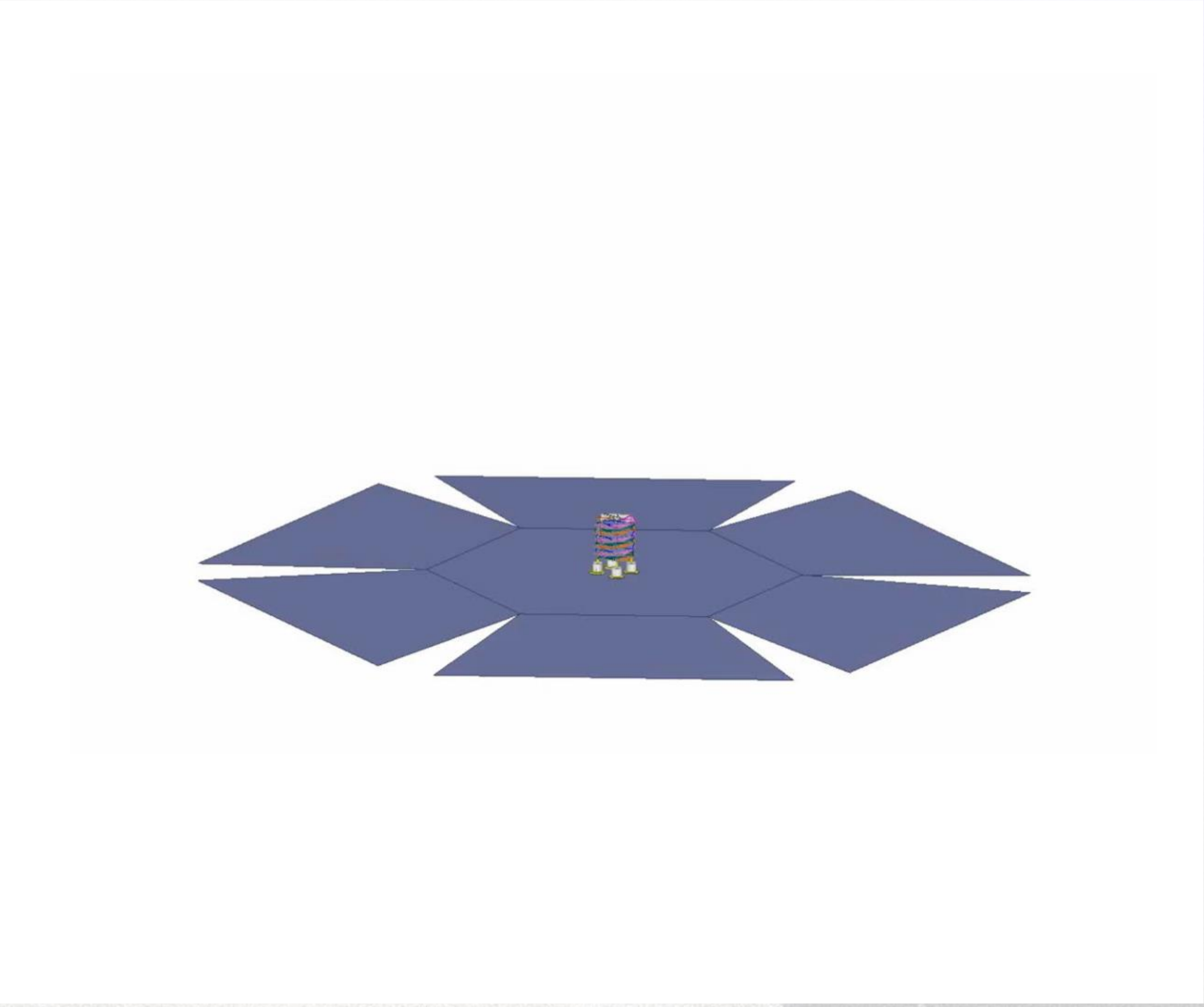




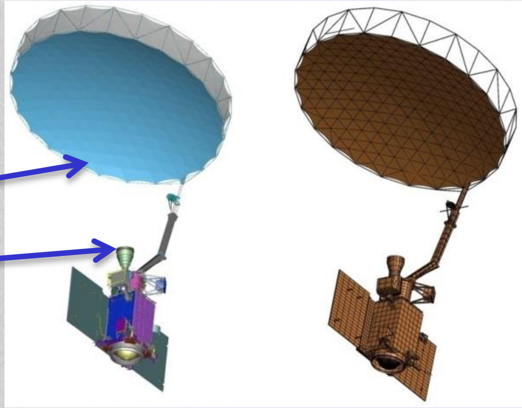




Origami Based Reconfigurable Array Unit Cell



Reflector Antennas



- Consists of two major assemblies
  - reflector assembly
  - feed assembly

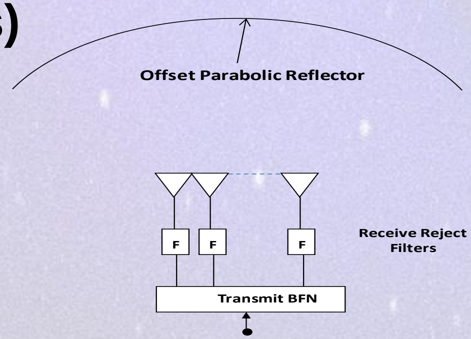
- Reflector assembly: provides required gain, determines coverage shape, scan loss, beam squint etc. Comprises reflector, thermal paint/cover, deployment boom mechanisms/gimbals, pointing error
  - key design drivers: surface accuracy, loss, X-pol, thermal stability

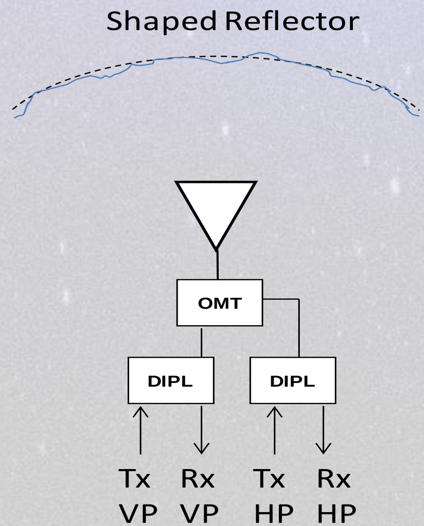
- Feed assembly (horn + OMT + polarizer + filters/diplexers +TCs +W/G Interfaces to repeater): provides proper illumination on the reflector, dictates bandwidth, polarization, X-pol isolation, filtering etc.
  - key design drivers: minimize loss, power handling, tolerances, thermal, low PIM, wide bandwidths

Reflector & Feed Assembly performances are most crucial for satellite antennas

Contoured Beam Antennas

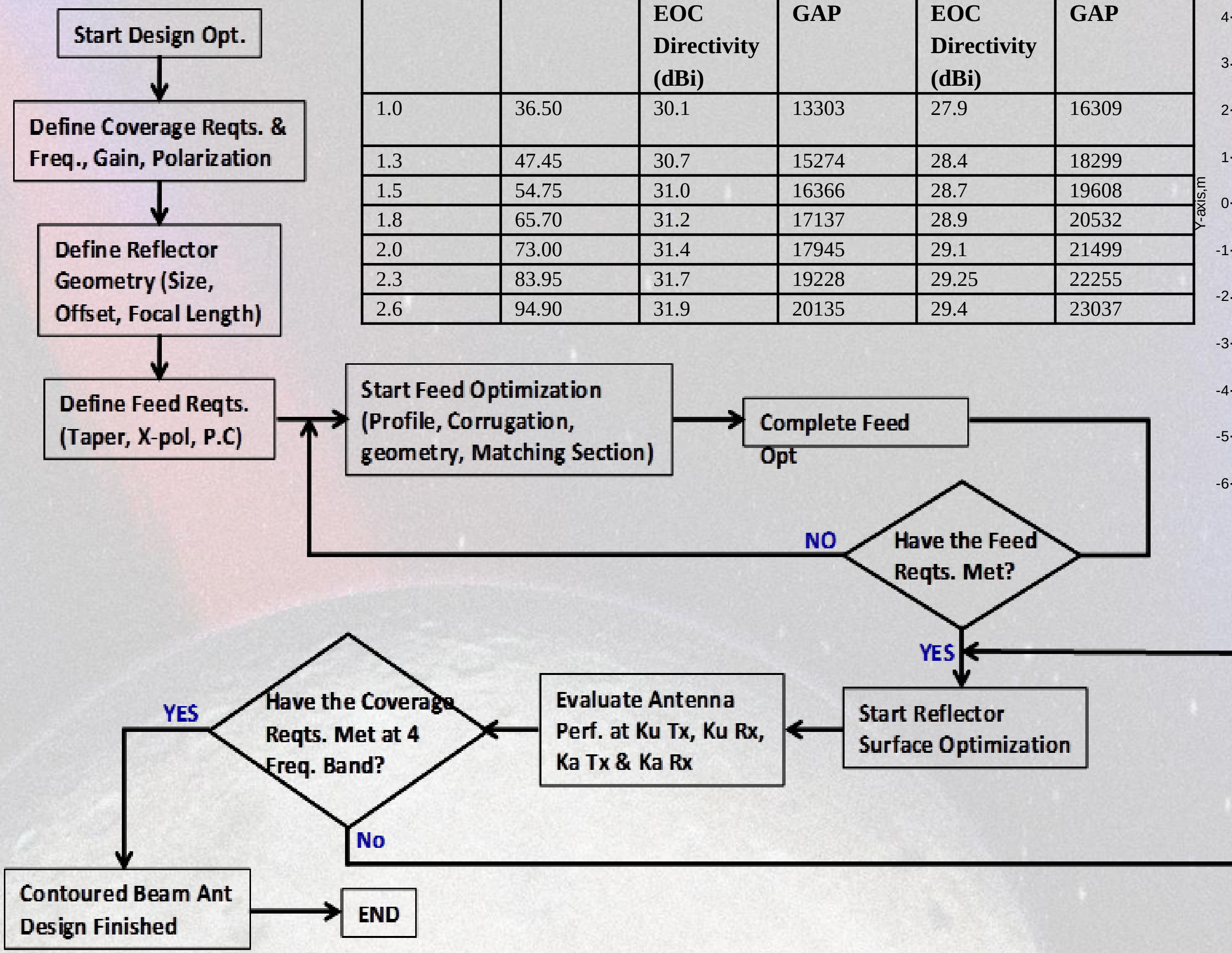
- The beam shape fits closely to the coverage of a country or a region. Used for FSS and BSS satellite services
- Contoured or shaped beams are synthesized using two methods
- Most common and cost-effective method is using shaped surface of reflector to synthesize the beam (phase-only synthesis)
- Key design aspects:
  - maximize the minimum coverage area gain (MCAG)
  - maximize C/X > 33 dB
  - minimize the copol levels outside the coverage and with interfering beam (C/I > 30 dB)
- Antenna types:
  - parabolic reflector with feed array (old technology)
  - dual-gridded reflector (limited to LP applications only)
  - single shaped reflector (LP & CP)
  - dual-reflector shaped Gregorian antenna (LP & CP)
  - other types (SFOC, FFOC, Imaging, ADE etc.)

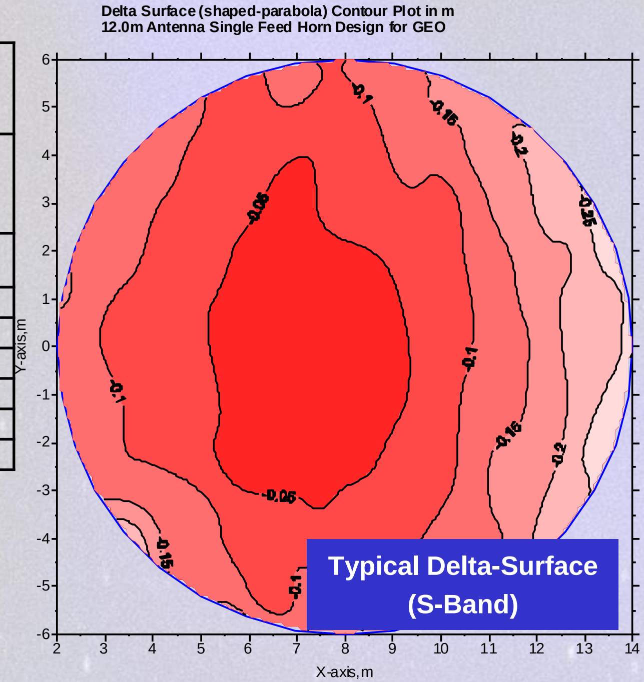




Synthesis Method for Shaped Reflector

Reflector Diameter (meters)	D/λ	CONUS (13 sq. degrees) Ku-Band		South America (26.45 sq. degrees) Ku-Band	
		EOC Directivity (dBi)	GAP	EOC Directivity (dBi)	GAP
1.0	36.50	30.1	13303	27.9	16309
1.3	47.45	30.7	15274	28.4	18299
1.5	54.75	31.0	16366	28.7	19608
1.8	65.70	31.2	17137	28.9	20532
2.0	73.00	31.4	17945	29.1	21499
2.3	83.95	31.7	19228	29.25	22255
2.6	94.90	31.9	20135	29.4	23037

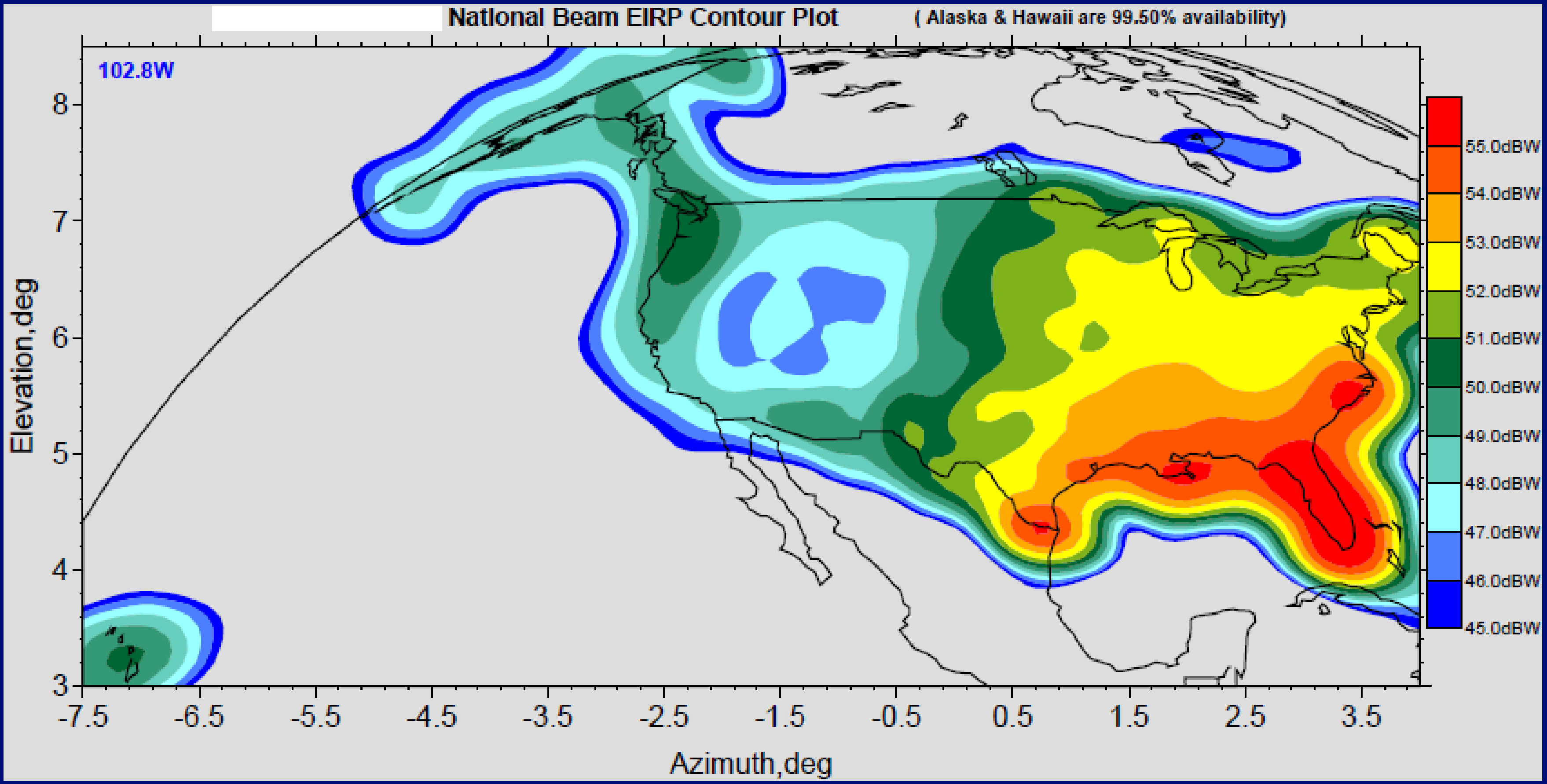




Antenna	Dir., Analysis* (dBi)	Dir., Computed (dBi)
Case 1 (shaped)	27.66	27.60
Case 2 (shaped)	21.40	21.65
Case 3 (MBA)	46.68	46.54
Case 4 (MBA)	42.20	42.05

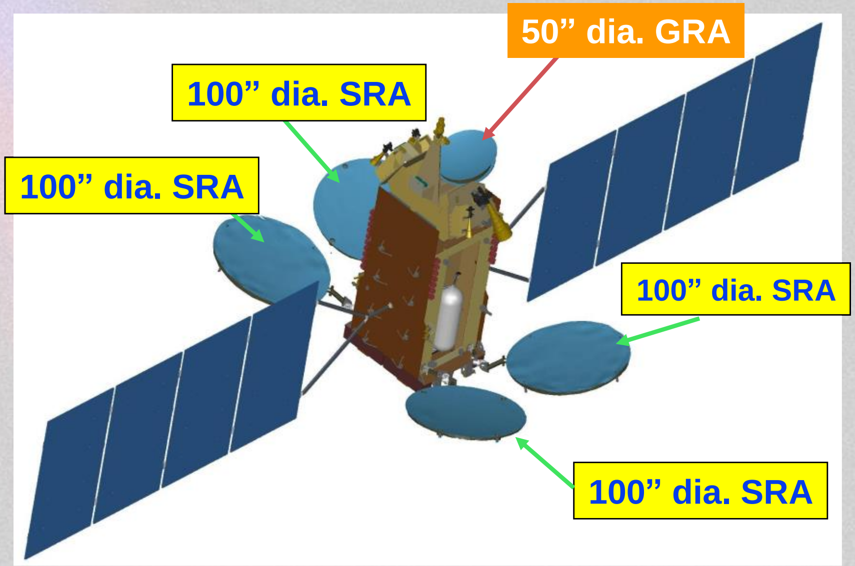
* S. Rao, “Design and Analysis of Multiple-Beam Reflector Antennas”, IEEE AP-Magazine, pp. 53-59, August 1999

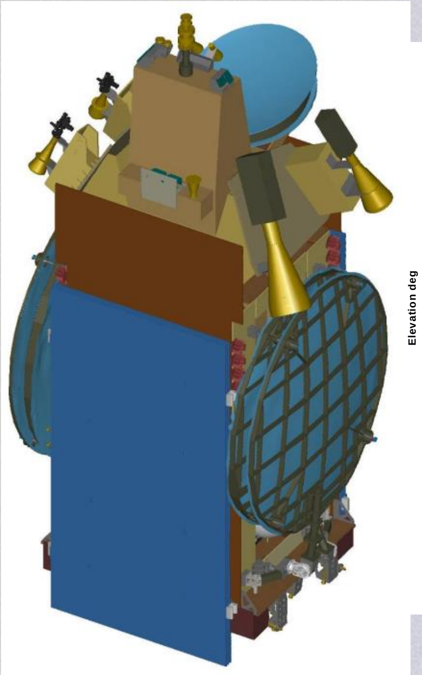
CONUS Beam for DBS

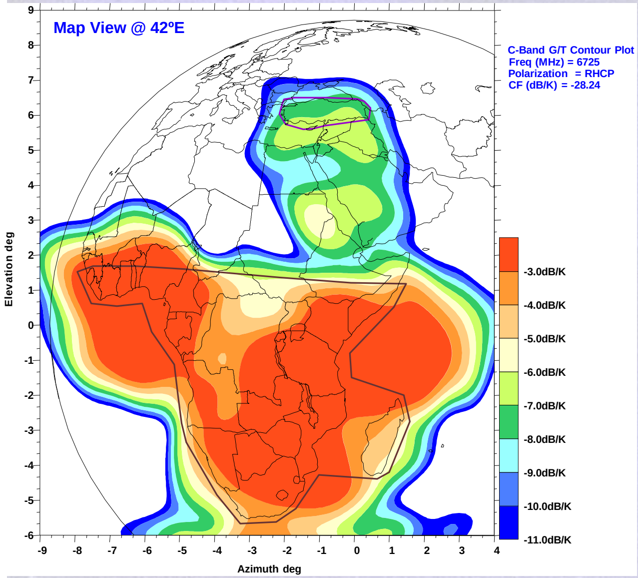


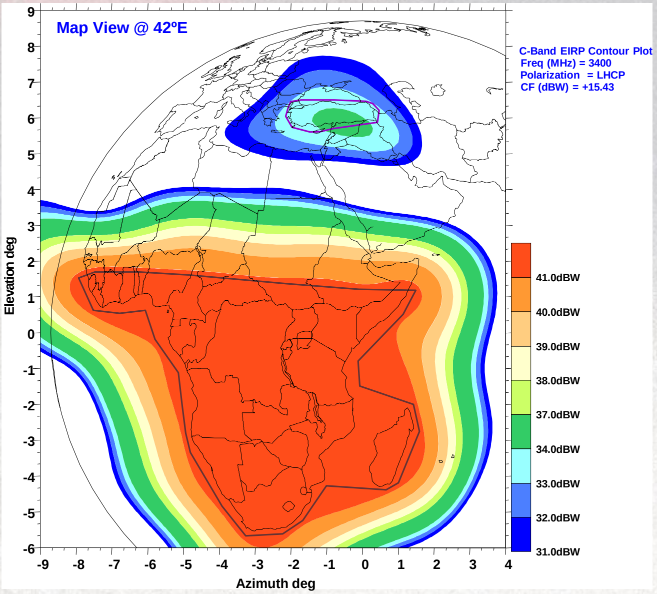
Highly Weighted Beam to compensate for Rain Fade

Contoured Beam Antennas: Multiple Coverage Regions



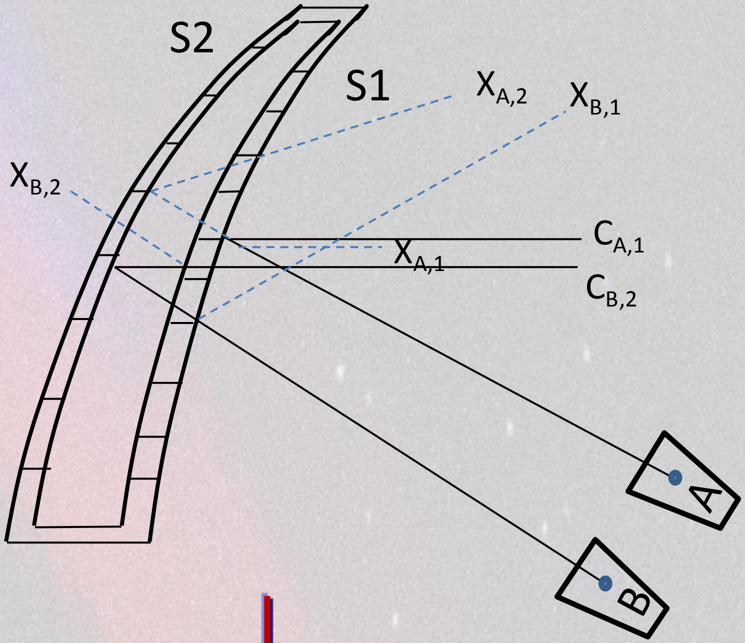


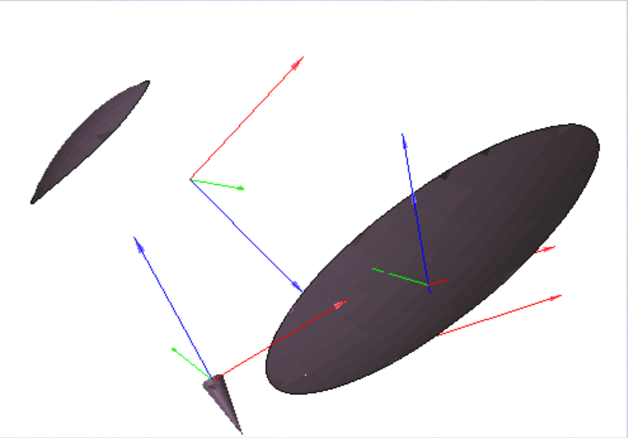


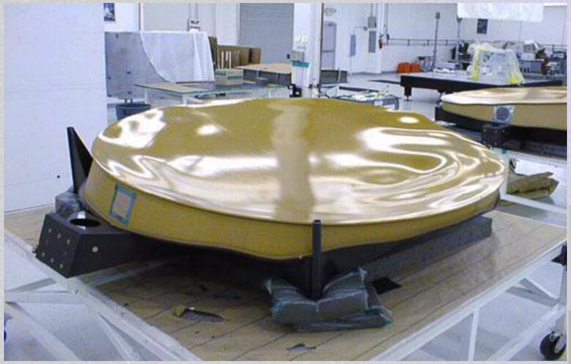


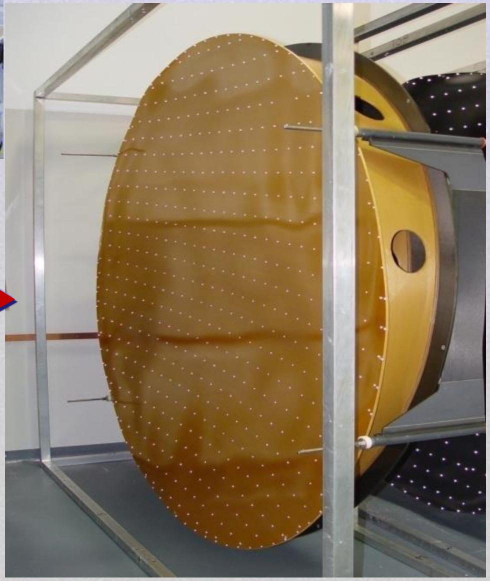
Single Beam Provides Weighted C-Band Coverage to Africa and Turkey

Gridded Reflectors & Gregorian Antennas (High XPD)









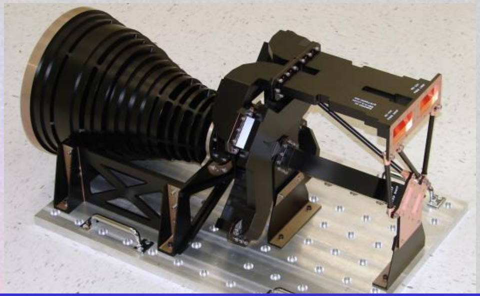
Low X-polar Antennas

Feed Assembly Design Considerations

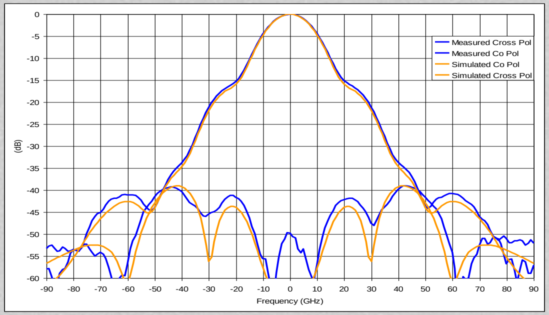
- **Meet bandwidth requirements including thermal excursions**
- **Provide desired illumination (> 15 dB taper) for the reflector or beamwidth if used as the antenna**
- **Meet the low X-pol requirements (< -40 dB for FSS/BSS)**
- **Low sidelobe levels (to minimize spill-over losses)**
- **Power handling (6 dB margin by design, 3 dB by test)**
- **PIM-free design features (< -135 dBm typical, thermal PIM)**
- **Return loss > 25 dB**
- **Low insertion loss (< 0.25 dB)**
- **Meet desired isolation between bands (> 70 dB) & filter other bands**
- **Low mass**
- **Meet thermal requirements (-140^{0}c to +170^{0}c)**
- **Better manufacturing tolerances**

Advanced feed assemblies with high power handling, low PIM, low loss & multi-band capability with low mass and compact size are key for future SATCOM antennas

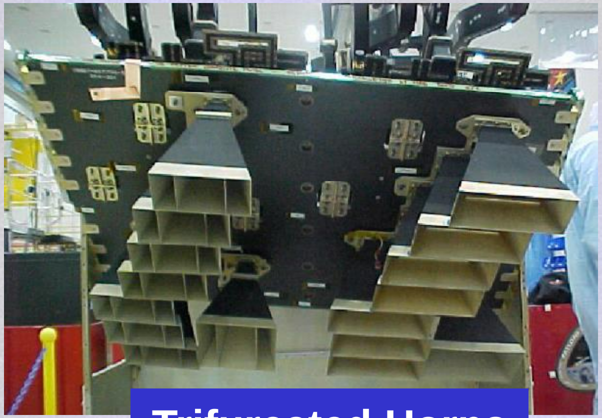
Feed Types



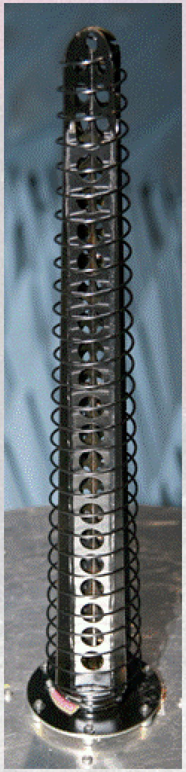
C-Band Tx/RX Feed Assembly



Parameters	Measured Performance
Frequency, GHz	Tx: 3.625 - 4.2 Rx: 5.85 - 6.425
Axial Ratio	< 0.2 dB on Axis
Insertion Loss	Tx: < 0.15 dB Rx: < 0.05 dB
Return Loss	Tx: > 28 dB Rx: > 32 dB
Isolation	RHCP ↔ LHCP > 25 dB Rx ↔ Tx > 60 dB
Peak Power	10 kW Multipaction
PIM	< -140 dBm, 7^{th} Order
Edge Taper	20 dB (±30°) Typical
Cross-Polar Levels	< - 38 dB (±30°) relative to peak
Size, Feed	28.5"(L) x 12"(W) x 12.7"(H)
Mass, Feed	< 12 Kg (with brackets)



Trifurcated Horns



Helix

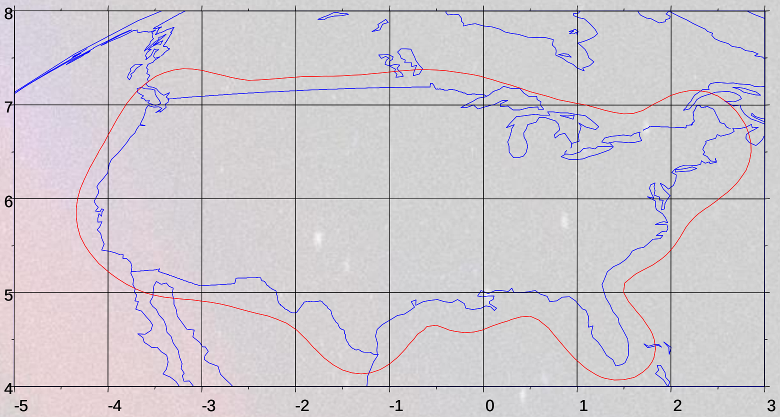
Multi-Mode Horn

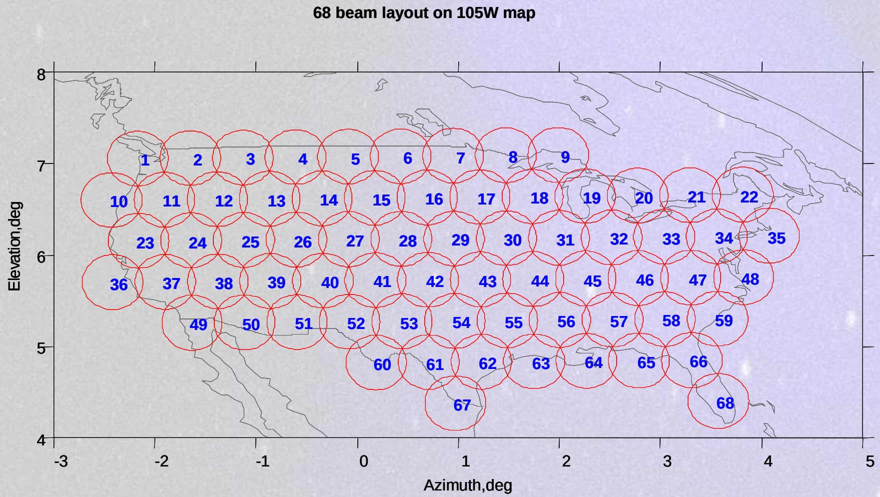
Ku-Corrugated Horn

Ku-Tracking Feed

PEC

MBA versus Contoured Beam Payloads



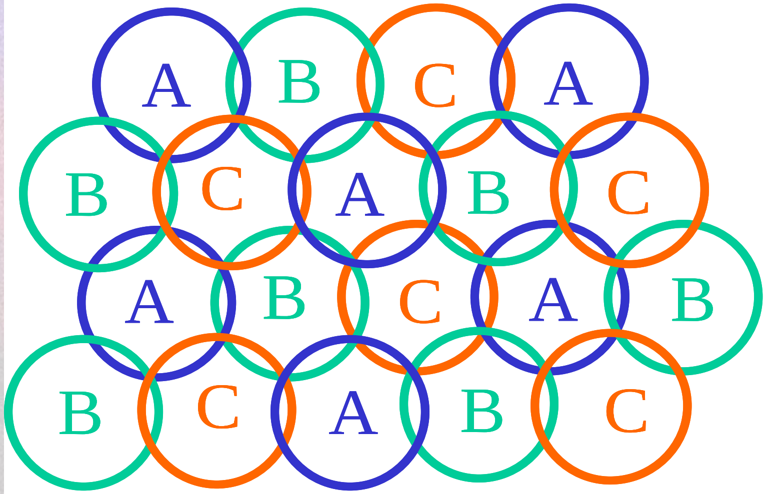


- EOC Gain ~ 31dBi
- Spectral Reuse Factor =1
- X-pol Isol ~ 30dB

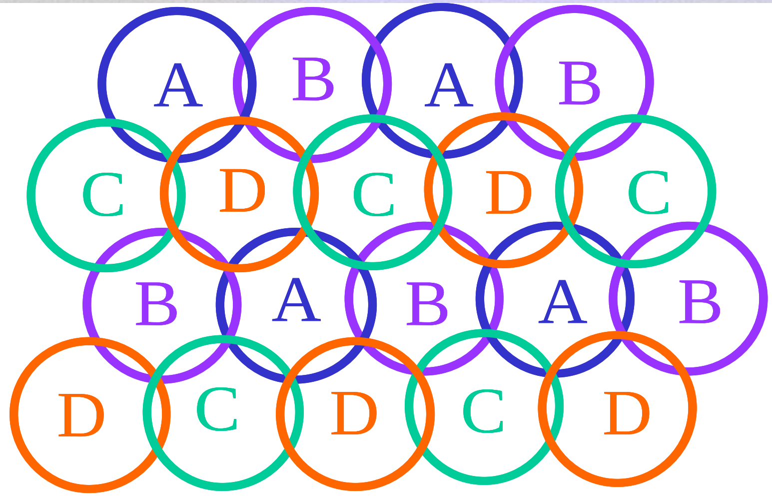
- Beam diameter = 0.6°
- Beam Spacing = 0.52°
- EOC Gain ~ 46dBi
- Spectral Reuse Factor =15 (4-cell)
- X-pol Isol ~ 25dB
- C-pol Isol ~ 12dB

MBAs Allow Reuse of Spectrum Several Folds and Provide Increased Gain

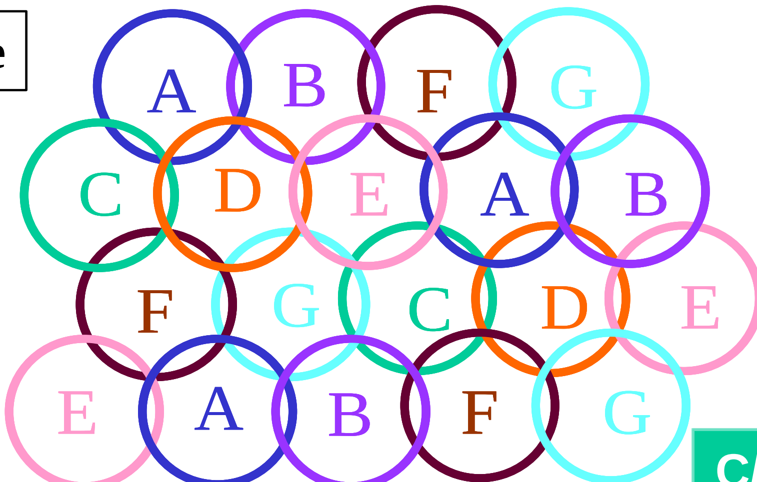
Frequency Reuse Schemes



3-cell reuse



4-cell reuse



7-cell reuse

Reuse Factor (64 beams):

3-cell = 21.3

4-cell = 16

7-cell = 9.14

Closest Spacing Between Reuse Beams:

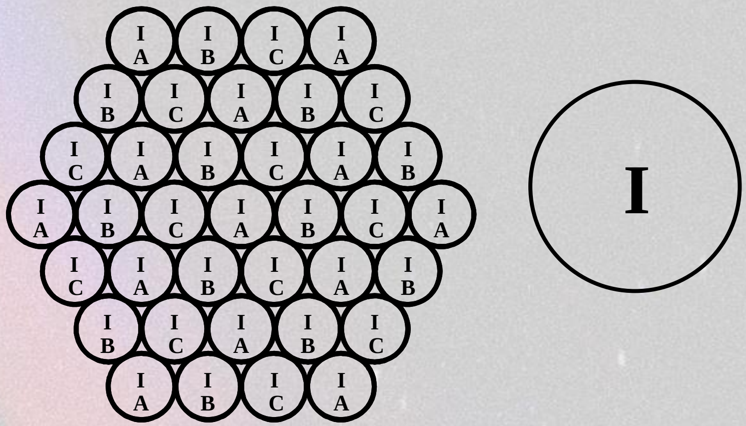
3-cell = 0.58 Adj. Beam Sp

4-cell = 0.85 Adj. Beam Sp

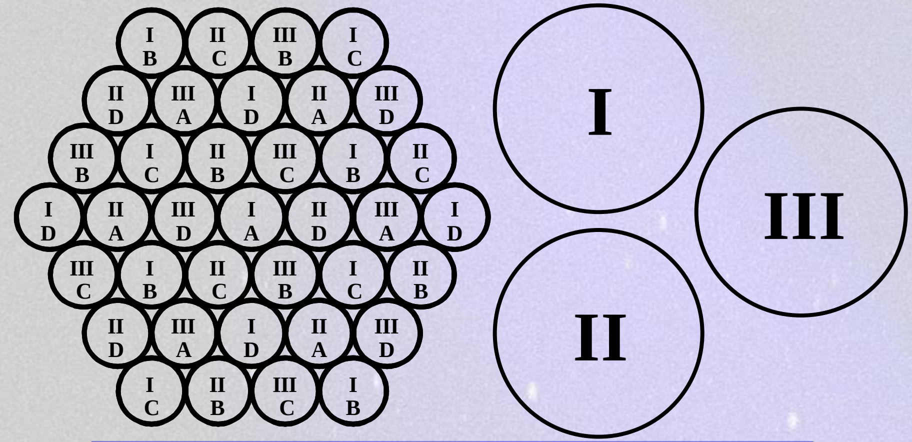
7-cell = 1.49 Adj. Beam Sp

C/I = 9 dB, 12 dB, & 18 dB for 3-C, 4-C, & 7-C

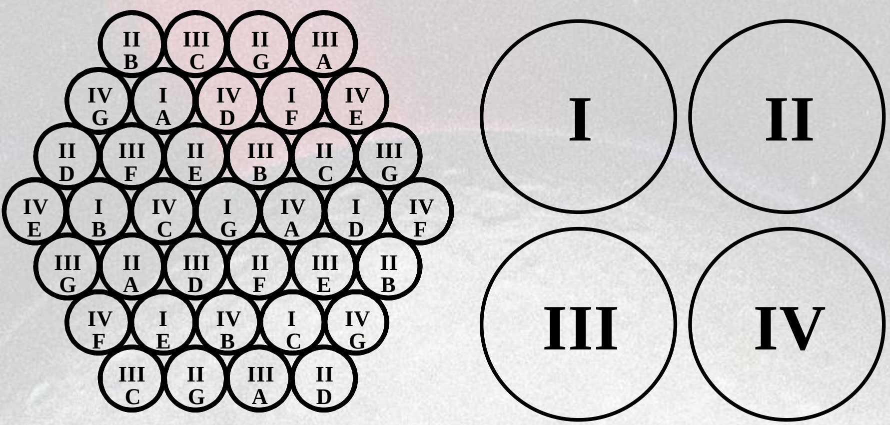
Frequency/Aperture Reuse Schemes



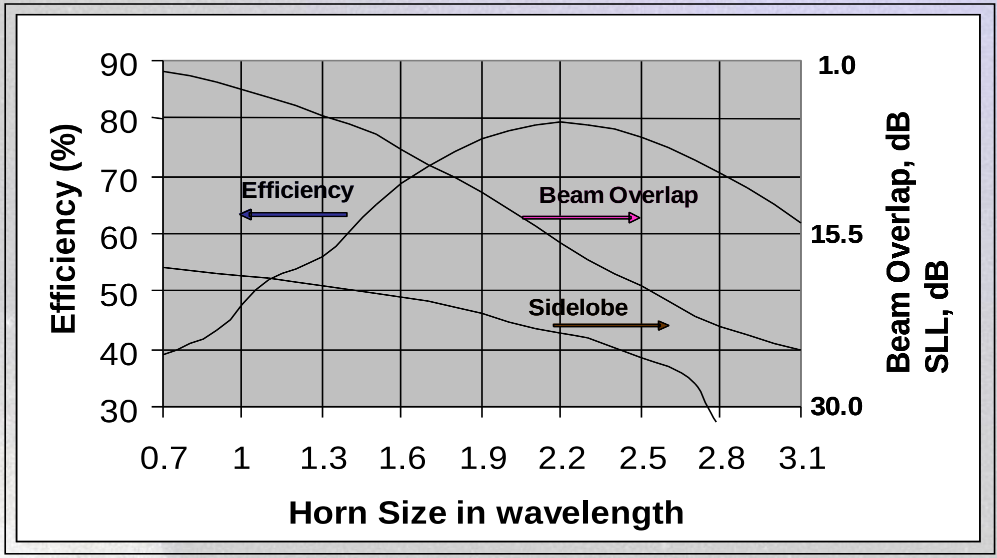
3-Cell Reuse with 1 Aperture



4-Cell Reuse with 3 Apertures



7-Cell Reuse with 4 Apertures

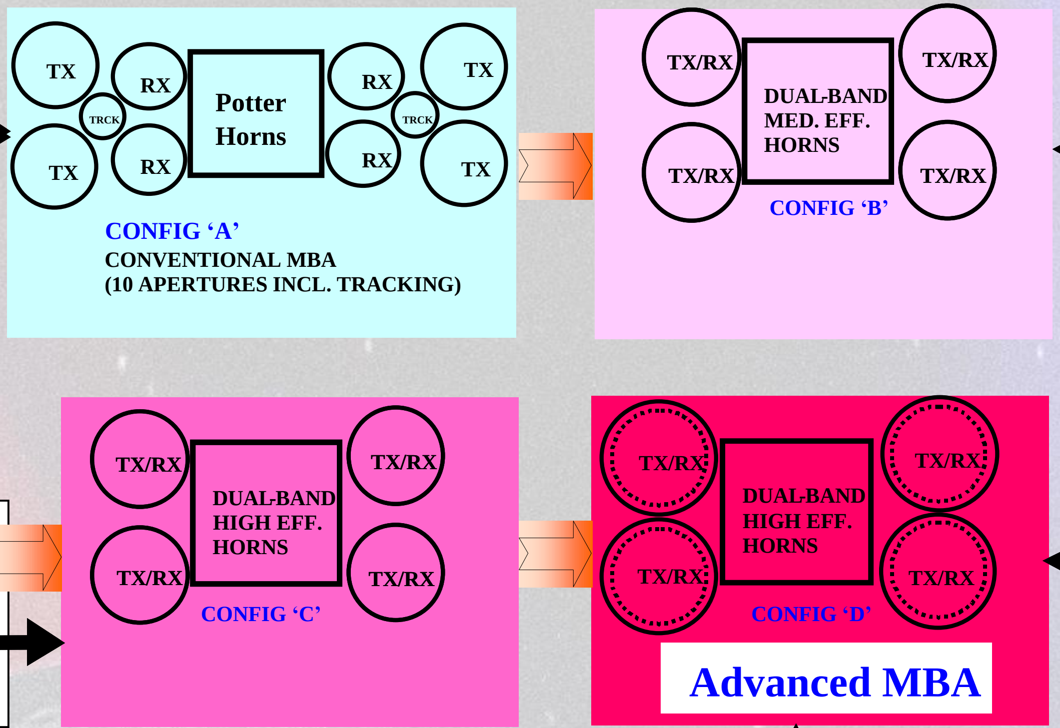


S. Rao et al., "Development of a 45 GHz multiple-beam antenna for military satellite communications", IEEE Trans. Antennas & Propagation, vol. 43, 00. 1036-1047, October 1995

Evolution of MBA Technology

Single-Band Antennas (require 10 apertures)

Dual-band Antennas (low efficiency of 54%): Corr. Feed

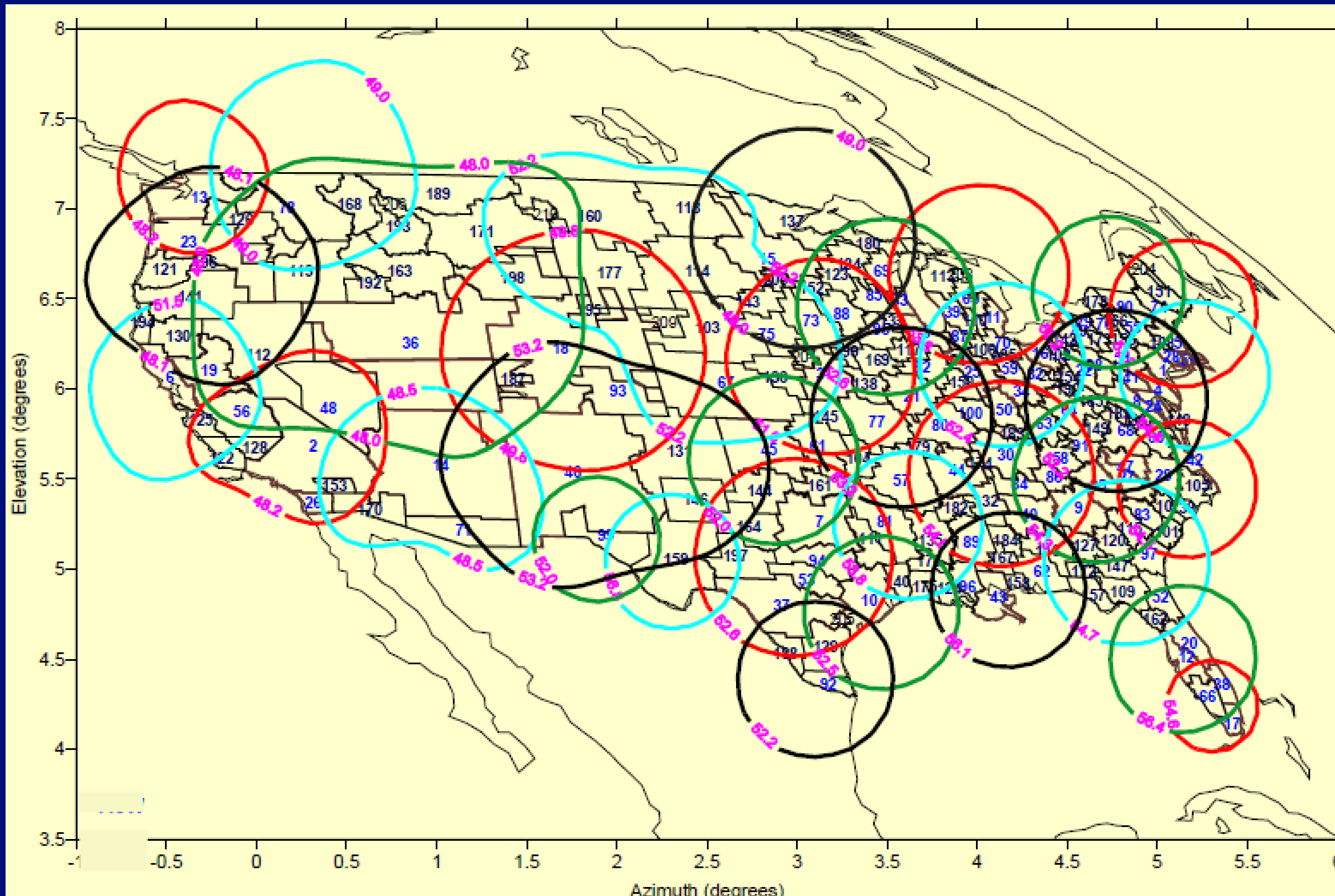


Dual-band Antennas (high efficiency of about 84%)

Multi-band Antennas (supports 5 bands with efficiency of 74% to 82%)

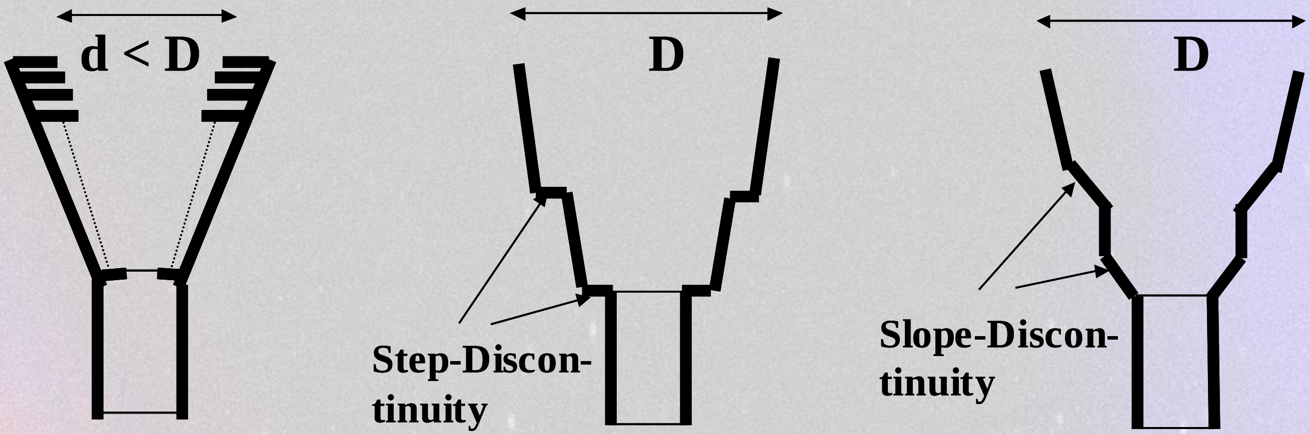
Example: MBA supporting 5 bands and 3 different services using Common antenna

MBA for Local-Channel Broadcast



Multiple Beams with Non-Uniform Spacing & Non-Uniform Size

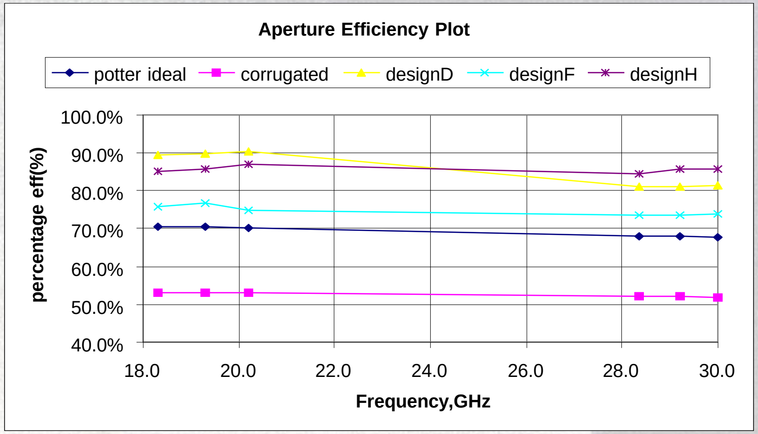
MBA Horn Comparison



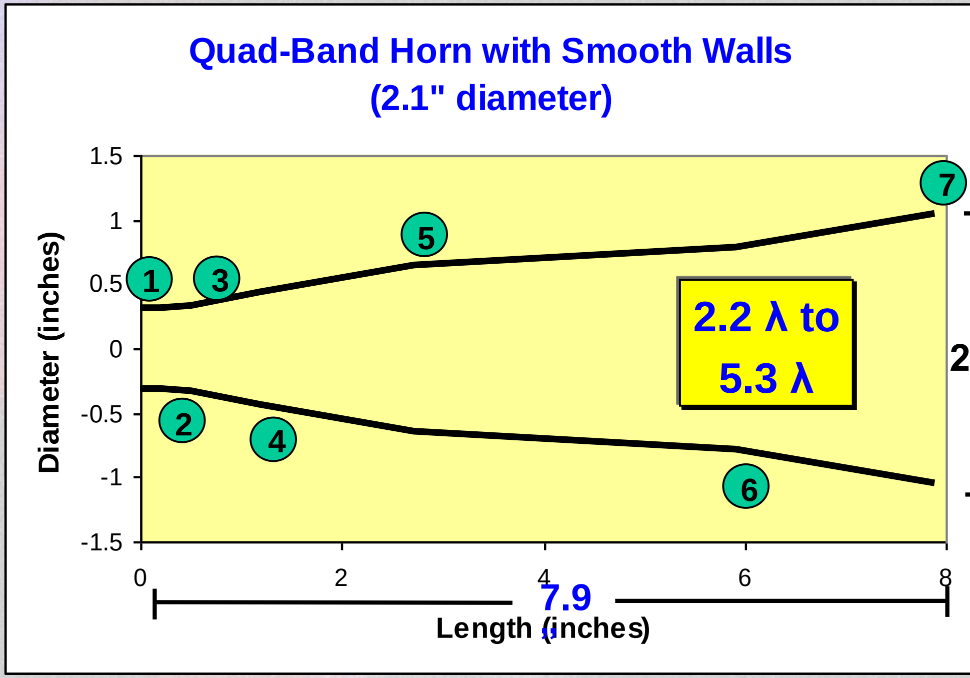
CONVENTIONAL HORN (CORRUG.)
DUAL-BAND
Thick Corrugations
54 % Eff. Tx & Rx
Heavy & Bulky

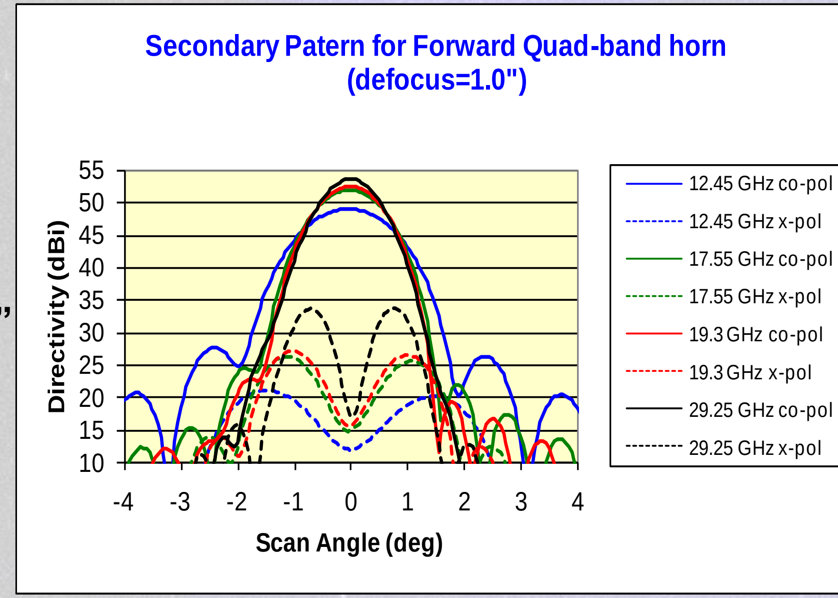
MULTI-MODE HORN NARROW BAND
SINGLE BAND
Step-Discontinuities
> 85 % over Tx or Rx
Light & Compact

MULTI-MODE HORN WIDE BAND
DUAL-BAND
Slope-Discontinuities
> 85% over Tx & Rx
Light & Compact



Multi-band Antenna Performance



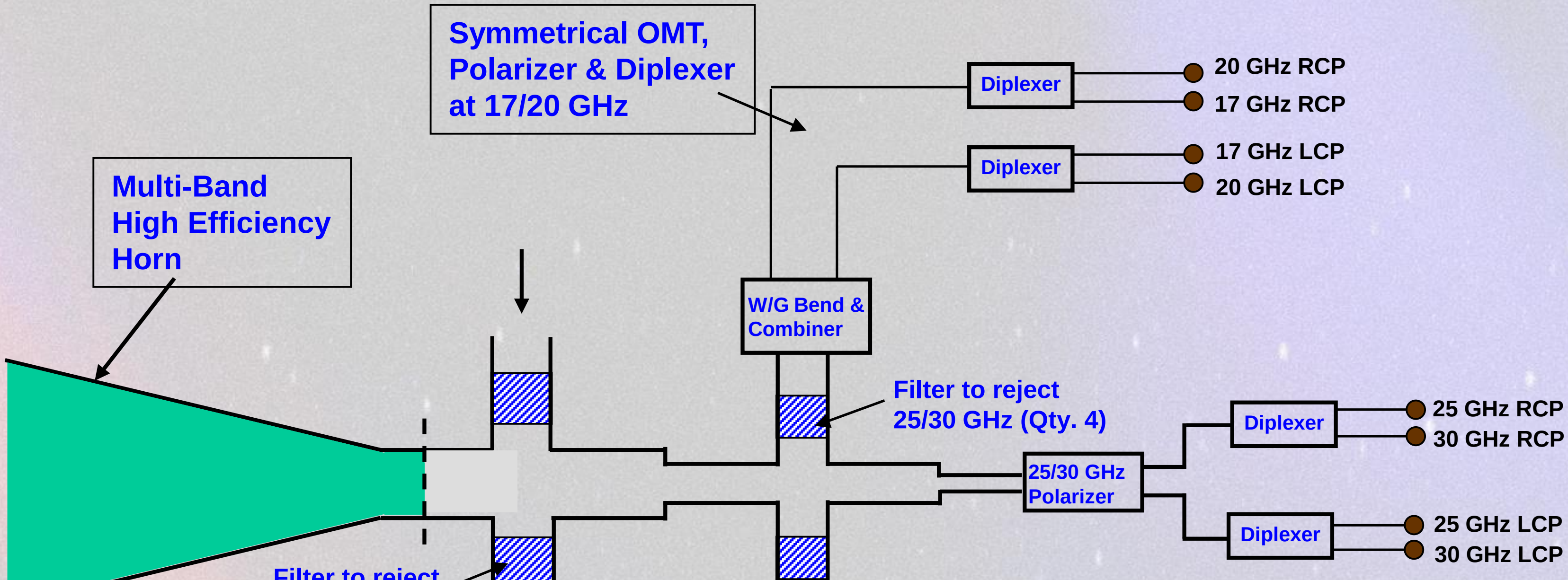


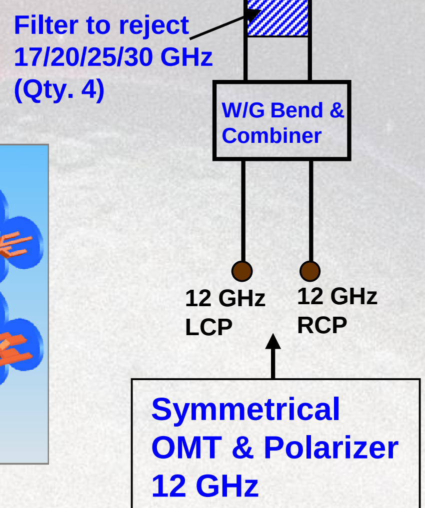
Frequency (GHz)	Return Loss (dB)	X-pol (20º) (dB)	Efficiency (%)
12.5	-26.5	-22.3	82
17.3	-48.0	-22.5	80
17.8	-50.2	-23.6	80
18.4	-43.6	-23.6	79
20.2	-41.7	-22.1	76
24.8	-50.1	-23.0	76
25.3	-44.3	-23.7	76
28.5	-44.0	-23.9	75
30.0	-45.2	-22.1	74

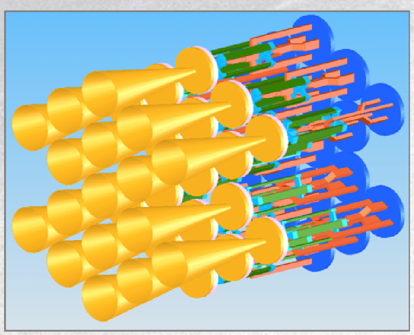
EOC Directivity

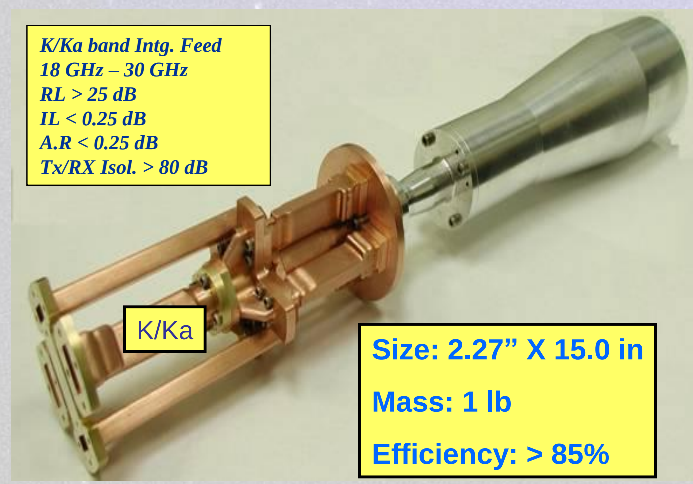
Freq	Coverage	Peak	Co-pol	C/X
12.45	±0.5º	49.0	47.4	32.8
17.55	±0.5º	51.9	49.5	28.7
19.30	±0.5º	52.6	49.8	27.4
25.00	±0.5º	53.5	50.1	23.3
29.25	±0.5º	53.6	50.0	18.4

Multi-Band Feed Assembly Schematic



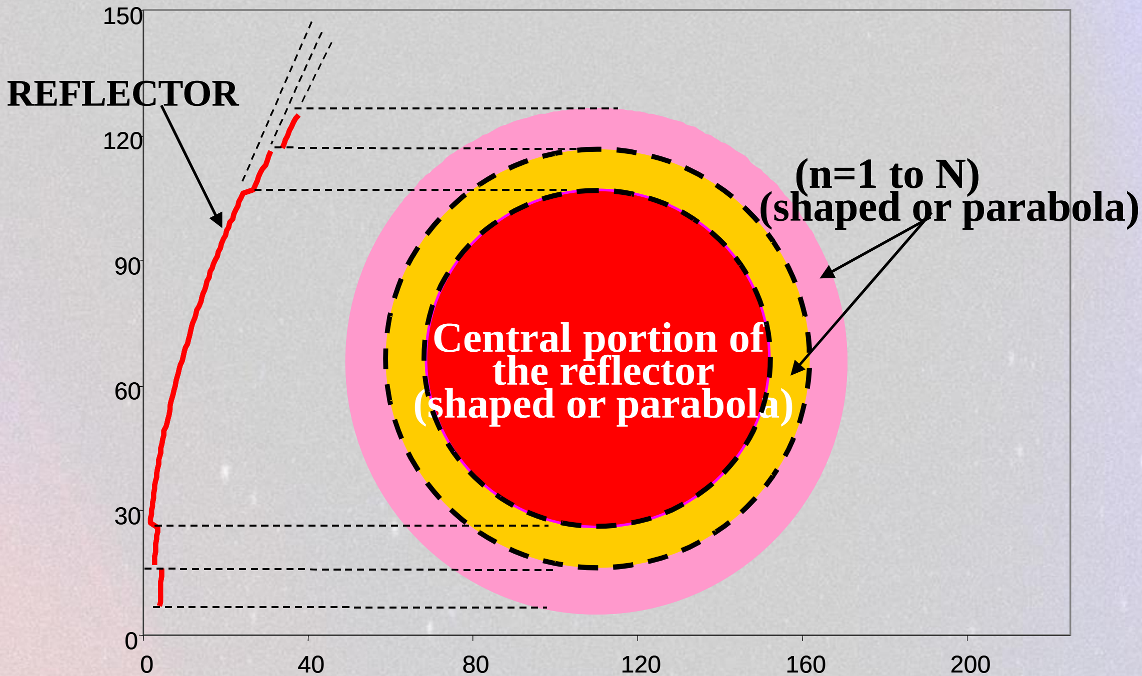


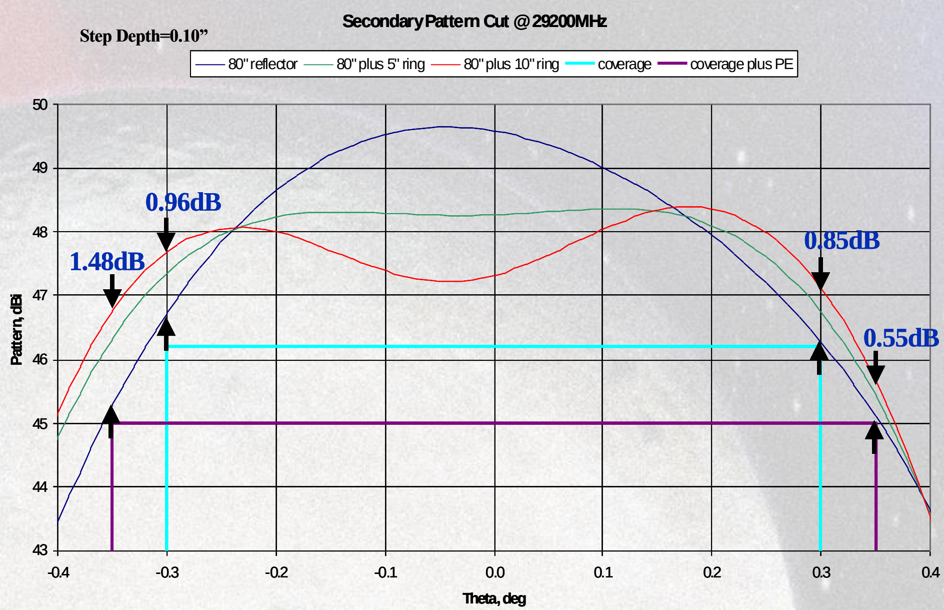




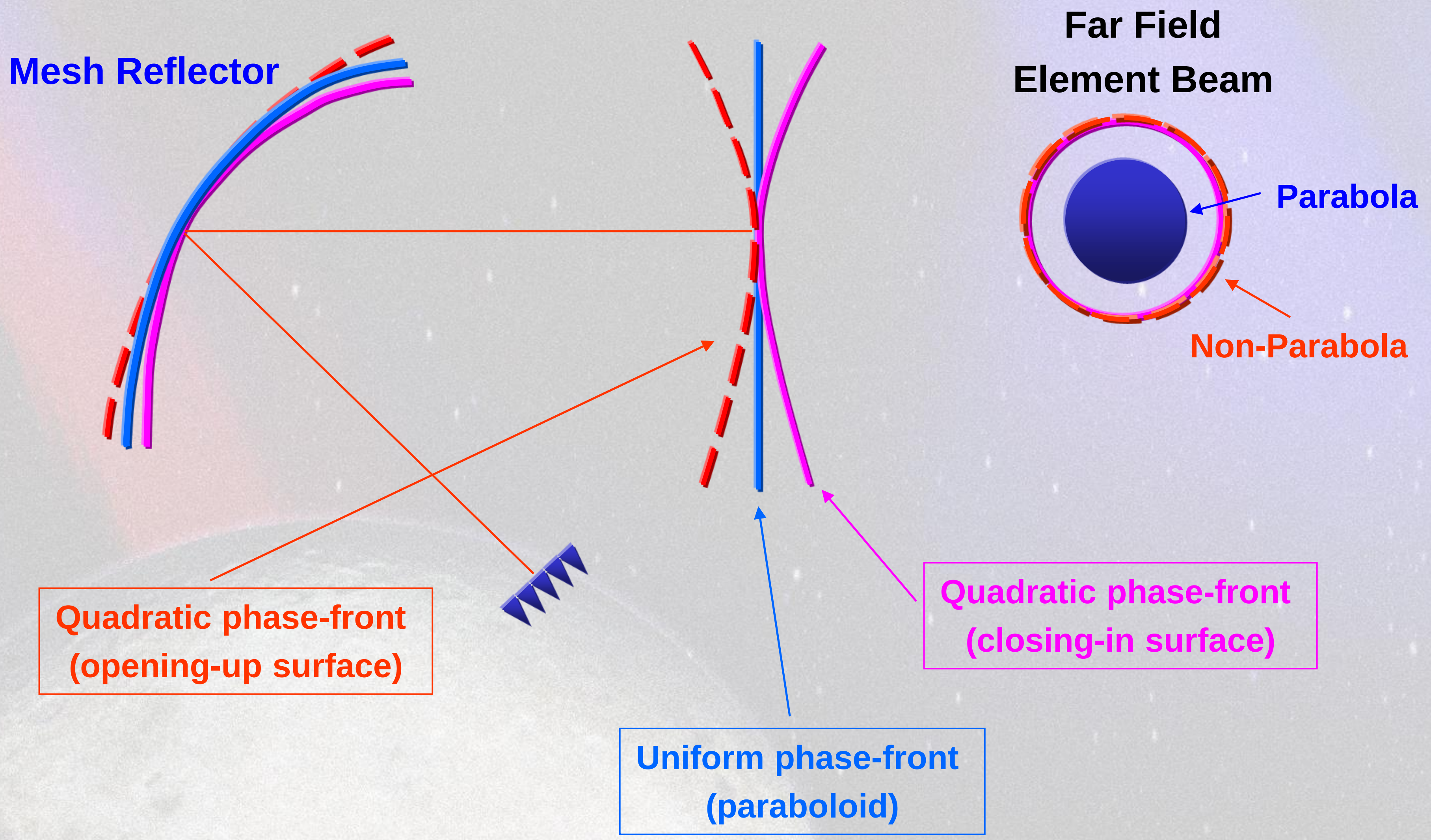
The feed network need to fit within the real-estate dictated by the horn aperture

Stepped Reflector for Multi-Band Applications





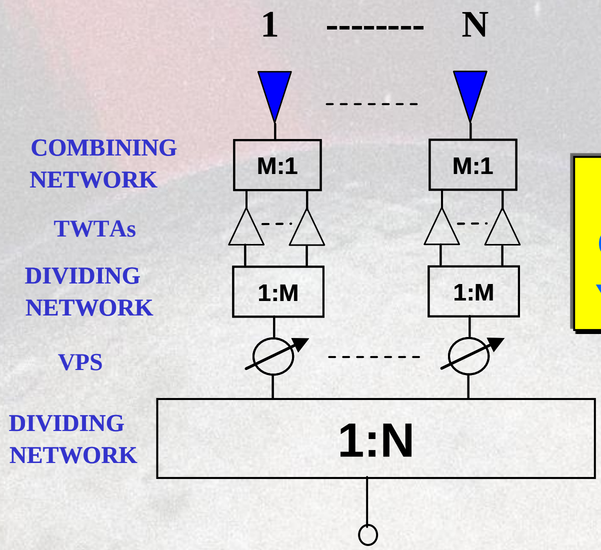
Non-Focused Reflector



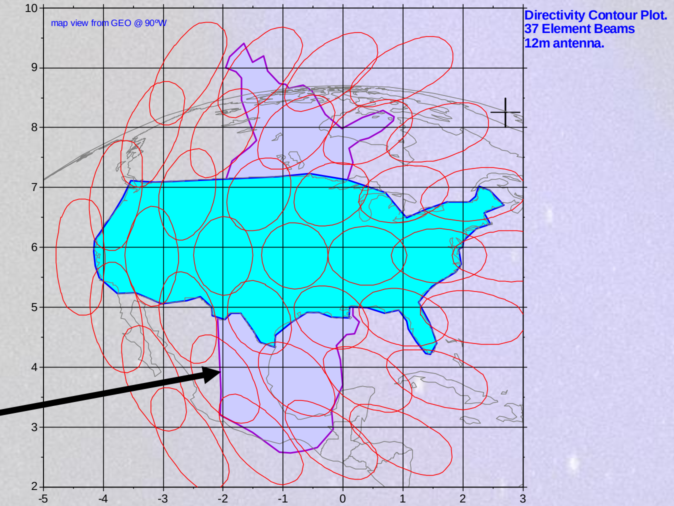
S. Rao et al., "Reconfigurable Payload Using Non-Focused Reflector Antenna for HEO and LEO Satellites", U.S. Patent # 7710340, May 04, 2010

NFR For Flexible CONUS Coverage (DABS)

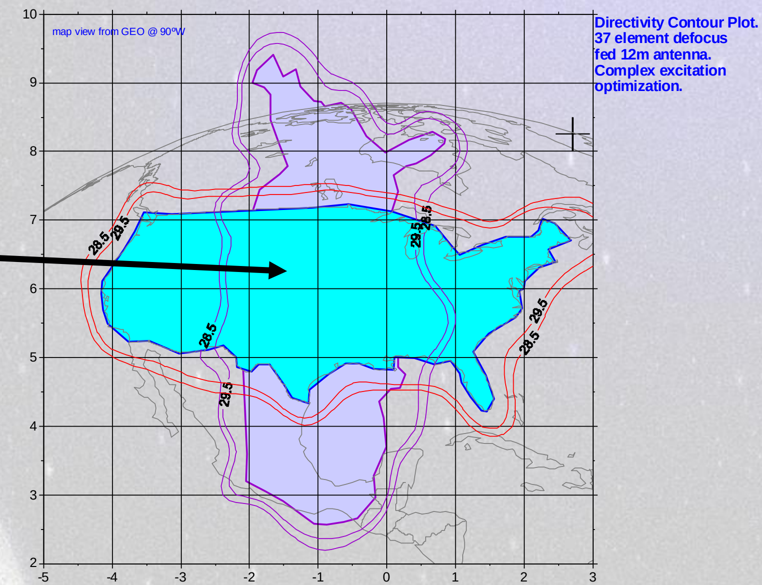
12m Mesh Non-Focused Reflector
(non-parabolic)



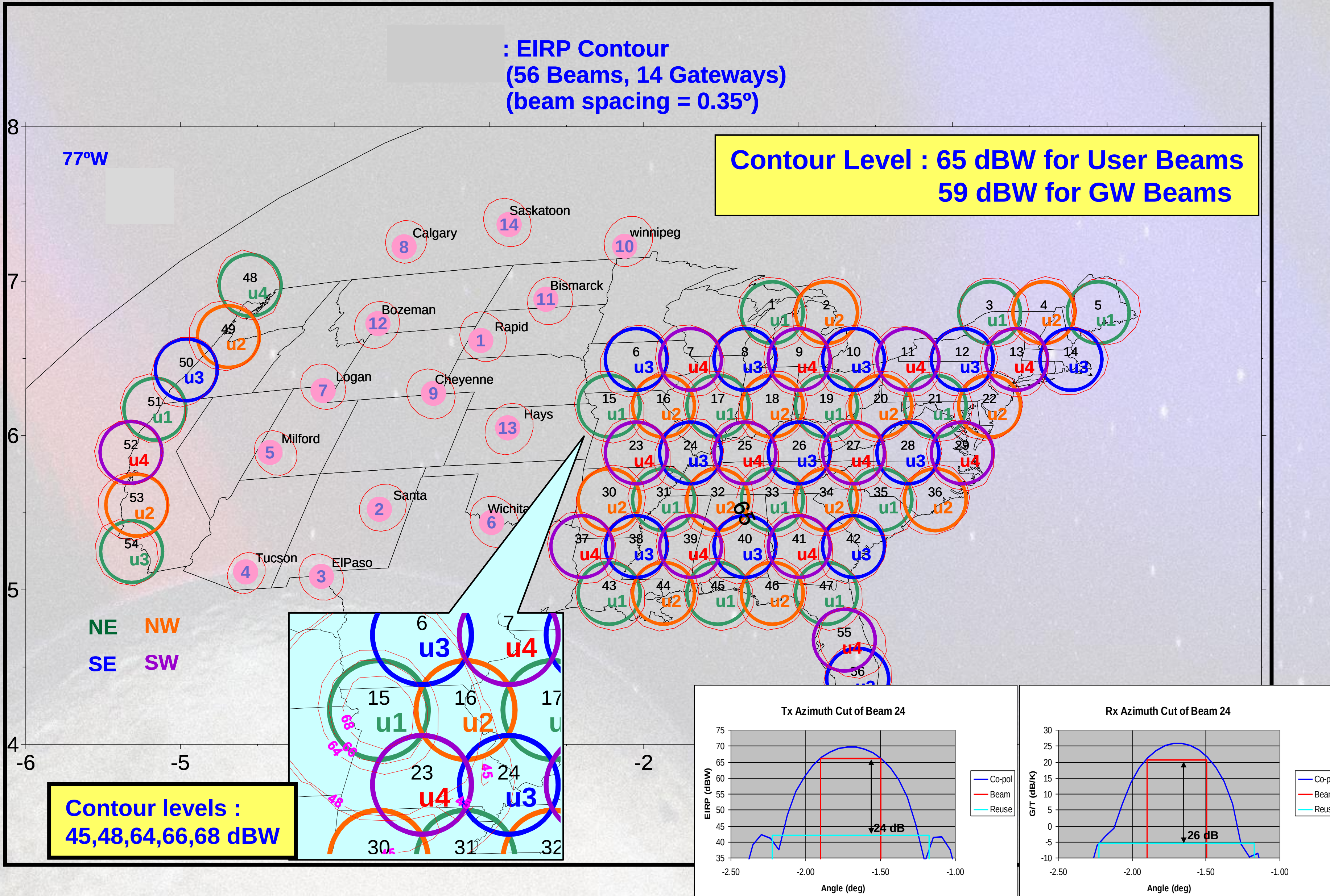
Element Beams



Synthesized CONUS Beam for Yaw = 0 & 90 deg.



MBA for High Capacity Satellites



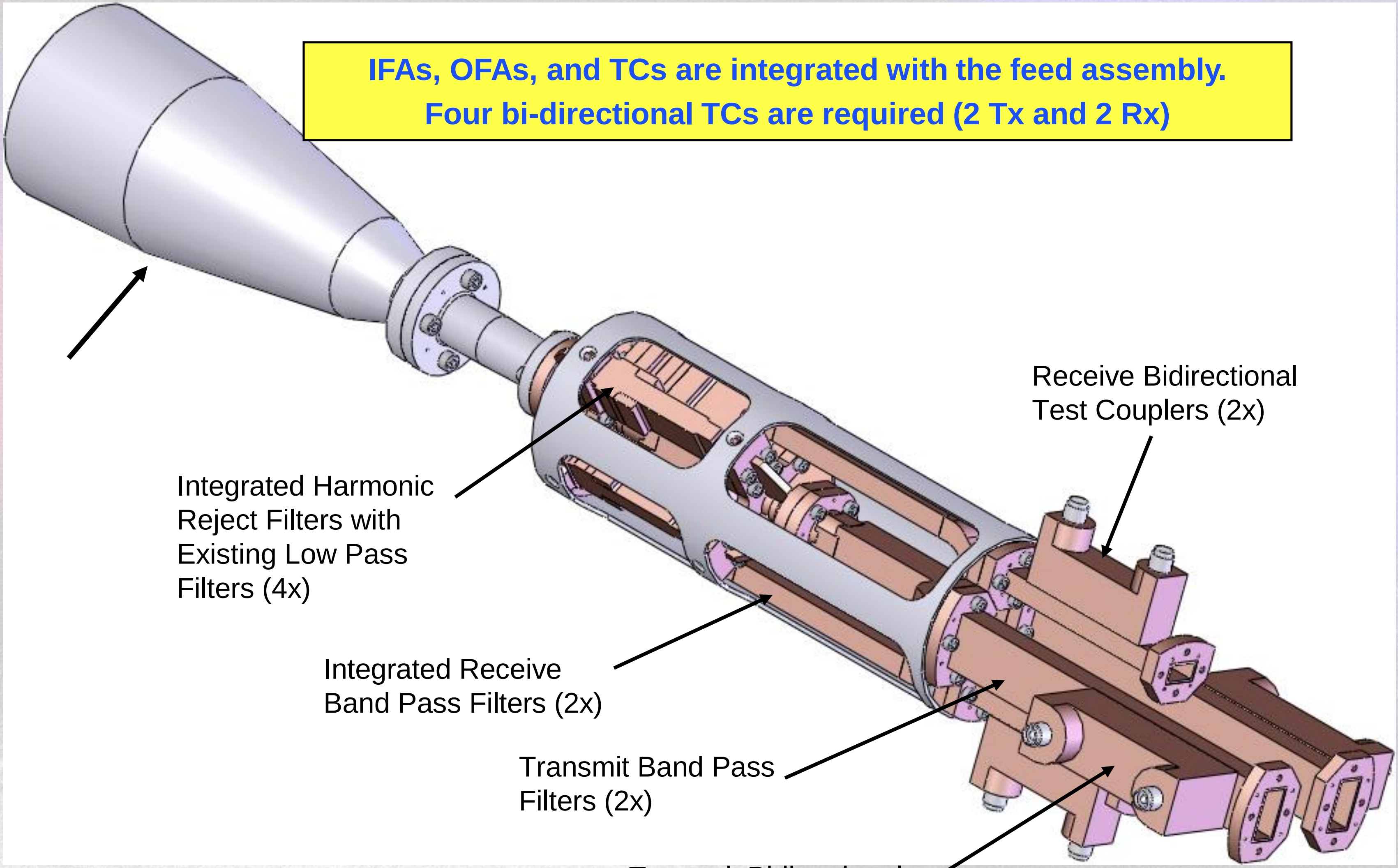
EIRP > 65 dBW
C/I > 24 dB (single interferer)

G/T > 20 dB/K
C/I > 26 dB (single interferer)

S. Rao

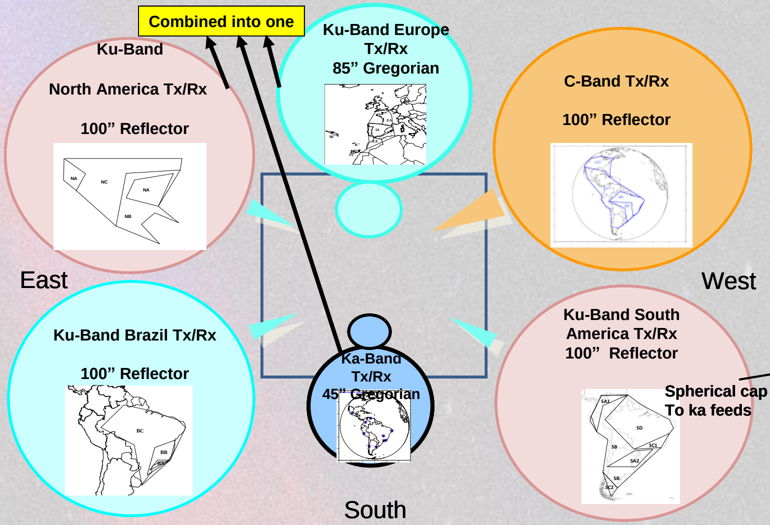
Dual-Band Feed Assembly Integrated with IFAs & OFAs, & TCs

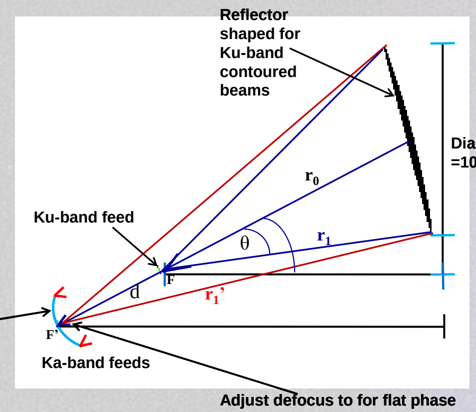
IFAs, OFAs, and TCs are integrated with the feed assembly.
Four bi-directional TCs are required (2 Tx and 2 Rx)

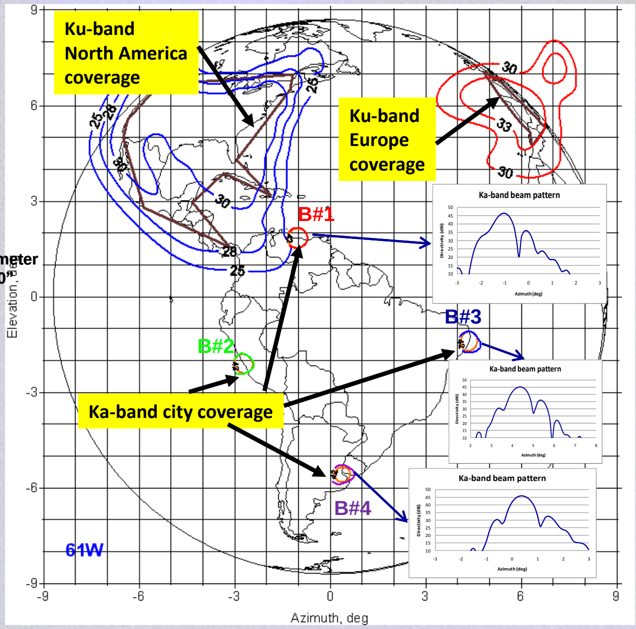


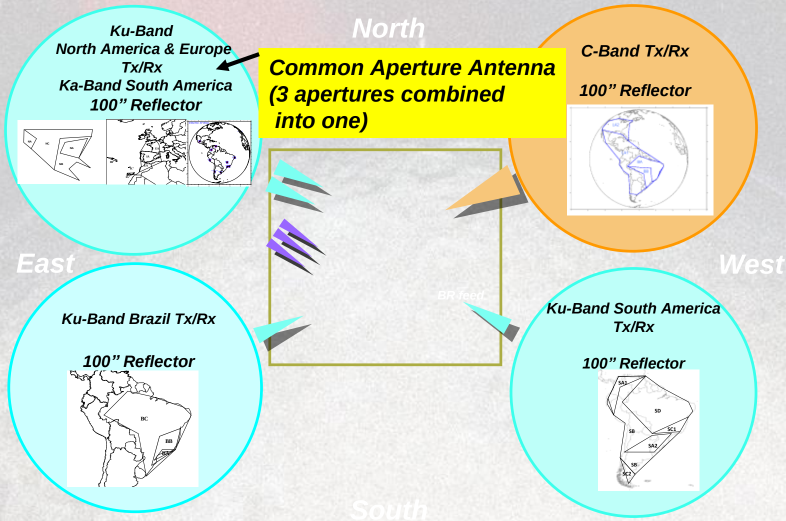
High-level integration of the feeds provides about 21 Kgs mass savings, $ 6 million cost saving, and 0.40 dB improved RF performance

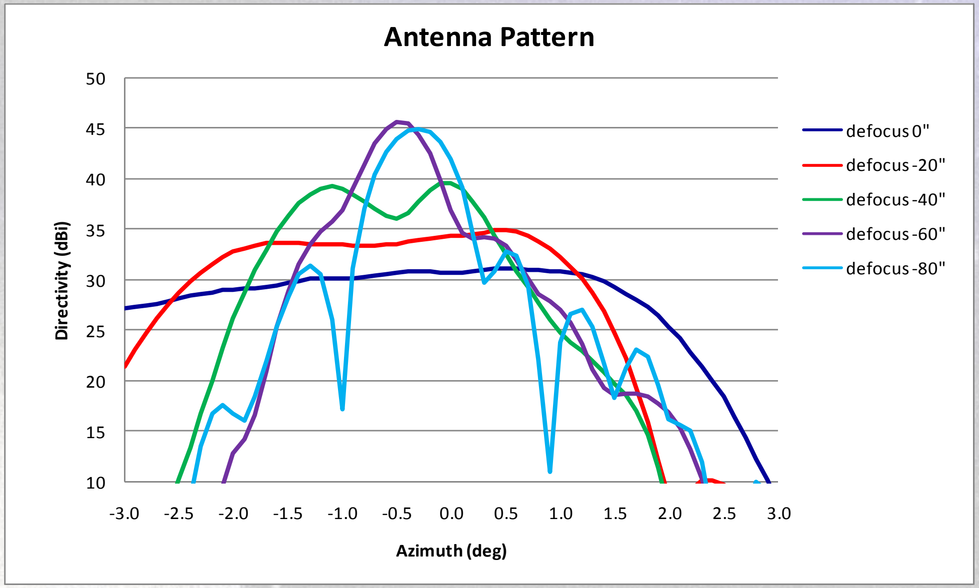
Common Aperture Antenna for Shaped and Spot Beams



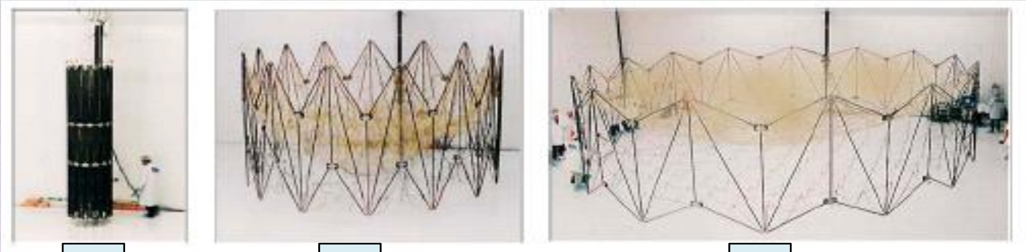






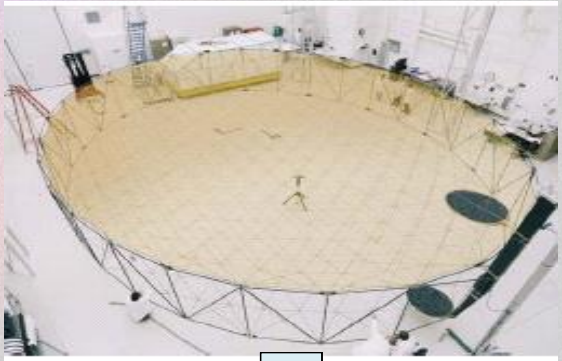


Large Deployable Reflectors for MSS

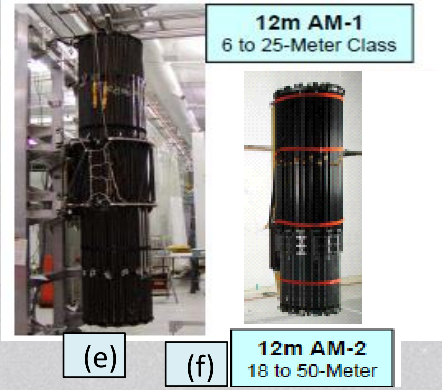


(a) (b) (c)

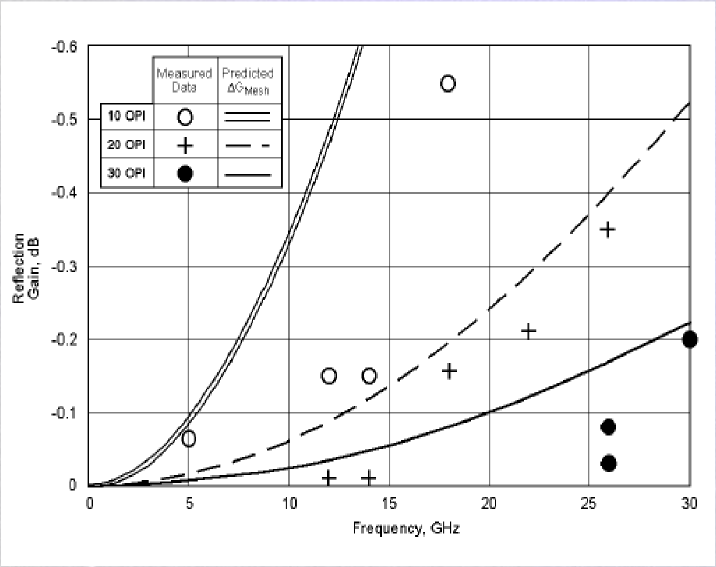
AstroMesh
12 meter Antenna
(Perimeter Truss)



(d)

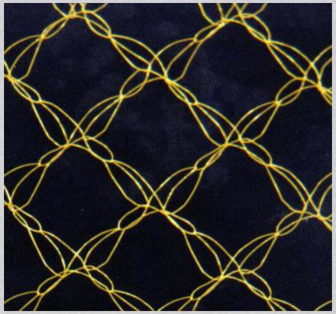


(e) (f)



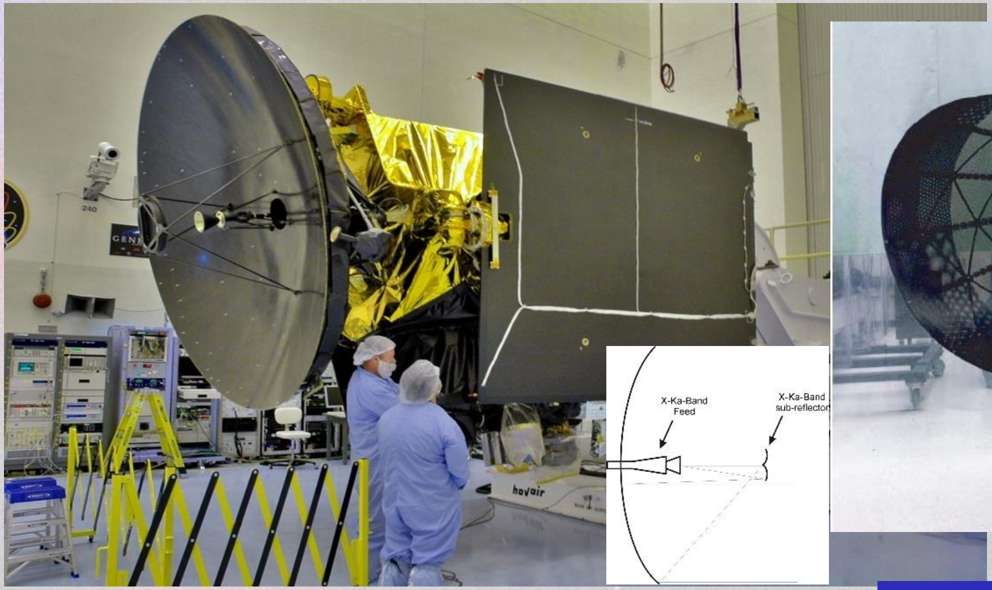
Mesh Reflectivity Loss [13]

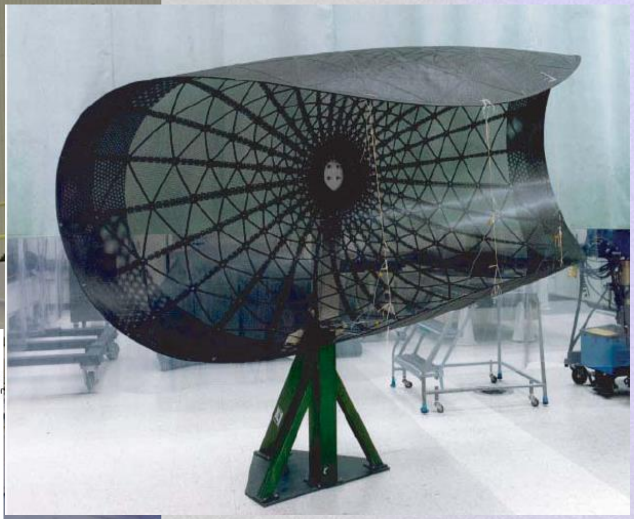
Harris 22 meter Antenna (Hoop Truss)

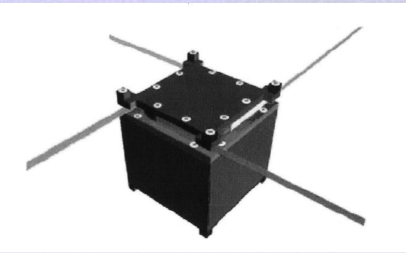


Knitted gold-moli mesh closeup [8]

Antennas for Scientific Missions





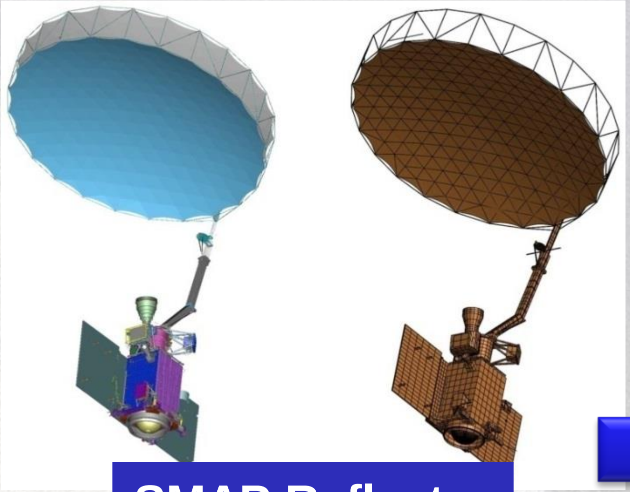


Micro-Satellite

Spring-back Reflector

MRO's antenna after integration.

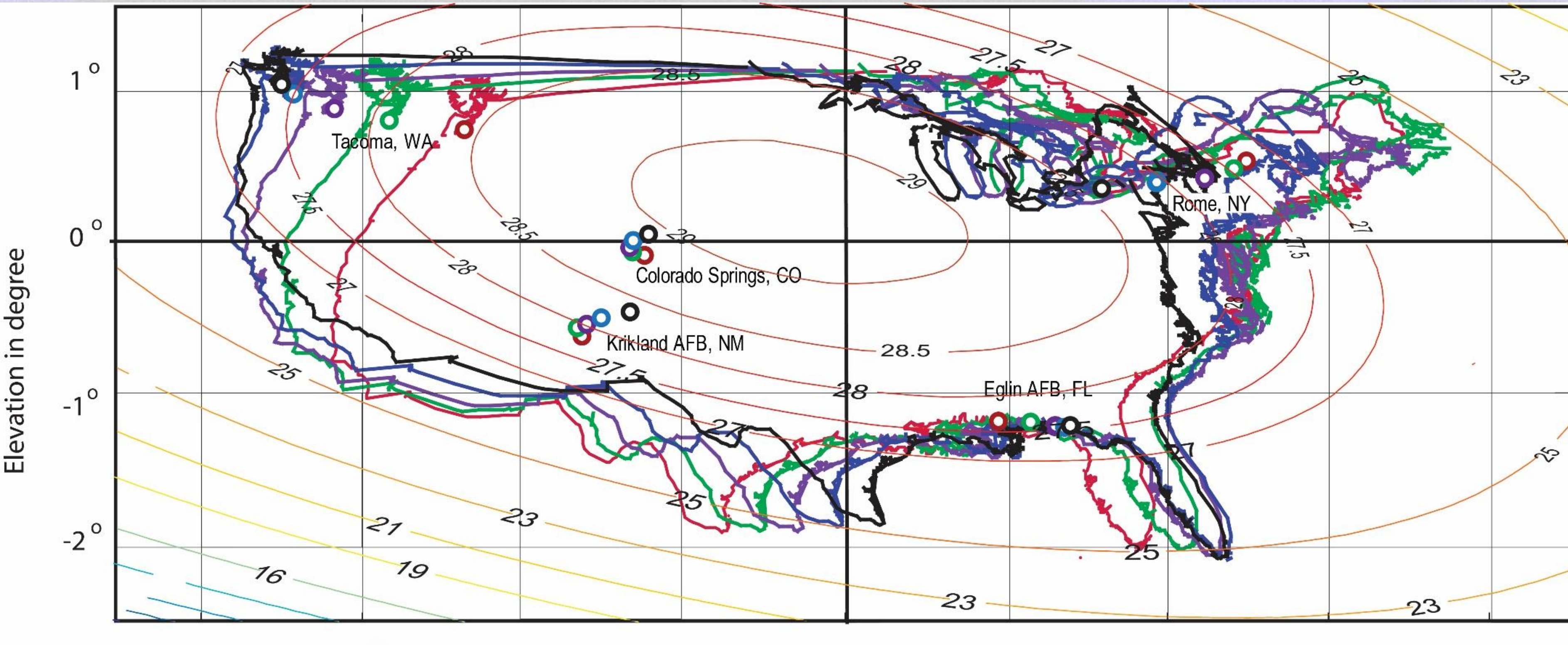
Galileo Reflector



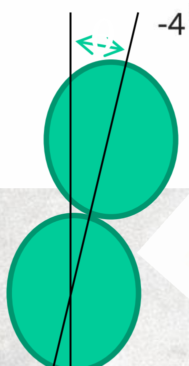
SMAP Reflector

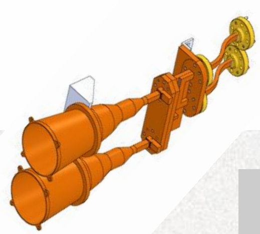
Voyager Mission

Exploration Future Bands: 72 GHz & 84 GHz (V/W Bands)

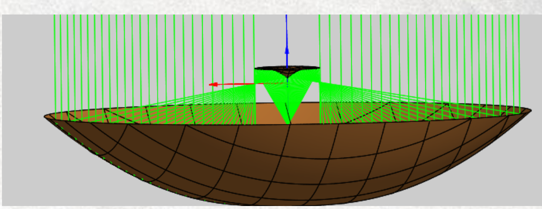


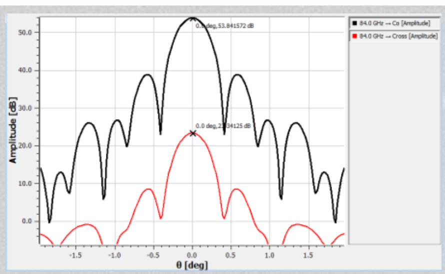
80° W
90° W
100° W
110° W
120° W





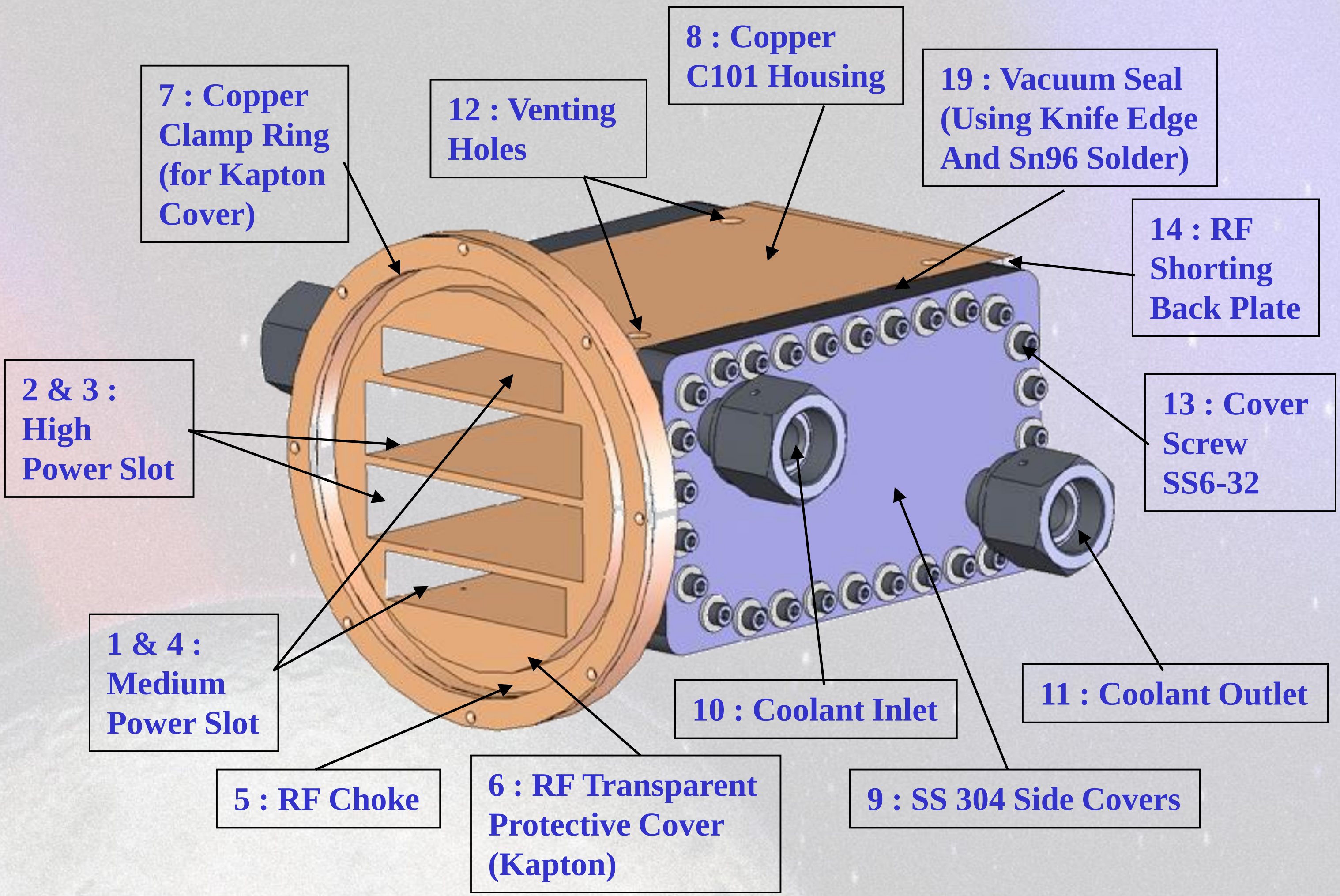
Antenna Layout





S. Rao

High Power Test Method: Pick-Up Horn Load



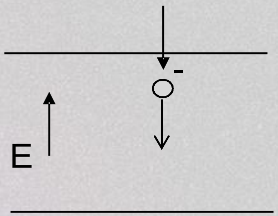
S. Rao et al., “A novel method for high-power thermal vacuum testing of satellite payloads using pick-up horns”, IEEE Antennas & Propagation Magazine, Vol. 49, #3, pp. 134-145, June 2007

S. Rao et al., U.S. Patent #s 7598919 & 7692593, 2010

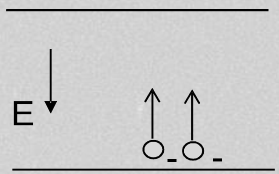
Multipaction

- **In order to prevent multipactor breakdown, special considerations need to be made during design and planning phases**
- **Selection of materials is important**
  - Certain materials are less susceptible to free electron generation. Choosing these materials can generate higher capabilities
- **Proper analysis is critical**
  - Analysis of critical components is the best way to understand margins
  - Today's field analysis tools are quite accurate
  - Detailed field analysis combined with industry available empirical data on measured breakdown thresholds can provide an accurate assessment of the risk
- **Test critical components with low margins**
  - If design margin is <3 dB, a qualification unit is recommended
  - If design margin is <6 dB, flight testing should be considered
- **Cleanliness in manufacturing & handling**

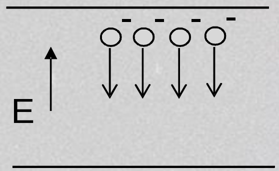
Multipaction Principles



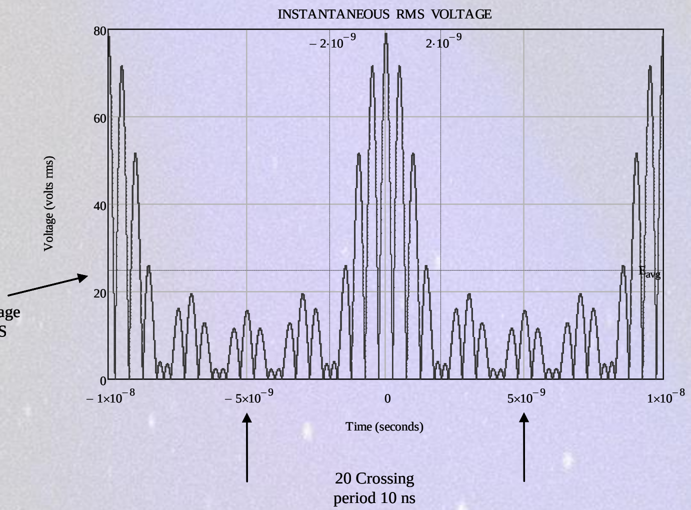
A stray electron from the environment enters and is accelerated by the RF electric field

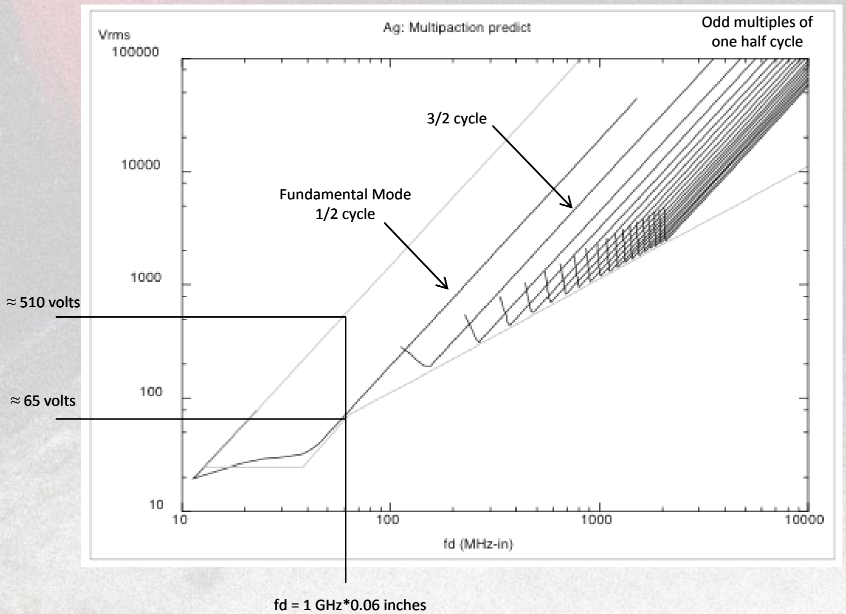


Striking the opposite $\delta=2$ surface at high velocity produces 2 secondary electrons accelerating in the opposite direction



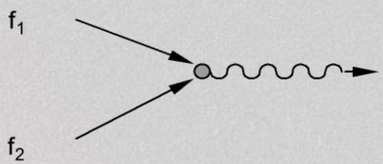
Electrons striking the opposite surface at high velocity form a *sheet* of secondary electrons





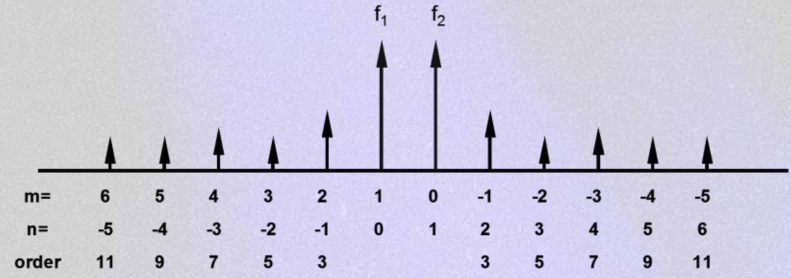
De-rating Factor	Margin, dB
VSWR	2.0 to 2.5
Oxidation	1.0 to 0.5
Contamination	2.0
Migration of contamination	1.0
TOTAL	**6.0**

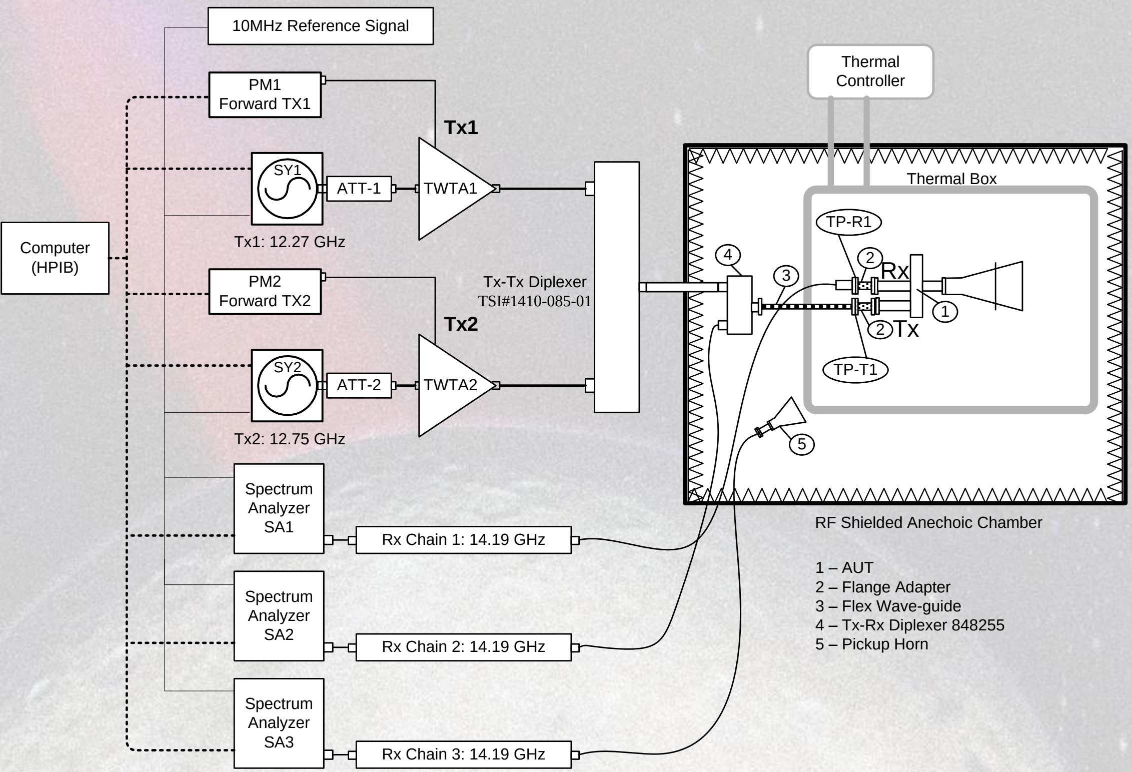
Passive Inter-Modulation (PIM)

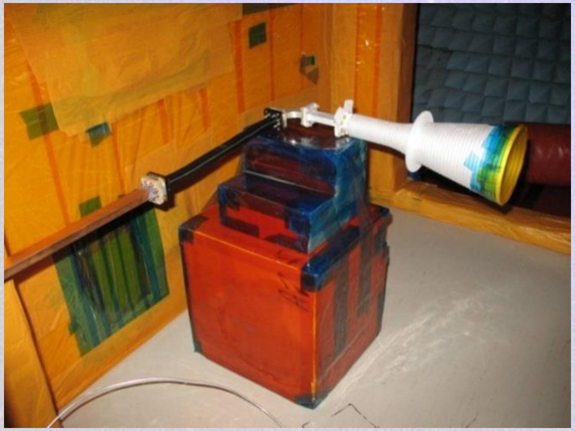


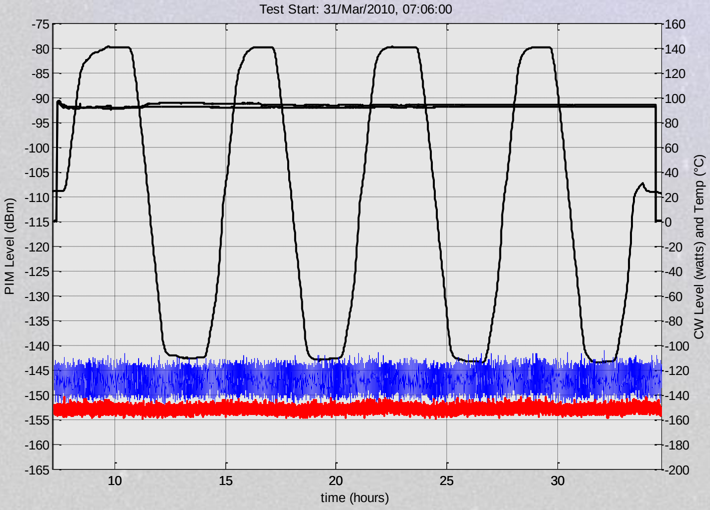
$$f_{pim} = mf_1 + nf_2$$

$$\text{order} = |m| + |n|$$



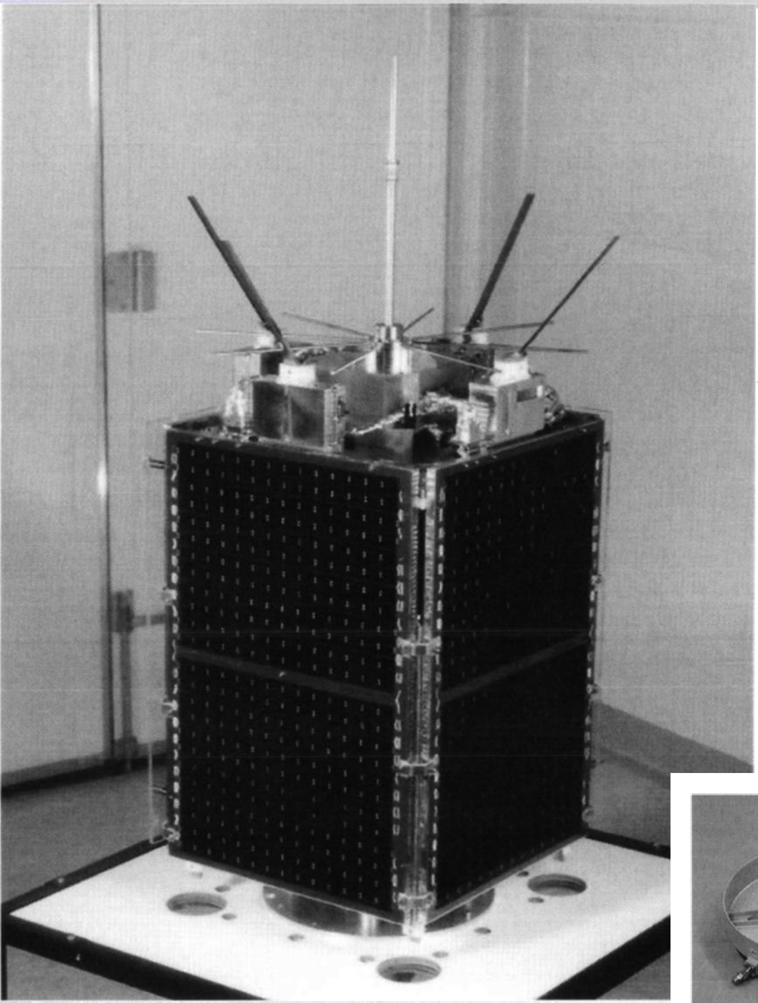




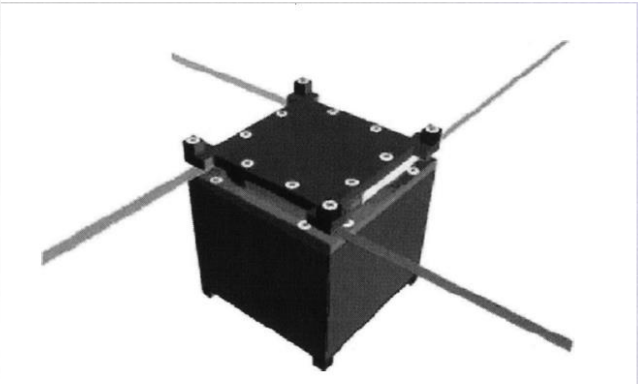


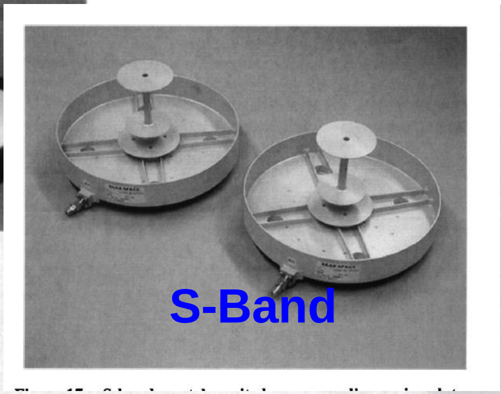
S. Rao

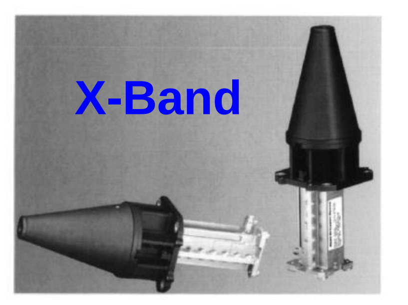
Small Satellites

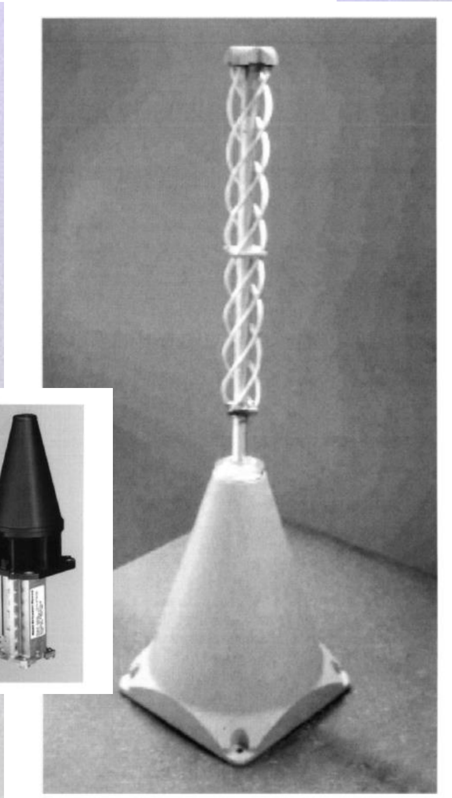


Type	Mass (kg)	Cost (US $)	Time of Development from Proposal to Launch
Conventional large satellite	>1000	0.1-2 B	>5 years
Medium satellite	500-1000	50-100 M	4 years
Mini-satellite	100-500	10-50 M	3 years
Micro-satellite	10-100	2-10 M	~1 year
Nano-satellite	1-10	0.2-2 M	~1 year
Pico-satellite	<1	20-200 k	<1 year
Femto-satellite	<0.1	0.1-20 k	<1 year





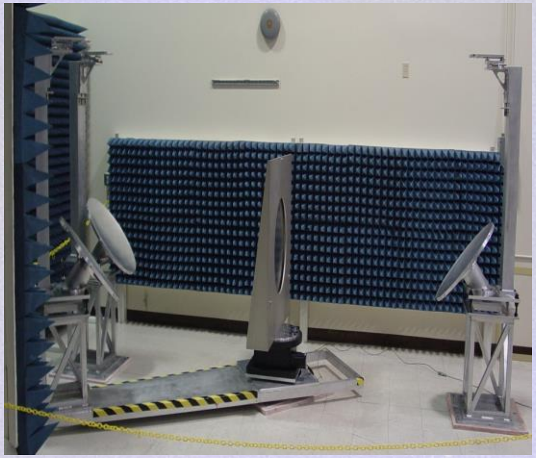




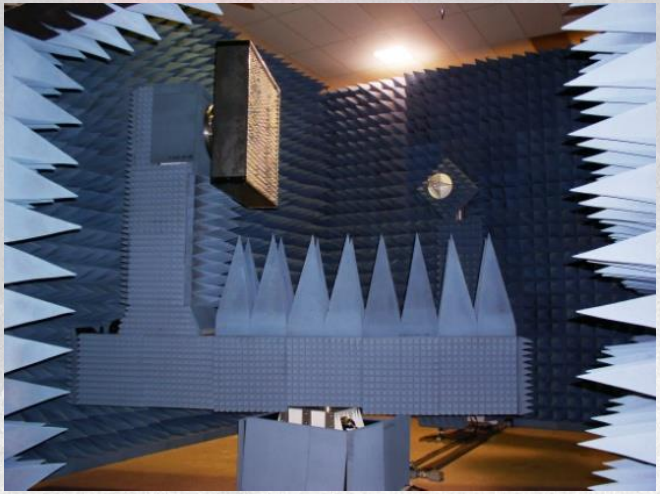
Antenna Ranges

50’ X 50’ Planar Near-Field

Two 12’ X 12’ PNF



Bistatic Range



Spherical Near-Field

CATR
6’ QZ

Anechoic
Chamber

Conclusions

➢ **Future trends in satellite antennas and payloads:**

- High capacity satellites for PCS with > 1 Tbps capacity
- Large deployable mesh-reflectors (> 50 m) with large OPI for high freqs
- Multiple band hybrid payloads, light-weight compact feed assemblies
- Larger power TWTAs, larger power spacecrafts (> 30 KW DC)
- Reconfigurable antennas, origami based antenna structures
- Agile payloads with anti-jamming capability
- Low-cost payloads, meta-materials, EBG, nano-technology etc.
- Ultra wideband antennas with > 20:1 bandwidth ratio
- High power handling and low PIM feed technologies

➢ **Antenna engineer needs several skills to develop advanced hardware needed for complex antenna systems of the 21st century**

21st Century satellites need innovative antenna solutions leading to advanced payloads