Advanced Antenna Systems for 21\textsuperscript{st} Century Satellite Communications Payloads

by

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**AGENDA**

- Introduction to Satellite Communications
- Contoured Beam Antennas
- Multiple Beam Antennas
- Multi-Band Antennas
- Reconfigurable Beam Antennas
- Hybrid Antennas
- PIM, Multipaction, Test Methods
- Conclusions


IEEE Introduction & Membership

- The IEEE is the largest professional society in the world. At present, there are more than 460,000 members in about 175 countries.
- The IEEE and its predecessors date to 1884.
- The IEEE produces 30 percent of the world's published literature in electrical engineering, computers and control technology.
- There are more than 1,200 student branches.
- There are 38 technical Societies + 10 Divisions & 10 Regions

Membership grades:
- Student Member
- Member
- Senior Member
- Fellow
- Life Fellow

Who Qualifies for Student Membership?
- Undergraduate or graduate students
- 50% of a normal full-time course of study (at least part-time studies)
- Electrical, electronics or computer engineering, computer sciences
- An allied branch of engineering, engineering technology or the related arts and science
- Student membership dues are 20% of regular memb ($30 vs $147)

The IEEE is largely a volunteer organization. Enhance your career by getting involved!
Satellite uses a space platform as a relay or broadcast node
Satellite serves as an information collection, management and dissemination center with a relatively vast communications area compared to ground based relay networks
Advantages of Satellite Based Communications

- Only three or four satellites in geosynchronous orbit are necessary to provide near global coverage.
- One satellite for national/regional coverage.

  * Earth Radius = 6832 kms
  * Satellite Altitude = 35786 kms
  * Subtended Angle = +/- 8.7°

Benefits of satellites over conventional ground media (cable, wire, fiber, point-to-point) include:
- Fast development and establishment of a communications infrastructure
- Higher availability
- Immediate coverage of desired area after launch
  - Satellites do not respect natural limitations such as mountains, water, etc. or political boundaries
- Distance insensitive for point-to-multi-point communications
  - Fiber optic systems are optimal for point-to-point connections with a limited number of distribution nodes
- Lower cost for 100% coverage of a region
  - More cost effective for providing thin route services

Requires only 3 or 4 satellites for global coverage.
GEO Satellites

Actual geostationary orbit use (2001)

Solar panels aren’t wings...

The GEO Belt

Note gap over the Pacific – too large to span (unlike Atlantic); small populations
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)
Communications Satellite System Connectivity

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 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.

- **Gain**
  - $\text{Gain} = \text{Directivity} - \text{Antenna Losses}$

- **Isotropic Radiator**

- **Directive Antenna**

- **Vertical**
- **Horizontal**

- **Left Hand Circular**
- **Right Hand Circular**

- **OMTs (symmetric, asymmetric)**
- **Polarizers**
**Spacecraft Antenna Types**

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

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

- **Low Gain Antennas (0 dBi to 12 dBi)**
  Biconical Antennas
  Waveguides
  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.
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 & Payloads

Payload = Antenna + Repeater

High dissipation

OLD TECHNOLOGY

NEW TECHNOLOGY

Vertical Polarization

Horizontal Polarization

TFB BFN
Receive Reject Filters

Offset Parabolic Reflector

Shaped Reflector
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 the X-pol isolation within the coverage (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


Define Coverage Reqs. & Freq., Gain, Polarization

Define Reflector Geometry (Size, Offset, Focal Length)

Define Feed Reqs. (Taper, X-pol, P.C)

Start Feed Optimization (Profile, Corrugation, geometry, Matching Section)

Complete Feed Opt

Have the Feed Reqs. Met?

NO

YES

Have the Coverage Reqs. Met at 4 Freq. Band?

No

Contoured Beam Ant Design Finished

END

Evaluate Antenna Perf. at Ku Tx, Ku Rx, Ka Tx & Ka Rx

Start Reflector Surface Optimization

<table>
<thead>
<tr>
<th>Reflector Diameter (meters)</th>
<th>D/λ</th>
<th>CONUS (13 sq. degrees) Ku-Band</th>
<th>South America (26.45 sq. degrees) Ku-Band</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>EOC Directivity (dBi)</td>
<td>GAP</td>
</tr>
<tr>
<td>1.0</td>
<td>36.50</td>
<td>30.1</td>
<td>13303</td>
</tr>
<tr>
<td>1.3</td>
<td>47.45</td>
<td>30.7</td>
<td>15274</td>
</tr>
<tr>
<td>1.5</td>
<td>54.75</td>
<td>31.0</td>
<td>16366</td>
</tr>
<tr>
<td>1.8</td>
<td>65.70</td>
<td>31.2</td>
<td>17137</td>
</tr>
<tr>
<td>2.0</td>
<td>73.00</td>
<td>31.4</td>
<td>17945</td>
</tr>
<tr>
<td>2.3</td>
<td>83.95</td>
<td>31.7</td>
<td>19228</td>
</tr>
<tr>
<td>2.6</td>
<td>94.90</td>
<td>31.9</td>
<td>20135</td>
</tr>
</tbody>
</table>


Typical Delta-Surface (S-Band)

Delta Surface (shaped-parabola) Contour Plot in m
12.0m Antenna Single Feed Horn Design for GEO
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

100” dia. SRA
50” dia. GRA
100” dia. SRA
100” dia. SRA
100” dia. SRA
100” dia. SRA

Map View @ 42ºE

C-Band EIRP Contour Plot
Freq (MHz) = 4140
Polarization = LHCP
CF (dBW) = +15.43

C-Band G/T Contour Plot
Freq (MHz) = 6725
Polarization = RHCP
CF (dB/K) = -28.24

Azimuth deg
Elevation deg

41.0dBW
40.0dBW
39.0dBW
38.0dBW
37.0dBW
36.0dBW
35.0dBW
34.0dBW
33.0dBW
32.0dBW
31.0dBW
-11.0dB/K
-10.0dB/K
-9.0dB/K
-8.0dB/K
-7.0dB/K
-6.0dB/K
-5.0dB/K
-4.0dB/K
-3.0dB/K

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Pg.16
Gridded Reflectors & Gregorian Antennas

Koreasat F1 Shaped Reflector Assembly

DL Talk: 2015
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°C to +170°C)
- Better manufacturing tolerances
Horn Types for SATCOM

- Corrugated Horns: wideband, supports dual-band, low X-pol, heavy
- Potter Horns: Limited Bandwidth, smooth-wall, low mass
- Multi-flare Horn: Multi-band capability (> octave BW), high efficiency, low-mass, suitable for PCS 7 MBAs
- Tri-furcated Horn: Suitable for LP, low spill-over loss, low X-pol
- Bi-conical Horn: Suitable for TT&C
- Waveguides, Quadri-filar helices (volutes) etc. (low gain)
- Dielectric Horns: Not suitable for space (ESD issues)
- Cup-Dipoles & PEC: Suitable for mobile satellites
- Helical Antennas: Suitable at L-Band & UHF (GPS)
**Feed Types**

- **C-Band Tx/RX Feed Assembly**
- **Trifurcated Horns**
- **Ku-Corrugated Horn**
- **Multi-Mode Horn**
- **Ku-Tracking Feed**

### Parameters and Measured Performance

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

### Typical Test Plan

1. Initial Ambient Network Test
2. High Power and/or Multipaction if required
3. RF Test of Network over Temperature
4. Assembly of Horn to Network
5. Initial Ambient Feed Test with Pattern
6. Sine & Random Vibe Test
7. Health Check
8. Thermal Cycling
9. Final Ambient Feed Test with Pattern
10. Thermal or Ambient PIM Test if Required
C-Band Feed Assemblies (Discrete vs Integrated)

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>Discrete</th>
<th>Integrated</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>21&quot; X 21&quot; X 33&quot;</td>
<td>12&quot; X 12&quot; X 12&quot;</td>
<td>INTG Feed is 8 times more compact</td>
</tr>
<tr>
<td>Mass</td>
<td>18.3 lbs</td>
<td>12 lbs</td>
<td>INTG Feed is 35% lighter than ANTEK’s</td>
</tr>
<tr>
<td>Tx Insertion Loss, dB</td>
<td>0.16</td>
<td>0.13</td>
<td>INTG Feed has lower insertion loss due to compact size and use of Cu</td>
</tr>
<tr>
<td>Rx Insertion Loss, dB</td>
<td>0.09</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>Tx Axial ratio, dB (Ambient/Thermal with 5 deg. delta)</td>
<td>0.13 / 0.26</td>
<td>0.15 / 0.20</td>
<td>Thermal A.R of INT feed is better</td>
</tr>
<tr>
<td>Rx Axial ratio, dB (Ambient/Thermal)</td>
<td>0.13 / 0.20</td>
<td>0.16 / 0.19</td>
<td></td>
</tr>
<tr>
<td>Tx Return Loss, dB</td>
<td>30</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Rx Return Loss, dB</td>
<td>31</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Bench Tuning</td>
<td>Extensive</td>
<td>None</td>
<td>Bench tuning is required for Disc feed</td>
</tr>
<tr>
<td>Qualification Status</td>
<td>Flight</td>
<td>Flight</td>
<td></td>
</tr>
</tbody>
</table>

Integrated feed assembly is more compact, better RF performance and low PIM risk
Multiple Beam Antennas

- Multiple beam payload systems are extensively used for both military and commercial satellites. Advantages are higher EIRP, G/T, spectral re-use, & smaller ground terminals
  - Direct Broadcast Satellites (12/17 GHz): EchoStar, DirecTV, HNS
  - Ka Broadband Satellites (19/29 GHz): Anik-F2, ViaSat, EutelSat
  - Military Satellites (20.5/30 GHz): Wideband Gapfiller Satellite (WGS)
- Above systems operate in dual-bands and support single service
- Future systems are required to support multiple satellite services
  - Ku & Ka supporting DBS & broadband (12/18/20/30 GHz)
  - TSAT and FABT (20/30/45 GHz) combining existing WGS & AEHF
- Advanced antenna systems developed recently that simultaneously supports three services (DBS, reverse DBS, and broadband) covering **FIVE DISCRETE BANDS** over 12.3 GHz to 30.0 GHz (with BWR of 2.44)
- Key components are:
  - Multi-mode smooth wall horn supporting 5 discrete bands
  - MBA design producing multiple beams at 5 bands simultaneously

Single satellite supporting multiple services is the future trend
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 for MBAs**

**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**
3-Cell Reuse with 1 Aperture

4-Cell Reuse with 3 Apertures

7-Cell Reuse with 4 Apertures

Evolution of MBA Technology

Single-Band Antennas (require 10 apertures)

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

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

Advanced MBA

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

- Higher EIRP & G/T
- High Spectral Re-use (8 times freq X 2 times pol = 16)
- Satellite Capacity > 100 Gbps
MBA for Local-Channel Broadcast

Multiple Beams with Non-Uniform Spacing & Non-Uniform Size
**MBA Horn Comparison**

<table>
<thead>
<tr>
<th>Type</th>
<th>Narrow Band</th>
<th>Wide Band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional Horn (Corrug.)</td>
<td>DUAL-BAND</td>
<td>Multiple-Mode Horn</td>
</tr>
<tr>
<td>Dual-Band</td>
<td>Single Band</td>
<td>Multiple-Mode Horn</td>
</tr>
<tr>
<td>Thick Corrugations</td>
<td>Step-Discontinuities</td>
<td>Slope-Discontinuities</td>
</tr>
<tr>
<td>54% Eff. Tx &amp; Rx</td>
<td>&gt; 85% over Tx or Rx</td>
<td>&gt; 85% over Tx &amp; Rx</td>
</tr>
<tr>
<td>Heavy &amp; Bulky</td>
<td>Light &amp; Compact</td>
<td>Light &amp; Compact</td>
</tr>
</tbody>
</table>

- **d < D**
- **D**

**DL Talk: 2015**
Design Procedure for HEH

- Define horn aperture size, waveguide size, and the efficiency
- Select modal content (e.g., TE11, TE12, TE13/1.0, 0.31, 0.21)
- Determine radial dimension based on modes to set profile breakpoints for the horn & use “slope-discontinuities”
- Optimize horn geometry to satisfy cost function:

\[
F = \sum_{i=1}^{nfrq} \left[ wt_r (\rho_i - \rho_{di})^2 + wt_x (xp_i - xp_{di})^2 + wt_o (\eta_i - \eta_{di})^2 \right]
\]

- Aperture efficiency that can be achieved depends on the horn size.
  - Larger the size, higher will be the aperture efficiency and lower bandwidth
  - Typical efficiency values for dual-band operation at K/Ka are in the range 85% to 90%
  - Trade is the higher efficiency at K, better match at K, and lower off-axis x-pol at K/Ka

HEH Performance Summary

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Directivity (dBi)/Efficiency</th>
<th>Cross-Pol (dB)</th>
<th>Return Loss (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Predict</td>
<td>Measured</td>
<td>Predict</td>
</tr>
<tr>
<td>18.30</td>
<td>20.08 (83.4%)</td>
<td>20.10 (83.8%)</td>
<td>19.8</td>
</tr>
<tr>
<td>19.30</td>
<td>20.60 (84.5%)</td>
<td>20.60 (84.5%)</td>
<td>20.5</td>
</tr>
<tr>
<td>20.20</td>
<td>21.05 (85.6%)</td>
<td>21.1 (86.6%)</td>
<td>20.6</td>
</tr>
<tr>
<td>28.30</td>
<td>23.89 (83.9%)</td>
<td>23.8 (82.1%)</td>
<td>24.1</td>
</tr>
<tr>
<td>29.20</td>
<td>24.23 (85.2%)</td>
<td>24.2 (84.6%)</td>
<td>26.0</td>
</tr>
<tr>
<td>30.00</td>
<td>24.46 (85.1%)</td>
<td>24.5 (85.9%)</td>
<td>23.0</td>
</tr>
</tbody>
</table>

Aperture Efficiency Plot

<table>
<thead>
<tr>
<th>percentage eff(%)</th>
<th>Frequency, GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>40.0%</td>
<td>18.0</td>
</tr>
<tr>
<td>50.0%</td>
<td>20.0</td>
</tr>
<tr>
<td>60.0%</td>
<td>22.0</td>
</tr>
<tr>
<td>70.0%</td>
<td>24.0</td>
</tr>
<tr>
<td>80.0%</td>
<td>26.0</td>
</tr>
<tr>
<td>90.0%</td>
<td>28.0</td>
</tr>
<tr>
<td>100.0%</td>
<td>30.0</td>
</tr>
</tbody>
</table>

edge taper

<table>
<thead>
<tr>
<th>edge taper (dB)</th>
<th>Frequency (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-25.0</td>
<td>18.0</td>
</tr>
<tr>
<td>-20.0</td>
<td>20.0</td>
</tr>
<tr>
<td>-15.0</td>
<td>22.0</td>
</tr>
<tr>
<td>-10.0</td>
<td>24.0</td>
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<tr>
<td>-5.0</td>
<td>26.0</td>
</tr>
<tr>
<td>0.0</td>
<td>28.0</td>
</tr>
<tr>
<td>5.0</td>
<td>30.0</td>
</tr>
</tbody>
</table>
Multi-band Horn Geometry & Performance

Key Performance Results
• Return Loss: > 26 dB
• Efficiency: 74% to 82%
• X-pol: < -22 dB

<table>
<thead>
<tr>
<th>D (in.)</th>
<th>L (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.640</td>
</tr>
<tr>
<td>2</td>
<td>0.640</td>
</tr>
<tr>
<td>3</td>
<td>0.646</td>
</tr>
<tr>
<td>4</td>
<td>0.877</td>
</tr>
<tr>
<td>5</td>
<td>1.299</td>
</tr>
<tr>
<td>6</td>
<td>1.560</td>
</tr>
<tr>
<td>7</td>
<td>2.100</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Return Loss (dB)</th>
<th>X-pol (20º) (dB)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.5</td>
<td>-26.5</td>
<td>-22.3</td>
<td>82</td>
</tr>
<tr>
<td>17.3</td>
<td>-48.0</td>
<td>-22.5</td>
<td>80</td>
</tr>
<tr>
<td>17.8</td>
<td>-50.2</td>
<td>-23.6</td>
<td>80</td>
</tr>
<tr>
<td>18.4</td>
<td>-43.6</td>
<td>-23.6</td>
<td>79</td>
</tr>
<tr>
<td>20.2</td>
<td>-41.7</td>
<td>-22.1</td>
<td>76</td>
</tr>
<tr>
<td>24.8</td>
<td>-50.1</td>
<td>-23.0</td>
<td>76</td>
</tr>
<tr>
<td>25.3</td>
<td>-44.3</td>
<td>-23.7</td>
<td>76</td>
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<tr>
<td>28.5</td>
<td>-44.0</td>
<td>-23.9</td>
<td>75</td>
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<tr>
<td>30.0</td>
<td>-45.2</td>
<td>-22.1</td>
<td>74</td>
</tr>
</tbody>
</table>
Feed Pattern (Defocus=0” & 1”)

Quad-band Forward DBS Horn Pattern

Quad-band Reverse DBS Horn Pattern

Quad-band Horn Phase (no defocus)

Quad-band Horn Phase (defocus = 1”)

Feed defocus of 1.0” improved higher band performance
Secondary Pattern (Defocus=1.0”)

EOC Directivity

<table>
<thead>
<tr>
<th>Freq</th>
<th>Coverage</th>
<th>Peak</th>
<th>Co-pol</th>
<th>C/X</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.45</td>
<td>±0.5°</td>
<td>49.0</td>
<td>47.4</td>
<td>32.8</td>
</tr>
<tr>
<td>17.55</td>
<td>±0.5°</td>
<td>51.9</td>
<td>49.5</td>
<td>28.7</td>
</tr>
<tr>
<td>19.30</td>
<td>±0.5°</td>
<td>52.6</td>
<td>49.8</td>
<td>27.4</td>
</tr>
<tr>
<td>25.00</td>
<td>±0.5°</td>
<td>53.5</td>
<td>50.1</td>
<td>23.3</td>
</tr>
<tr>
<td>29.25</td>
<td>±0.5°</td>
<td>53.6</td>
<td>50.0</td>
<td>18.4</td>
</tr>
</tbody>
</table>

Peak Directivity of various Horn Defocus
Multi-Band Feed Assembly Schematic

Symmetrical OMT, Polarizer & Diplexer at 17/20 GHz

W/G Bend & Combiner

Filter to reject 25/30 GHz (Qty. 4)

20 GHz RCP
17 GHz RCP
17 GHz LCP
20 GHz LCP

25 GHz RCP
30 GHz RCP
25 GHz LCP
30 GHz LCP

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

K/Ka band Intg. Feed
18 GHz – 30 GHz
RL > 25 dB
IL < 0.25 dB
A.R < 0.25 dB
Tx/RX Isol. > 80 dB

Size: 2.27” X 15.0 in
Mass: 1 lb
Efficiency: > 85%
Typical Multiple Beam Layout over CONUS Coverage (119° W orbital location)

DMA Ranking (2006 Nielsen Ranking)

26 Beams cover 40 top DMAs (6 to 7 beams per aperture)
Step Size $h = m \cdot \left[ 180 \pm (\text{feed phase}(\Theta_i) - \text{feed phase}(\Theta_0)) \right] \cdot \frac{\pi}{180} \cdot \frac{\lambda}{2\pi} \cdot \frac{1}{2}$
**SRA with Frequency-Dependant Horn Design**

- **DBHEH Design** can exploit phase center variation between bands to minimize SRA step height.
- **Phase patterns of horns** for dual-band & multi-band horns are critical to optimize antenna performance.

\[
\Delta \text{Phase} = kd(1 - \cos \theta_0)
\]

\[
\Delta \text{Phase} = 84^\circ \ (\theta_0 = 25^\circ, d=1'', \text{Freq}=30 \text{ GHz})
\]
Impact of SRA on Receive Beam Patterns

Step Depth=0.10"

Secondary Pattern Cut @ 29200MHz

- 80" reflector
- 80" plus 5" ring
- 80" plus 10" ring
- coverage
- coverage plus PE

Pattern, dBi

Theta, deg

1.48dB
0.96dB
0.85dB
0.55dB

Step Depth=0.10"
Large Deployable Reflectors for MSS

AstroMesh
12 meter Antenna (Perimeter Truss)

Harris 22 meter Antenna (Hoop Truss)

Knitted gold - moli mesh closeup

Mesh Reflectivity Loss [13]
Reconfigurable Antenna Block Diagram

Mesh Reflector (~ 15 m diameter)  
(SRI, DRI or NFR)

- Test Couplers (N)
- BPFs (N)
- 8x8 OHMs (Qty. 5 to 8)
- Redundancy Output Switch Matrix (N)
- SSPAs with Redundancy (50 to 80)
- Redundancy Input Switch Matrix (N)
- 8x8 IHMs (Qty. 5 to 8)
- Combining Networks (N)
- Dividing Networks (M)
- Beam Ports (M=8 to 10)

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Page 41
Non-Focused Reflector (NFR) Concept

• Non-Focused Reflector (NFR) with symmetrical shaping

• By opening-up or closing-in the paraboloid gradually, a quadratic phase-front is created in the aperture plane (instead of uniform phase-front)

• The quadratic phase-front broadens the element beams significantly (1.5 to 3 times)

• Main advantage is fewer number of feed elements (by a factor of 3 or more)

• Scan performance improves (a) due to symmetrical shaping, and (b) due to feed array & reflector geometrical relation is more optimal

• Element beams are combined in the far-field with non-uniform amplitude and non-uniform phase excitations to synthesize the antenna beam contour

• MPA allows uniform loading of the amplifiers

NFR Concept

Mesh Reflector

Uniform phase-front (paraboloid)

Quadratic phase-front (opening-up surface)

Quadratic phase-front (closing-in surface)

Far Field Element Beam

Parabola

Non-Parabola
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

Contour Level: 65 dBW for User Beams
59 dBW for GW Beams

Contour levels: 45, 48, 64, 66, 68 dBW

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

G/T > 20 dB/K
C/I > 26 dB (single interferer)
Common Aperture Antenna for Shaped and Spot Beams

- Combined into one
- Ku-Band Europe Tx/Rx 85° Gregorian
- C-Band Tx/Rx 100° Reflector
- Ku-Band Europe Tx/Rx 85° Gregorian
- South America Tx/Rx 100° Reflector
- Spherical cap To ka feeds
- Ku-band feed
- Adjust defocus to for flat phase
- Reflector shaped for Ku-band contoured beams
- KW-feed
- IB'
- IB'
- EIA
- EA
- IB
- IB
- IC'
- SC1
- SC2
- SA2
- SA1
- SB
- SB
- SD
- S. Rao
- DL Talk: 2015

Antenna Pattern

- defocus 0°
- defocus -20°
- defocus -40°
- defocus -60°
- defocus -80°

North American and Europe
- Ku-band North America coverage
- Ku-band Europe coverage
- Ku-band South America
- 100" Reflector
- Common Aperture Antenna (3 apertures combined into one)
- Antenna beam pattern
- South America
- Common Aperture Antenna
- 100" Reflector
- North America Tx/Rx
- C-Band Tx/Rx
- 100" Reflector
- Picture of South America
- Europe
- North America
- West
- East
- South
Advanced Reflectors: X-Link & Gateway Applications
Phased Arrays with Flexible Beams

WBR OPA Rx Patterns; Peak = 43.86 dBi

Directivity (dB)

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Array Design

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

\[
D_A = G_p + L_S + SL + T_L + I_m
\]

<table>
<thead>
<tr>
<th>Scan Angle (degrees)</th>
<th>Element Spacing in ( \lambda ) at Highest Freq. *</th>
<th>Number of Elements for 1000 ( \lambda^{**2} ) at Highest Freq</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Square Lattice</td>
<td>Hexagonal Lattice</td>
</tr>
<tr>
<td>80</td>
<td>0.50</td>
<td>0.58</td>
</tr>
<tr>
<td>70</td>
<td>0.52</td>
<td>0.60</td>
</tr>
<tr>
<td>60</td>
<td>0.55</td>
<td>0.64</td>
</tr>
<tr>
<td>50</td>
<td>0.61</td>
<td>0.70</td>
</tr>
<tr>
<td>40</td>
<td>0.71</td>
<td>0.82</td>
</tr>
<tr>
<td>30</td>
<td>0.88</td>
<td>1.02</td>
</tr>
<tr>
<td>20</td>
<td>1.19</td>
<td>1.37</td>
</tr>
</tbody>
</table>

* Assumes closest grating lobe location as 10 deg. larger than the maximum scan angle.
Wideband Arrays (> 3:1 BWR)

RIDGE ELEMENT ARRAY

Stacked-Patch Array
High-level integration of the feeds provides about 21 Kgs mass savings, $6 million cost saving, and 0.40 dB improved RF performance.
Antennas for Scientific Missions (cont’d)

MRO’s antenna after integration.

Spring-back Reflector

Galileo Reflector

SMAP Reflector

Voyager Mission
High Power TVAC Test Method Using Pick-Up Horn (PUH) Loads

FWD & RTN
PWR Monitoring

Ground Equipment

Rf Power Monitor

Freq Synth

1

Freq Synth

GPIB

Audible Alarm

PUH Monitor & Ctl
Will Shut off rf input if temp/pwr exceeds threshold automatically

PUH Cooling Ctl and LN2 Regulator
Regulates LN2 Temp to -100C

HP Load

HP Load

Horn 1

PUH 1

1600 w Avg

Horn 4

PUH 4

OMUX X 2

Cooled by Florinert Unit

OMUX X 2

Horn 5

PUH 5

300 w Avg

German Spot

TWTAs 1-4

OMUX X 2

Flt Cplr

TCs for Temp Monitoring

1

52 TCs

KOSM

X

X

KOSM

X

OMUX X 2

GPIB

TCs for Temp Monitoring

FWD & RTN
PWR Monitoring

GPIB

Audible Alarm

PUH Monitor & Ctl
Will Shut off rf input if temp/pwr exceeds threshold automatically

PUH Cooling Ctl and LN2 Regulator
Regulates LN2 Temp to -100C

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Pg.53
S. Rao et al., U.S. Patent #s 7598919 & 7692593, 2010
Passive Inter-modulation (PIM)

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Page 55
A stray electron from the environment enters and is accelerated by the RF electric field.

Striking the opposite 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.

\[ \delta = 2 \]

\[ E_{avg} \approx 510 \text{ volts} \]

\[ \approx 65 \text{ volts} \]

Fundamental Mode

\[ \frac{1}{2} \text{ cycle} \]

Odd multiples of one half cycle

\[ \frac{3}{2} \text{ cycle} \]

\[ f_d = 1 \text{ GHz} \times 0.06 \text{ inches} \]

20 Crossing period 10 ns

Average voltage 25 volts RMS

INSTANTANEOUS RMS VOLTAGE

Time (seconds)

Voltage (volts rms)
**TT&C Antennas**

**TT&C RF Equipment**

- Command receivers
- Telemetry transmitters
- Command Horn Antenna(s)
- Telemetry Horn Antenna(s)
- Command and Telemetry Omni Antenna
- Miscellaneous RF Hardware

**TT&C RF Antenna Gains @ TX and RX Frequencies**

- **Gain Difference**
  - 35
  - 30
  - 25
  - 20
  - 15
  - 10
  - 5
  - 0
  - 5
  - 10
  - 15

- **Angler from Z Axis (°)**
  - 180
  - 150
  - 120
  - 90
  - 60
  - 30
  - 0
  - 30
  - 60
  - 90
  - 120
  - 150
  - 180

- **Gain (dBi)**
  - Omni
  - Wide Angle Horn
  - Requirement

**Earth Deck Panel**

- TCRX1
- TCRX2
- TTX1
- TTX2
- RX WCA (LHCP)
- RX OMNI (LHCP)
- TX WCA (RHCP)
- TX OMNI (RHCP)
- COMM ANTENNA

**High Power**

**Low Power**

**H**

**TT&C RF Antenna Gains @ TX and RX Frequencies**

- **Gain (dB)**
  - 15
  - 10
  - 5
  - 0
  - -5
  - -10
  - -15
  - -20
  - -25
  - -30
  - -35

- **Angle from Z Axis (°)**
  - 180
  - 150
  - 120
  - 90
  - 60
  - 30
  - 0
  - 30
  - 60
  - 90
  - 120
  - 150
  - 180

- **Gain Difference**
  - Omni
  - WA Horn
  - Requirement
Test Ranges & Equipment

- High Bay

- Planar near-field range: High gain and medium gain antennas
  - measure near-fields over +/- 80°

- Spherical near-field range: Typically used for medium gain and low-gain antennas
  - precise probe to AUT alignment and probe compensation required (not used often)

- Far-field range: Out-door range with real-time measurements
  - suffers from ground reflections and weather conditions

- Compact range: the best range allowing real-time measurements of high gain/medium gain antenna patterns
  - employs SFOC dual-reflector system to create plane-wave quiet-zone region for AUT placement and measurements

- Anechoic chamber: indoor far-field measurements for medium and low gain antennas
  - global horns, omni-antennas

- Test Equipment: PIM test equipment, high power test set-up, thermal chamber, TVAC chamber, network analyzer etc.
Conclusions

- Future trends in satellite antennas and payloads include:
  - high capacity satellites for PCS with > 500 Gbps capacity
  - used of large deployable mesh-reflectors with apertures > 20 meters
  - multiple band hybrid payloads, light-weight compact feed assemblies
  - larger power TWTAs, larger power spacecrafts (> 20 KW DC)
  - reconfigurable antennas with flexible beam shape and beam location, 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 plays a critical role in future payloads for satellites.
- Conceptual development matching the customer needs
- 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