# Advanced Antenna Technologies for Satellite Communications Payloads

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*(Invited Paper)*

***Abstract*—A review of various antenna technologies suitable for satellite communications and applicable to fixed satellite, broadcast satellite, mobile communications, and personal communications services is presented. Antenna technologies suitable for generating contoured beam and multiple-beam antennas are reviewed. Design considerations for reflector antennas and feed assemblies and antenna performance in terms of coverage gain, sidelobe isolation, and cross-polar isolation are discussed. Current and future technological trends are presented in the above areas.**

***Index Terms*—Contoured beam antennas, feed assembly, multiple-beam antennas, satellite antennas.**

## I. INTRODUCTION

SATELLITE antenna technology has had a tremendous growth over the last three decades. This is due to the introduction of new services such as direct broadcast satellites, mobile communication satellites, and high-capacity personal communication satellites in addition to conventional fixed satellite services. Each of these satellite services demands different types of antennas in order to meet the varying performance requirements. Communication satellites such as Echo 1, Telstar, Syncom III, Early Bird during the 1960s and 1970s utilized reflector antennas to provide higher gain over the coverage regions [1], [2]. The launch of Telstar satellite paved the way for bent-pipe transponded satellites at C-band frequencies. Late 1970s and 1980s saw significant development in both satellite communications antennas and earth-station antennas. Very large earth-station antennas have been deployed at several sites in Japan, United States, and Europe to communicate with the geo-stationary communication satellites at C- and Ku-band frequencies. These earth stations employed shaped dual-reflector antennas and fixed-feed beam-waveguide technologies in order to improve the overall efficiency of the antenna system and ability to track various satellites on-orbit. During this period, dual-gridded reflector antennas were developed and successfully launched by Canada and USA for various satellites [3]. This technology allowed the reuse of physical space by two reflectors, and each reflector providing one of the two orthogonally polarized linear signals.

During the late 1980s and 1990s, large deployable mesh reflector antennas have been developed by Harris Corporation and AstroMesh (now Northrop Grumman) for mobile satellite applications at L- and S-band frequencies [4]. This technology allowed the use of reflectors in the range 5–12 m that are stowed in a small volume during launch and deployed once the satellite is in orbit. Larger reflectors of 18–22 m and even bigger have been built and flown by the space industry in the recent past for both commercial and military applications. Extension of this technology to higher frequency bands such as Ka-band is being currently considered. Another important development occurred in the U.K. during the 1980s in the form of shaped reflector antennas for contoured beam coverage applications at C- and Ku-bands [5]. This technology allowed cost and schedule reductions of satellite payloads significantly by eliminating the conventional beam-forming networks. In the 1970s and 1980s, cluster feeds were used with parabolic reflectors to create shaped beams, and key issues were mutual coupling among feeds in arrays and complexity of the beam-forming networks that combine the RF signals from all feeds. The success and adoption of shaped reflectors allowed single feed that eliminated the drawbacks of earlier designs. A single feed illuminating a reflector whose surface is shaped to fit the desired coverage shape on the ground is employed. Single- and dual-reflector antenna configurations have been used for dual-linear or dual-circular polarization applications. Direct broadcast satellites using high-powered downlink beam over the coverage region were developed in 1990s that allowed users to receive high-definition TV channels using pizza-sized dishes mounted on the roof-tops of houses and buildings.

Multiple-beam antenna payloads have been developed in 1990s and 2000s mainly to reuse the frequency spectrum several times and to provide high gain beams over the coverage region [6], [7]. A large number of satellites such as M-Sat, Thuraya, ACeS, Globalstar, Anik-F, WGS, MUOS, and AEHF have used multiple-beam antenna technology with various frequency reuse schemes that increased the effective bandwidth by factors of 4 to 30 relative to the available bandwidth. Local channel broadcast satellites augmented DBS service through the use of multiple beams during the period 2000–2010. EchoStar and DirecTV operators have several satellites that now provide local channel broadcast in addition to DBS services. Personal communication satellites with high data rates have been launched more recently using hundreds of spot beams with large frequency reuse factor in order to realize very large bandwidths. These satellites require high-power spacecrafts in order to realize satellite capacities exceeding 100 Gb/ps. Development of high-power spacecrafts in the 13–20 kW dc power has enabled deployment of complex and

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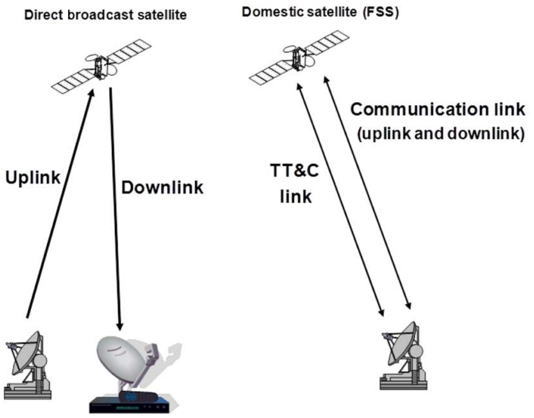


Fig. 1. Illustration of the communication links using spacecraft and ground antennas.

high-power hybrid payloads at various bands including the popularization of hosted payloads by Intelsat Corporation that combine military services with commercial services on a single satellite. A detailed treatment of satellite antenna technology is given in a recent book [8].

## II. TYPES OF SATELLITE SERVICES AND ANTENNA SYSTEMS

Different types of satellite services that are widely being used for commercial and military communications include the following. 1) Fixed satellite service (FSS) providing shaped or contoured beams for domestic or regional satellite services at C-, Ku-, or Ka-band frequencies. 2) Broadcast satellite service (BSS) providing downlink beams over a coverage region such as CONUS (Continental United States) and providing weighted contoured beams to compensate for the rain attenuation. 3) Personal communication service (PSS) providing K/Ka band multiple beams employing multiple reflector antennas. Each reflector uses a large number of feeds for personal communication and data transfer from user-to-user via satellite. It typically employs forward link from ground-to-satellite-to-user and reverse link from user-to-satellite-to-ground. 4) Mobile satellite service (MSS) providing communications to mobile users via satellite. These mobile satellites operate at low frequencies UHF, L- or S-bands and, therefore, need to use large deployable mesh reflector technology. The feed array employs a large number of feeds with overlapping beams on the ground. and 5) Inter satellite service (ISS) providing communication links and data transfers from satellite to satellite. A constellation of satellites is used for global communications. They employ large gimbaled dual-reflector antennas with auto-track capability.

The communications links are established between satellite and ground, satellite to aircrafts, satellite to user, or satellite to satellite. The satellite links for FSS and direct broadcast service (DBS) satellites are illustrated in Fig. 1. The FSS has both uplink and downlink covering the domestic region with contoured beams, whereas the BSS has mainly downlink-contoured beam covering the domestic region and the uplink is provided through spot beams from ground sites. Satellite payloads have a number of reflector antennas and associated repeaters to support hybrid payloads serving multiple services. The spacecraft bus needs to accommodate several large reflectors stowed in a small volume to fit in the launch fairing envelope diameter of 4–5 m. This critical requirement demands that several reflectors be deployed in space from the stowed launch configuration of the spacecraft. The deployed reflectors are mostly accommodated on the east and west side of the spacecraft and in some cases on the nadir deck also. Fixed smaller reflectors without deployment mechanisms are placed on the nadir deck of the spacecraft along with tracking, telemetry, telecommand, and global horn antennas. The feeds for all the reflectors are fixed on the east–west corners of the spacecraft and on the nadir deck. This is due to the fact that the feed assemblies carry high power and are sensitive to passive-inter-modulation (PIM). Fig. 2 shows a typical satellite in the deployed configuration. Solar panels are deployed along the north–south directions to track the sun.

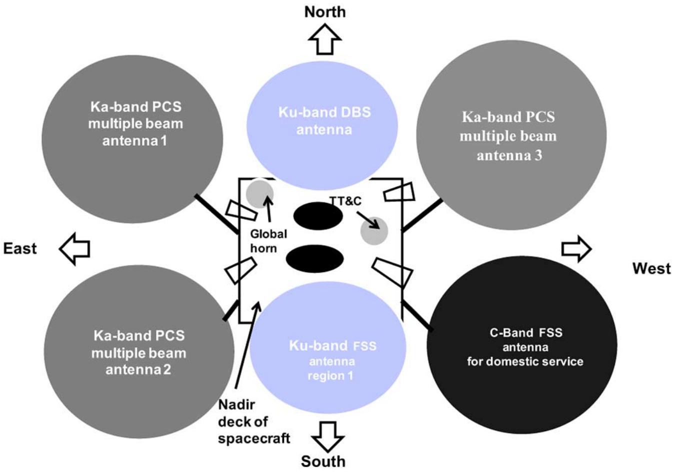


Fig. 2. Spacecraft layout showing various antennas supporting multiple satellite services.

The payload for any satellite service includes antenna and repeater subsystems. The antenna provides the desired radiation characteristics in terms of beam shape tailored to the coverage region, required gain to close the communication links, desired polarization, diplexing function between transmit and receive bands, high cross-polar isolation for polarization reuse systems, co-polar isolation outside the coverage, and sidelobe shaping.

Key system parameters for the satellites are gain-to-noise temperature ratio (G/T) and effective isotropic radiated power (EIRP). Both these parameters are the figure of merits for the satellite design and depend on the antenna gain at both transmit and receive bands. The communication link quality is determined by the signal-to-noise power ratio, which depends heavily on transmit and receive antenna gain values. Many designers spend significant amount of time in optimizing the antenna gain values to the last fraction of a decibel. Other technical challenges include minimizing the front-end antenna losses, designing the feed components to meet the high-power handling, meeting the low PIM requirements, and improving the co-polar and cross-polar isolations of the antenna.

There are many types of reflector antennas used for satellite communications. The type of reflector antenna depends on the satellite payload requirements and the accommodation

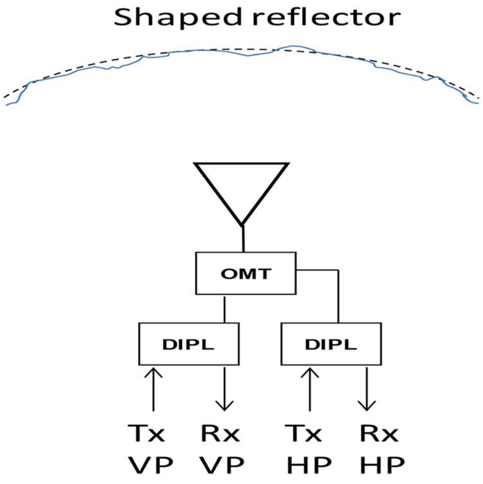


Fig. 3. Contoured beam antenna using a shaped reflector, a single feed, an OMT, and two diplexers providing both up- and downlink beams.

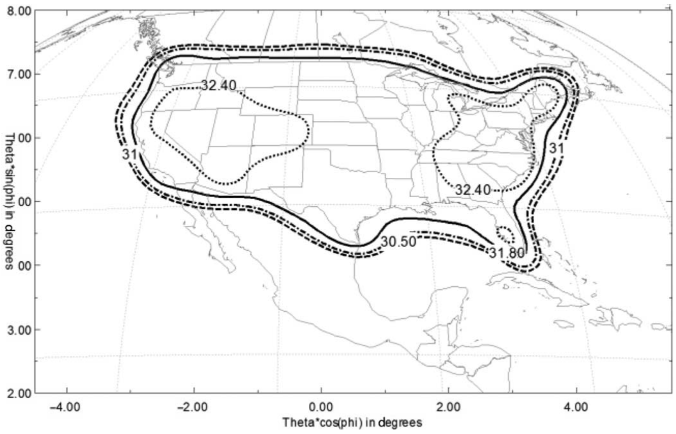


Fig. 4. Computed directivity contours of a Tx/Rx contour beam FSS antenna at Ku-band ($D = 2.3\,\mathrm{m}$).

on the spacecraft. Commonly used reflector antennas for communication satellites are: single offset reflector, dual-reflector Gregorian in both offset and symmetric configurations, gridded reflector for linear polarization reuse, center-fed Cassegrain reflector for inter-satellite links, offset-fed Cassegrain reflector, large deployable mesh reflectors for mobile services, single-reflector imaging antennas, dual-reflector antennas for large scan applications [side-fed offset Cassegrain (SFOC) and front-fed offset Cassegrain (FFOC) antennas], and confocal reflector antennas. The above are the reflector-based antennas and some of them will be discussed in Sections III, IV, and VI. Other types of antennas used in satellites are lens antennas and phased array antennas. Lens antenna types that have been used in the past with limited success include both dielectric lenses and waveguide lenses. Phased array antennas have limitations of narrow bandwidth, lower efficiency of solid state power amplifiers (SSPAs), higher dc power dissipation, increased mass and cost, but have capabilities to reconfigure the beams, and are more suitable for military communications. Reflector-type antennas are widely used in satellite applications.

## III. CONTOURED BEAM ANTENNAS

Contoured beam antennas are also called shaped beam antennas and are commonly used for FSS and BSS payloads. These antennas provide uplink, downlink, or both up/downlinks where the beam is broadened from a high gain spot beam to a medium gain beam that is synthesized to fit the coverage region, such as CONUS. There are two methods used to generate contoured beams:

1) parabolic reflector antenna (PRA)with a feed array and high-level beam-forming network;
2) shaped reflector with a single feed (SRA).

The shaped reflector antenna (SRA) technology with a single feed avoids the need for the beamforming networks (BFNs) and typically requires a wideband feed supporting both transmit and receive contoured beams from a single antenna. The two frequency bands are separated using a diplexer(s) and the two orthogonal polarizations are separated using an OMT for linear polarizations and an OMT/polarizer assembly for circular polarizations, as shown in Fig. 3. The SRA reflectors are made of graphite material for thermal stability and lower mass. The main objective of the contour beam antenna design is to maximize the minimum gain over the coverage region. The advantages of SRA relative to conventional PRA for contoured beams are better antenna coverage gain due to low spill-over losses, low insertion loss due to elimination of BFN, better cross-pol performance due to avoidance of mutual coupling effects among array elements, and wideband capability allowing support of both up- and downlink frequencies from a single antenna. Key design parameters for the reflector are its projected diameter $D$, focal length $F$, off-set clearance $h$, and the feed illumination taper $T$ at the edge of the reflector. $F/D$ ratio is generally in the range 0.8–1.5, and is selected as a compromise in achieving good cross-polar isolation and smaller beam-squint for circular polarization versus mechanical constraints to minimize deployment boom size and mass. Offset clearance $h$ is selected to create blockage-free condition over an area larger than the desired coverage region. The angular relationships to reflector dimensional parameters are given earlier [6], [7]. The reflector surface is initially defined in terms of a base surface such as an offset parabolic and a perturbed surface is superimposed on the base surface [5]. The perturbed surface is defined in terms of a series expansion function such as Zernike polynomials or cubic spline functions. At each iterative stage, the far-field is computed at a number of sample points and compared with the objective function and the coefficients of expansion functions are changed iteratively till a desired match is obtained. TICRA's POS and GRASP commercial software programs are universally used throughout the space industry for design and analysis of contoured beam antennas. Combination of GO/PO/GTD/PTD methods is used for computing the antenna radiation patterns. Fig. 4 shows the computed directivity contours of an SRA designed to cover CONUS at Ku-band Tx (10.95–12.2 GHz) and Rx frequencies (14.0–14.5 GHz) from a 101° west orbital location of a geostationary satellite for FSS. The reflector is 2.3-m diameter and is illuminated with a corrugated horn providing 14-dB illumination taper at Tx and 19-dB taper at Rx to minimize spill-over losses. Minimum antenna directivity over the coverage region is 31.7

TABLE I
CONTOURED BEAM DESIGN RESULTS AT KU-BAND

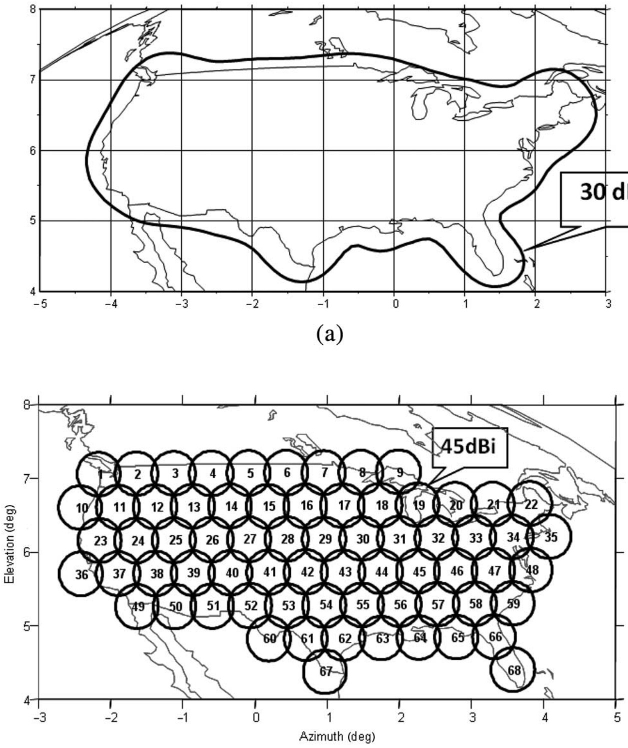
| *D* (m) | *D/λ* | CONUS (13 sq. deg) Ku-band | | South america (26.45 sq. deg) Ku-band | |
|---|---|---|---|---|---|
| | | EOC dir. (dBi) | GAP | EOC dir. (dBi) | GAP |
| 1.0 | 36.50 | 30.1 | 13 303 | 27.9 | 16 309 |
| 1.3 | 47.45 | 30.7 | 15 274 | 28.4 | 18 299 |
| 1.5 | 54.75 | 31.0 | 16 366 | 28.7 | 19 608 |
| 1.8 | 65.70 | 31.2 | 17 137 | 28.9 | 20 532 |
| 2.0 | 73.00 | 31.4 | 17 945 | 29.1 | 21 499 |
| 2.3 | 83.95 | 31.7 | 19 228 | 29.25 | 22 255 |

dBi with peak directivity of 33.1 dBi. There is a 1.4-dB directivity variation achieved over the coverage region, which is an indication of the flatness of the synthesized directivity contours. For BSS applications, where the satellite needs to transmit only to ground, weighted coverage directivity is typically required with large directivity variations to compensate for the rain-fade in the regions having more rain fall. Synthesized directivity contours for BSS transmit antenna for the same antenna size of 2.3 m result in peak directivity of about 35.5 dBi with more than 5 dB variation across the coverage region. The figure-of-merit of the contoured beam antenna is sometimes in terms of gain area product (GAP). An ideal GAP for a uniformly illuminated coverage area with no radiation outside the coverage is 41 253. The GAP for contoured beams typically varies in the range 10 000–25 000 for reasonably sized reflectors ($\mathrm{D}/\lambda > 25$). Table I shows computed GAP values and edge-of-coverage (EOC) directivity for two different coverage regions at Ku-band frequencies.

As can be seen, GAP increases with the increasing size of the antenna relative to wavelength and with increasing area of the coverage. Gridded reflectors are also used where front surface is gridded supporting one polarization and the back solid surface supports the other orthogonal polarization. It requires two feeds, one for each polarization, which are spatially separated to steer the X-pol away from the global field of view. However, gridded reflectors are limited to dual-linear polarization applications.

## IV. MULTIPLE-BEAM ANTENNAS

Multiple-beam antennas (MBA) have seen a tremendous growth during the past two decades for both commercial and military satellites. They have been used for mobile satellite services (M-Sat, Inmarsat, Thuraya, ACeS, MSV, XM radio, Sirius, etc.), local channel direct broadcast satellites (DTV-4S, DTV-7S, Echostar-10, Echostar-14, etc.), personal communication satellites (Anik-F, ViaSat-1, Jupiter-1, etc.), and military communication satellites (WGS, MUOS, etc.). The MBA technology uses a large number of spot beams to cover the geographic coverage region from the satellite instead of a single contoured beam. The available bandwidth is divided into a number of subbands and each of the subband is reused on a number of spot beams that are spatially isolated. This results in several-fold reuse of the limited spectrum in order to increase the effective bandwidth of the communications payloads resulting in significant increase in satellite capacity. The frequency reuse factor (FRF) is in the range 4–40 for practical systems due to limitation of spacecraft power, accommodation limitations of multiple large reflectors on spacecraft, the number of travelling wave tube amplifiers (TWTAs) that could be physically accommodated, and the power dissipation limitations of the spacecraft bus.



(a)

(b)

Fig. 5. Illustration of advantages of MBA relative to contoured beam. (a) Contoured beam coverage over CONUS. (b) Multiple beam coverage over CONUS.

Multiple beam coverage compared to conventional contoured beam coverage is illustrated in Fig. 5. The contoured beam has a gain of 30 dBi while each of the spot beams of the MBA has a gain of 45 dBi. There are 68 spot beams in a hexagonal lattice covering CONUS and having an inter-beam spacing of 0.52° and beam diameter of 0.60° at the triple-beam cross-over level. The MBA offers 15 dB gain increase combined with a spectral increase of 17 times (with a 4-cell reuse scheme) for each of the communication links (up and downlinks) that translates into multifold increase in satellite capacity. It also allows the use of smaller ground terminal antenna size. There are two types of MBA: 1) single-reflector antenna with multiple beams and 2) multiaperture reflector antenna with multiple beams. Various frequency reuse schemes that could be used for MBAs include regular 3-cell, 4-cell, 7-cell, or *N*-cell and also hybrid schemes that employ different schemes over different regions of the coverage region. The number of apertures in a multiaperture design depends on the size and stowage accommodation on the spacecraft bus.

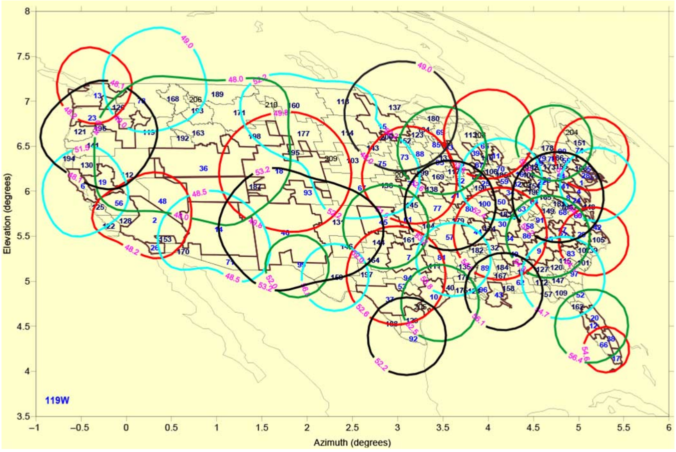


Fig. 6. Typical coverage of local channel direct broadcast satellite with 34 nonuniform beams covering about 200 DMAs over the CONUS.

For DBS satellites, the satellite provides downlink beams for local channel broadcast where the designated market areas (DMAs) are nonuniform in size and spacing. One or more channels serve each beam that covers few DMAs. Fig. 6 shows typical coverage of CONUS using nonuniform beams with nonuniform cell reuse. Smaller beams with higher gain are used in the east coast beams while large beams are used in the Midwest and western beams where the rain rate is low. There are 34 beams covering CONUS and covering more than 200 DMAs. The contour levels shown are in EIRP. The beam spacing among the reuse beams is designed to meet the co-polar isolation C/I of better than 13 dB for most cases. The design employs multiple reflectors where each reflector is fed with multiple feeds of nonuniform size and with nonuniform spacing in order to realize various beam sizes. Practical antenna systems that are suitable and often employed for multiple beam applications include the following designs:

1) single-reflector antenna with single element per beam;
2) single reflector design with overlapping feed clusters;
3) multiple reflector design with single feed per beam.

Single-reflector MBAs are mostly used at low frequencies such as UHF, L-band, and S-band. At these frequency bands, large deployable mesh reflectors ranging from 5 to 22 m have been successfully used for mobile satellites such as Thuraya, ACeS, Inmarsat, MSV, SkyTerra, and most recently MUOS. Single-reflector MBAs can be implemented using:

1) single feed per beam;
2) multiple feeds per beam (also called “enhanced feed concept”).

The single feed per beam MBA is simpler in terms of hardware since it does not require a beam-forming network. However, the element size required is small and is typically of the order of a wavelength in order to achieve good overlap of about 3–4 dB below the beam peak among the adjacent beams. The feed spacing/size depends on the *F*/*D* ratio of the reflector and is given approximately as

$$\frac{d}{\lambda} \approx 1.25\left(\frac{F}{D}\right). \qquad (1)$$

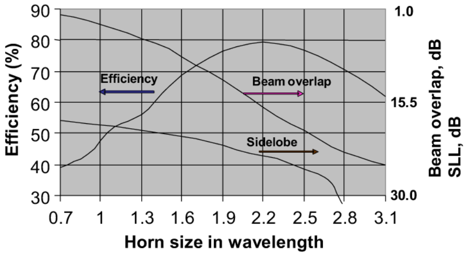


Fig. 7. Single-reflector MBA RF performance as a function of feed horn size (single horn per beam).

For large deployable reflectors, the *F*/*D* ratio is around 0.6 to 0.7 and the feed spacing is around $0.75\lambda$ to $0.88\lambda$ to achieve the desired overlap among adjacent beams. Fig. 7 shows typical performance of the MBA as a function of feed spacing/size. For a single-reflector MBA with small spacing of about $0.8\lambda$, the beam overlap is very good (less than 3 dB) but the beam efficiency is very low and is about 45% and suffers from high sidelobe levels of about 19 dB (below the beam peak). On the other hand, a multiaperture MBA with four reflectors provides alternate beams from the same reflectors allowing the feed horn spacing/size to increase twice as much as a single-aperture MBA. This combined with large *F*/*D* of about 1.0 allows the feed spacing in the range $2.0\lambda{-}3.0\lambda$. For such large horns, each reflector will be illuminated more optimally with a taper of about 10–15 dB increasing the antenna efficiency to about 78% and lowering the sidelobe levels to about 25 dB. Beam overlap is better than 17 dB among the beams generated from the same reflector allowing reuse of the same frequency for all the beams.

Because of the low efficiency and high sidelobe levels of single feed per beam, single-reflector MBAs employ feed clusters using typically seven horns per beam. This is called “enhanced feed concept” [6] where adjacent beam centers correspond to the feed horn centers, but each beam is broadened and illuminated more efficiently due to the use of feed cluster. Each beam is generated using seven horns and, therefore, produces an optimal illumination on the reflector. Therefore, the composite beams of the MBA are larger than the element beams with higher gain (or efficiency), lower sidelobe levels, and improved overlap among the beams. The beam layout of the two concepts is illustrated earlier [6]. The beams with enhanced feed concept are larger than the single feed concept and have better overlap among the beams. A single large offset reflector being fed with multiple feeds and combined through matrix power amplifier and low-level beam-forming network is typically used for generating multiple over-lapping beams over the desired coverage regions. Fig. 8 illustrates the block diagram of the MBA using a single-reflector antenna. The transmit MBA is shown in Fig. 8, which employs a low-level dividing network that distributes the individual RF signals from each beam to a number of output ports that are eventually connected to a number of feed elements within the large feed array through the matrix power amplifier (MPA) network. The reason for using MPA is for distributed amplification where each amplifier is shared among multiple beams and for redundancy in case of amplifier failures. The feed elements illuminate an offset mesh parabolic mesh

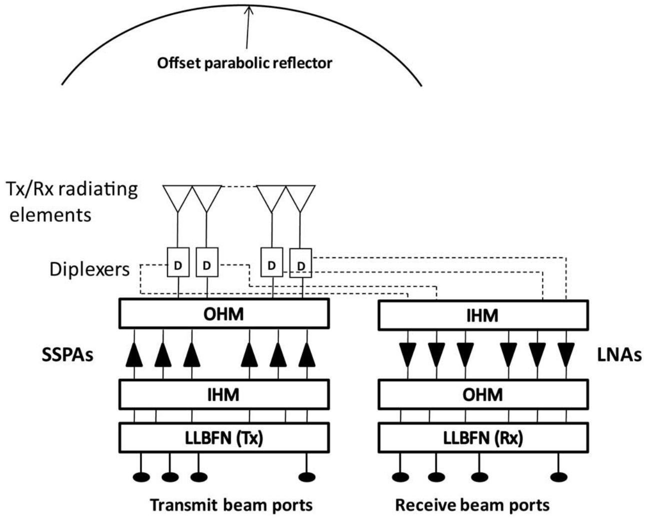


Fig. 8. Block diagram of a diplexed antenna system for mobile satellite services using a single mesh reflector.

reflector providing multiple over-lapping beams on the ground. The antenna is common to both up- and downlink frequencies.

The design and relevant analysis of reflector antennas for multiple beam applications have been well documented in the past [6], [7]. Key design objectives for the MBAs are:

1) maximize the minimum gain over the coverage;
2) maximize the co-polar and cross-polar isolations;
3) minimize the scan loss.

The above-mentioned objectives can be met closely by proper design choices of the reflector and feed systems of the MBA. Single-reflector antenna with single feed per beam requires small horns (about 1 wavelength diameter) in order to achieve high adjacent beam overlap. This results in low illumination taper on the reflector and increased spill-over losses. As a result, the gain values are about 2–3 dB lower than what could be achieved with a larger horn with optimal illumination. Single-reflector MBA with overlapping feed clusters improves the gain values, but requires a low-level beam-forming network to provide the element sharing among a number of beams (typically 3 or 7) and beam combining functions.

Multiple reflector design with single feed per beam employs either 3 or 4 reflectors on practical systems used on commercial satellites. These reflectors can easily be deployed to the east and west sides on the spacecraft leaving the nadir deck for other antennas for FSS/BSS and global horns and TT&C antennas. Adjacent beams are generated from different apertures forming an inter-leaved but contiguous spot beam coverage on the ground. The closest spacing between adjacent beams from the same aperture can be increased from $\theta_s$ to $1.732\theta_s$ for a three-reflector MBA, and to $2.0\theta_s$ for a four-reflector MBA, where $\theta_s$ is the center-to-center spacing between adjacent beams of the multiple beam coverage. The larger beam spacing using multiple reflectors allows proportionate increase in the horn size, which in turn improves the antenna gain through reduced spill-over losses and more optimal illumination taper on the reflector. Systematic design and analysis of multiple-beam antenna systems have been presented earlier based on Gaussian beam feed models and parametric design/analyses of multibeam reflector systems [7]. Co-polar isolation is the key dictating the MBA performance. It is defined as the ratio of co-polar gain at a given angular location of the beam of interest to the power addition of all the interfering signals from the other beams that reuse the same frequency.

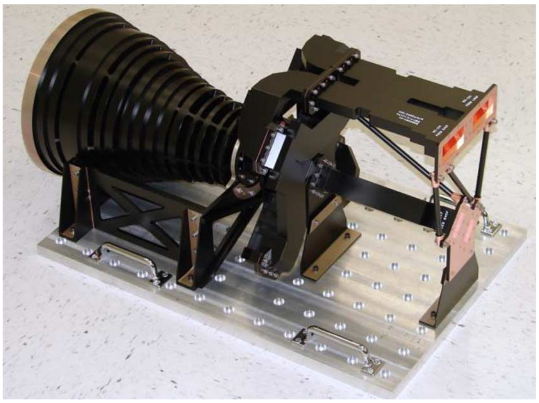


Fig. 9. C-band feed assembly with corrugated horn providing dual circular polarization at both 4- and 6-GHz bands for FSS (courtesy of Custom Microwave Inc.).

## V. SPACE CONSIDERATIONS

Key considerations for the design of antenna systems for satellite applications include survivability in the space environment. They include qualification of antenna designs over thermal variations, high power handling, passive inter-modulation (PIM), electrostatic discharge, vibration, shock, and acoustics. Antenna hardware consists of reflector assembly and feed assembly in most cases. Feed assembly is the key hardware in the satellite antenna system. It is mostly used to illuminate a reflector or as a direct radiating feed. It defines the polarization, bandwidth, power handling, PIM levels, ESD, etc. It also separates various frequency bands with sufficient isolation among them and is designed to provide a good match with free space.

A typical feed assembly comprises a horn, orthomode transducers (OMT), filters or diplexers, polarizers, transitions, combining/dividing networks, and an RF interface to the payload repeater. While the reflector provides the desired gain and beam shape on the ground, the feed assembly dictates most of the RF performance such as return loss, crosspol isolation or axial ratio, power handling, PIM, bandwidth of RF signals, and insertion loss. Feed systems for current communication satellites utilize mostly C-, X-, Ku-, K-, Ka-, EHF-, and V-band frequencies. At these frequency bands, the feed assemblies are often realized in waveguide structures without being too bulky. In addition to the size, waveguide structures have the advantages of low loss, high power handling capability, no ESD, and are very reliable, all of which are desirable features for communication satellites. C-band feed assembly for 4/6 GHz bands for FSS is shown in Fig. 9. It is a diplexed feed assembly functioning at both transmit and receive bands. The feed assembly comprises a wideband corrugated horn, a 6-port junction that extracts the Tx signals using symmetric 4-ports, filters to reject Rx signals,

TABLE II
MEASURED RF PERFORMANCE OF THE C-BAND FEED ASSEMBLYS (COURTESY OF CUSTOM MICROWAVE INC.)

| Parameters | Measured performance |
|---|---|
| Frequency (GHz) | Tx: 3.625–4.2<br>Rx: 5.85–6.425 |
| Axial ratio | < 0.2 dB on axis |
| Insertion loss | Tx: < 0.15 dB<br>Rx: < 0.05 dB |
| Return loss | Tx: > 28 dB<br>Rx: > 32 dB |
| Isolation | RHCP↔LHCP > 25 dB<br>Rx↔Tx > 60 dB |
| Peak power | 10 kW multipaction |
| PIM | < –140 dBm, 7 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) |

a hybrid coupler to generate dual-CP for Tx signals, an undersized circular waveguide to reject Tx signals in Rx path, and a septum polarizer to generate dual-CP at Rx frequencies. Losses are kept minimal by making it very compact using advanced manufacturing techniques such as electro-forming and minimizing the waveguide flange interfaces. The measured RF performance of the C-band feed assembly is shown in Table II. These results show very low insertion loss, low axial ratio, high power handling, low PIM levels, and good return loss at both bands for the feed assembly. While the RF requirements drive the purpose and general design of the feed, it has to work mechanically in the extreme environments of launch and space. The mechanical designer usually has the challenging task of optimizing size, weight, and structural integrity.

During the design process, the designer must also keep on mind other requirements such as insertion loss, high power, multipaction [9], PIM [10], operating temperature range, size, and mass constraints, port locations, achievable manufacturing tolerances, and variation over temperature. Too often, some of these requirements are overlooked at the start of the design process resulting in a waste of precious time, compromised feed performance, or worse still an unusable feed. The PIM order and power level will often drive the manufacturing method. In general, 19th-order PIM or higher is not as critical. Lower order PIM may necessitate reduction in flange joints or the use of special high pressure or choke flanges to minimize risk of generating PIM. Performance variation over temperature can usually be accounted for in the design by including thermal guard bands on either side of the operating frequency band. This accounts for the expansion and contraction of the feed at the temperature extreme. Frequency responses, other than insertion loss, should only shift side to side as opposed to up and down for a properly fabricated feed.

## VI. RECENT ADVANCES IN SPACE ANTENNAS

More recent developments in satellite communication antennas are related to dual-band multiple-beam antennas for high-capacity PCS services, multiple-band antennas, stepped-reflector antennas, high-efficiency feed systems, and integrated feed assembly technology offering low loss and multipolarization and multiband capability, and high power test methods. Some of these developments are described in this section.

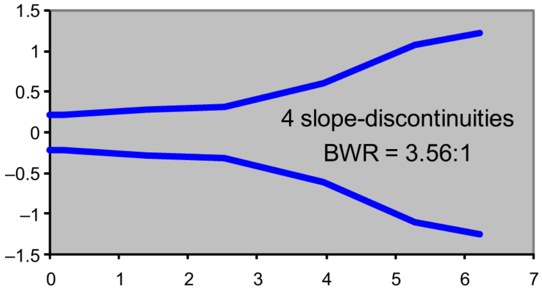


Fig. 10. Geometry of the multimode horn covering BWR of 3.56:1.

### A. Dual-Band Antenna With Single Feed

An advanced dual-band feed using a Cassegrain reflector has been developed recently [11]. This has the advantage of covering two discrete bands that are separated up to 3.5:1 bandwidth ratio and able to produce either similar beam shapes at two bands or different beam shapes at the two discrete bands. In order to produce similar beam shapes at low and high bands, the feed needs to be designed with frequency-dependent radiation characteristics. Such a design produces a highly tapered amplitude distribution on the subreflector at high band. In addition, the feed creates a phase distribution at high band such that it has a 180° phase reversal at the outer portion of the subreflector. As a result, the secondary patterns from the antenna are significantly broadened at high band and provide a beam shape similar at both bands that are widely separated in frequency [11]. The main challenge here is the feed system design that produces the desired frequency-dependant radiation characteristics. Corrugated horn can support dual-bands with limited bandwidth ratio of about 2:1, but cannot cover bands that are widely separated than this. Also, corrugated horns have the disadvantages of increased mass due to thick corrugations. A smooth-walled multimode horn is more suited for such applications. The reflector diameter is chosen to meet the desired gain and beamwidth requirements at the lowest frequency. Design of the horn is based on selecting the horn diameter to provide the desired illumination taper on the subreflector at the lowest frequency. An illumination taper of around 12 dB is optimum at the low band. For this application, it is required that the aperture distribution is more uniform at the low band and tapered at the high band. The feed horn synthesis process using mode-matching analysis has been developed earlier by Chan [12]. The required mode contents to create a tapered aperture distribution at high band are chosen. Based on the mode content, initial discontinuity points can be determined based on the mode cut-off wavelengths in a circular waveguide. Final optimization of the horn geometrical parameters can be performed by specifying the desired cost function at several frequencies covering both low and high bands and synthesizing the horn using mode-matching analysis [12]. Synthesized horn geometry is shown in Fig. 10.

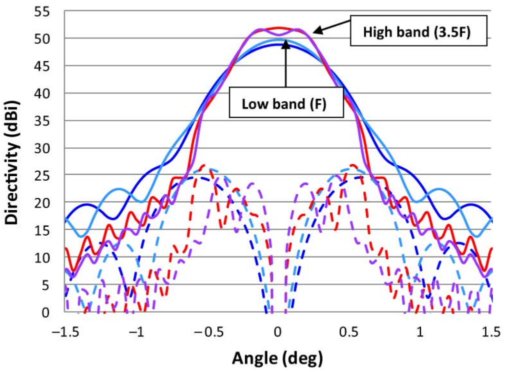


Fig. 11. Radiation patterns of wideband dual-reflector antenna providing similar coverage patterns.

It has four slope discontinuities in order to generate the desired radiation characteristic. The evaluated performance of the dual-band feed with $\mathrm{BWR} = 3.56$ has return loss better than 29 dB, axial ratio better than 1.37 dB over the frequency band, and the beamwidths are very close despite the wide frequency separation between low and high bands. At the high band, the feed patterns have an amplitude taper of better than 17 dB illumination taper. The phase patterns show 180° phase reversal within the subreflector illumination region. This phase nonuniformity is required in order to broaden the secondary patterns. The computed secondary patterns at two frequencies at low band and two frequencies at high band are shown in Fig. 11. The beam-flattening at the high band is the result of the nonuniform phase from the feed. The antenna beamwidths at both high and low bands are similar. The peak gain values are better than 48 dBi over both bands. The cross-polar isolation is better than 26 dB over the half-power beamwidth of the antenna. This dual-band antenna has the advantages of lower cost, feed simplicity, and beam congruency over both bands.

### *B. Dual-Band Reflector Antennas With Multiple Feeds*

Dual-band reflector antennas for multiple beam applications have been extensively employed for satellite applications supporting personal communication services. These systems are used to provide communications among several users that are spread over a given coverage region using multiple overlapping beams. Communications among users is established through the ground hubs and the satellite. The users establish communication with other users using a two-way communication link via satellite and the hubs through forward (hub uplinks, satellite down-converts, and downlinks to users) and return links (user uplinks to satellite, satellite down-converts, and downlinks RF signals to hub). Each beam is generated using a single feed that transmits to and receives from the ground the RF signals via the reflector antenna. A four-reflector system is typically used to generate all the desired beam. It employs 68 overlapping spot beams of 0.6° diameter over the CONUS region with beam spacing of 0.52°. The transmit band is 18.3–20.2 GHz and receive band is 28.3–30.0 GHz. Element diameter is dictated by the beam spacing among reuse beams (in this case, it is two times the inter-beam spacing) and the beam deviation factor that is dictated by the offset reflector geometry. The feed diameter is $2.27''$. Return loss, efficiency, and cross-polar levels of the dual-band horn are summarized in Table III. A number of dual-mode horns are used to illuminate each of the four-reflector MBAs to generate the 68 overlapping spot beams on the ground. The reflector has an $80''$ diameter, an $F/D = 1.45$, and offset clearance height of $26''$. The antenna radiation patterns for a typical beam computed for various designs of the dual-band horn are shown earlier [13]. A high-efficiency horn helps to improve peak and edge-of-coverage gain at the transmit band while it reduces the peak gain, broadens the beam, and improves the edge-of-coverage gain at the receive band, which is desired due to the fact that the reflector is over-sized for Rx frequencies. The transmit sidelobe levels are lower with high efficiency horn by about 3 dB, which helps in co-polar isolation when used with a typical 4-cell frequency reuse scheme for the multiple-beam antennas. Primary and secondary performances of dual-band MBA antenna are summarized in Table IV. It is seen that the high-efficiency horn improves gain over the transmit band by about 0.9 dB and improves gain by 2.0 dB over the receive band relative to the conventional corrugated horn. More importantly, the transmit co-polar isolation (C/I) is improved with HEH by about 3.7 dB with a 4-cell scheme with 1.2 dB degradation in Rx C/I (note that Rx C/I is less critical compared to Tx C/I).

### *C. Multiband Antennas Supporting Several Frequency Bands*

The satellite payloads are progressively becoming more complex and support multiple services from a single satellite. This is made possible due to the advent of high power satellites developed by several satellite manufacturers with dc power ranging from 12 to 20 kW. In addition, the recent trend toward the hosted payloads that combine the commercial payload with government payloads in a single satellite for cost reduction have placed demand for the multiband antennas. Few examples of multiband antennas are described below.

A single antenna supporting three bands covering 20, 30, and 45 GHz has been described [14]. These three frequency bands potentially combine the existing wideband global satellite (WGS) and advanced EHF (AEHF) satellite into one large satellite in future. It is designed to provide a 1.0° beam at 20 and 30 GHz and a 0.5° beam at 45 GHz.

*1) Multiband Antenna Supporting Five Frequency Bands:* An antenna system supporting five frequency bands and three satellite services has been described recently [14], [15]. The three satellite services include direct broadcast satellite (DBS), reverse DBS (RDBS), and personal communication satellite (PCS). With the approval of RDBS bands by FCC, the future satellites are expected to utilize the RDBS services in addition to DBS and PCS services. RDBS service uses the same frequency band for transmit as the receive band of the DBS.

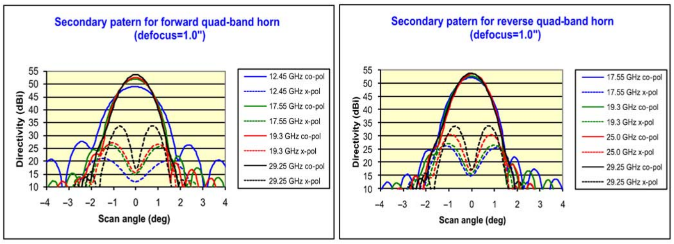
The receive band for RDBS is the new 25 GHz that has been recently allocated by the FCC. Therefore, either DBS or RDBS service is supported at a given time along with the PCS and hence four frequency bands are operational at a given time. The performance shows return loss better than 26.5 dB, cross-polar levels lower than $-22\,\mathrm{dB}$ relative to co-polar peak gain, and

TABLE III
PERFORMANCE SUMMARY OF THE DUAL-BAND HORN

| Frequency (GHz) | Directivity (dBi)/ efficiency | | Cross-pol (dB) | | Return loss (dB) | |
|---|---|---|---|---|---|---|
| | Predict | Measured | Predict | Measured | Predict | Measured |
| 18.30 | 20.08<br>(83.4%) | 20.10<br>(83.8%) | 19.8 | 18.8 | 30.6 | 30.8 |
| 19.30 | 20.60<br>(84.5%) | 20.60<br>(84.5%) | 20.5 | 20.5 | 26.5 | 25.7 |
| 20.20 | 21.05<br>(85.6%) | 21.1<br>(86.6%) | 20.6 | 20.7 | 24.2 | 24.2 |
| | | | | | | |
| 28.30 | 23.89<br>(83.9%) | 23.8<br>(82.1%) | 24.1 | 23.1 | 30.8 | 29.0 |
| 29.20 | 24.23<br>(85.2%) | 24.2<br>(84.6%) | 26.0 | 24.2 | 33.0 | 34.7 |
| 30.00 | 24.46<br>(85.1%) | 24.5<br>(85.9%) | 23.0 | 24.4 | 36.3 | 27.6 |

TABLE IV
PERFORMANCE COMPARISON OF DUAL-BAND MBA WITH TWO DIFFERENT HORN DESIGNS

| Performance parameter | Conventional horn (corrugated) | High eff. horn Design H |
|---|---|---|
| | TX/RX | TX/RX |
| **Efficiency (%)** | **54 / 52** | **85 / 85** |
| Edge taper (dB) | 7/18 | 13 / 17 |
| Primary C/X (dB) | 33 / 33 | 20 / 23 |
| | | |
| **EOC directivity (dBi)** | **43.8 / 41.7** | **44.7 / 43.7** |
| C/I, 3-cell (dB) | 11.1 / 13.0 | 14.2 / 11.6 |
| C/I, 4-cell (dB) | 12.0 / 15.8 | 15.7 / 14.5 |
| **C/I, 7-cell (dB)** | **18.2 / 19.5** | **22.7 / 21.9** |
| C/X (dB) | 30.0 / 28.0 | 21.0 / 20.0 |



**EOC directivity**

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

Fig. 12. Secondary radiation patterns of the multiband antenna with 1.0″ defocusing of the feed (feed aperture plane is 1.0″ toward reflector relative to the focal plane).

efficiency values ranging from 74% to 82% over the five bands. When used with the reflector, the phase patterns of the horn are important and could be used to improve the secondary patterns by changing the location of the horns relative to the focal plane for multiple beams or focal point for a single beam application. A 1.0″ defocus is optimum over all the five bands. Computed radiation patterns of a 100″ diameter offset reflector with 1.0″ defocus are plotted in Fig. 12. The summarized performance in Fig. 12 shows that better overall gain performance is achieved with 1.0″ defocus. Peak gain values of 49.0–53.6 dBi are achieved over the five bands with edge-of-coverage gains range from 47.4 to 50 dBi over the bands. The cross-polar isolation (C/X) is very high at low bands and varies from 32.8 to 18.4 dB over the bands. For PCS service at 30 GHZ, C/X of 18.4 dB is good since the interference is dominated by the co-polar isolation (C/I), which is typically about 14 dB. Fig. 13 shows beam layout for DBS, RDBS, and PCS services over CONUS covering the top 40 designated market areas (DMAs). It requires

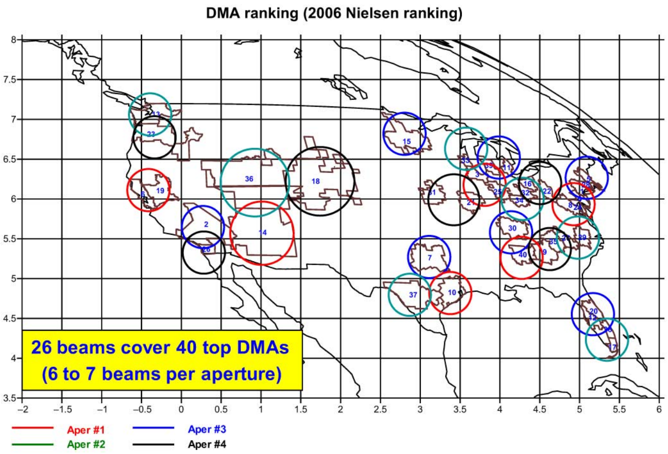


Fig. 13. Example of multiple-beam antenna supporting DRS, RDBS, and PCS. 26 beams are used to support top 40 DMAs.

TABLE V
PERFORMANCE SUMMARY OF THE MULTIBAND ANTENNA FOR FORWARD DBS AND FOR REVERSE DBS BANDS

**Forward DBS**

| Freq (GHz) | EOC (dBi) | C/X (dB) |
|---|---|---|
| 12.45 | 46.0 | 29.9 |
| 17.55 | 47.0 | 24.3 |
| 19.30 | 47.0 | 23.3 |
| 29.25 | 46.2 | 15.2 |

**Reverse DBS**

| Freq (GHz) | EOC (dBi) | C/X (dB) |
|---|---|---|
| 17.55 | 47.0 | 24.3 |
| 25.00 | 46.6 | 18.9 |
| 19.30 | 47.0 | 23.3 |
| 29.25 | 46.2 | 15.2 |

26 spot beams generated using four 100″ reflectors where each reflector provides 6–7 beams. The overall performance of the multiband antenna over five frequency bands is summarized in Table V. The feed assembly is the key hardware for these types of antennas that separates multiple-frequency bands through filters and diplexers and provides dual circular polarization at each band.

## *D. Stepped-Reflector Antenna*

A stepped-reflector antenna (STRA) suitable for dual-band and multiple-frequency band applications has been reported recently [16] for multiple beam applications. This advanced antenna utilizes reflector improvements in addition to the horn improvements that were described earlier. A typical reflector antenna supporting 20 and 30 GHz frequencies has dissimilar beamwidths at the two bands, high band beamwidth being smaller by about 50% compared to low band beamwidth. Since both bands need to cover the same area on the ground, the beamwidths have to be similar. Using a step near the outer annular region of the reflector, a 180° phase reversal is obtained between the inner and outer regions, thereby broadening the beam. The step height "$h$" can be designed to be quarter wavelength at the high band. However, a quarter wave height at high band results in about $0.17\lambda$ at the low band and impacts the low band performance. In order to have minimal impact at the low band, a frequency-dependant horn needs to be designed that produces Gaussian phase patterns at high band while producing near uniform phase at the low band. The combination of feed phase and reflector phase contribution can be made quarter wave at the outer annular region, which results in a smaller step size. This concept is illustrated in Fig. 14. The STRA consists of a hybrid reflector having a central portion that is either parabolic or shaped and an outer annular ring(s) that is (are) either parabolic or shaped. The reflector size is larger than the conventional design without the step and is required to create a "flat-top" beam. Use of slightly larger reflector is not a problem at higher frequency bands. With the combination of step-height and the feed quadratic phase variations, a 180° phase reversal is obtained in the reflector illumination near the step region at the high band. Such a nonuniform phase distribution at the reflector aperture results in a "flat-top" beam shape broadening the main beam at high band.

The step height $h$ is given by

$$h = [180 \pm (\varphi(\theta_1) - \varphi(\theta_0))] * (\pi/180) * (\lambda/(2\pi)) * 0.5 \quad (2)$$

where $\varphi(\theta_1)$ is the feed phase at an angular location corresponding to the step in the reflector, $\varphi(\theta_0)$ is the feed phase at the center of the reflector aperture, and $\lambda$ is the wavelength. All these parameters are at the center of the high-frequency band. The "flat-top" beam at high band has the advantages of higher edge of coverage gain by more than 1.0 dB, improved co-polar isolation (C/I) by about 3 dB, and reduced gain loss due to satellite pointing error. The computed patterns of the SRA with and without step ring are shown in Fig. 15. The step lowers the peak gain and improves the EOC gain by about 1.0 dB at high band.

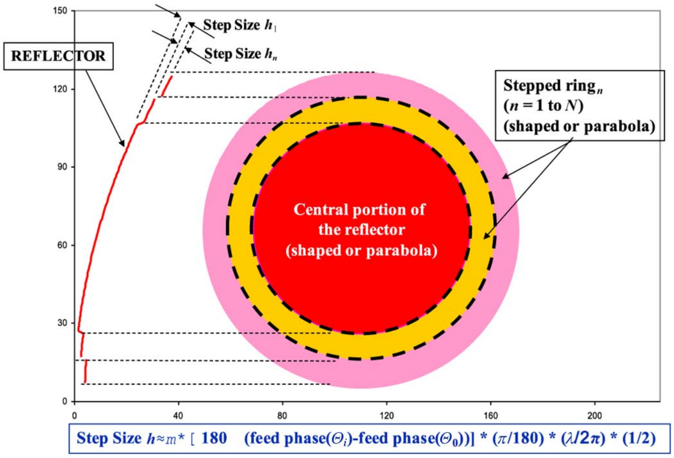


Fig. 14. Stepped-reflector antenna concept for dual and multiple bands.

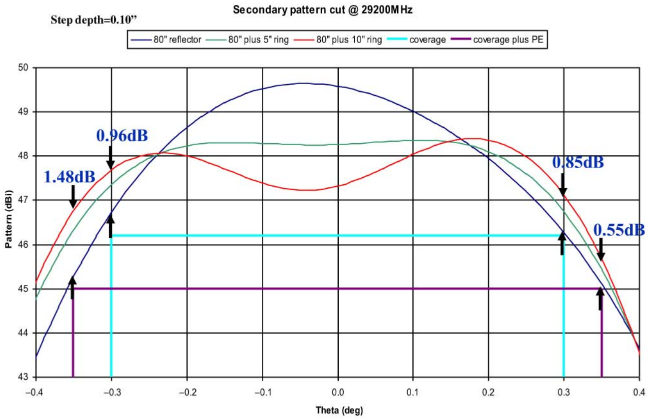


Fig. 15. Computed patterns of the stepped-reflector antenna at high band showing impact of the annular step.

The beam is Gaussian in shape at low band and "flat-top" at high band resulting in edge of coverage gain improvements in both bands. The STRA can be extended to more than two bands and can be optimized with multiple steps. The step size can be minimized by utilizing the quadratic phase distribution of the feed at high frequency in which case the step size becomes very small (about 0.03″ at 30 GHz), which can easily manufactured by creating the step blended over certain area of the reflector instead of an abrupt step. The manufacturing technique is very similar to shaped surface reflector. In addition, both central and edge regions can be shaped to provide additional performance benefits for the MBA. This can be done using physical optics synthesis of reflectors using commercial software such as TICRA's POS. Bandwidths in the range 5%–10% are achievable with the STRA, which is sufficient at Ka-band and EHF frequencies.

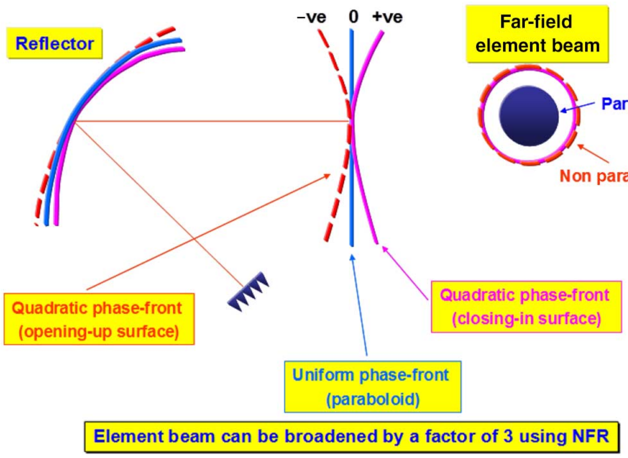


Fig. 16. Illustration of nonfocused reflector (NFR) concept.

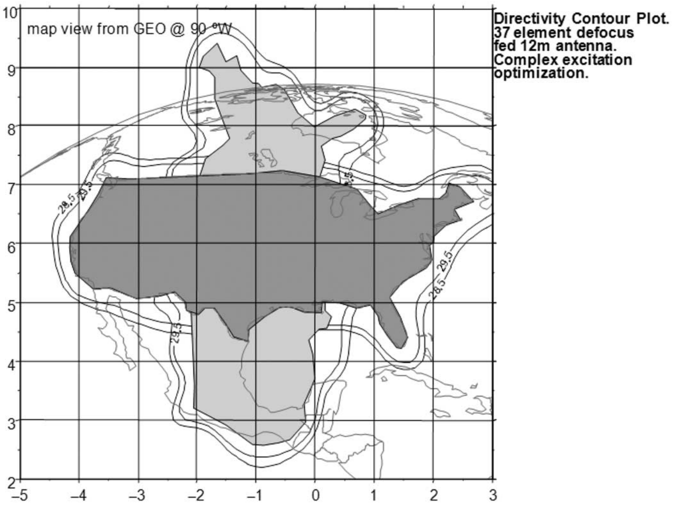


Fig. 17. Contoured beams over CONUS reconfigured over 90° yaw rotation using phase change of the feed array of a 12-m NFR antenna.

## E. Nonfocused Reflector Antenna

The nonfocused reflector (NFR) antenna has been introduced by Rao *et al.* [17] for mobile communication satellite applications. Typical MSS antennas employ large mesh reflectors using single-reflector imaging optics. This conventional antenna employs parabolic reflector either solid or mesh type and the feed array needs to be defocused, so that elements beams are broadened, which allows the use of overlapping feed array instead of single feed for generation of multiple beams in the far-field. The limitation with the conventional system is that it provides only small magnification and still requires large number of elements in the feed array. Other disadvantage is poor scan capability since the reflector geometry is not optimal and inferior cross-polar isolation. The main advantage of the NFR is that it allows significant reduction in the number of feeds for the array.

The concept of nonfocused reflector antenna is illustrated in Fig. 16. A quadratic phase is introduced on an offset parabolic reflector in order to broaden the element when the reflector is fed with multiple beams. The quadratic phase is achieved by closing-in or opening-up the parabolic reflector surface shape. A closed-in surface is preferred since the beam will be less dispersive compared to the opening-up surface. The feed array is located in the focal-plane of the starting paraboloid and hence the NFR scans better than the conventional single-reflector imaging antenna. Main advantage of NFR is that the element beams can be broadened by two to three times compared to parabolic reflector. This results in significant reduction in the number of feed array elements by a factor of 4–9 depending on the extent of the maximum quadratic phase introduced to the planar wavefront in the aperture plane. Reducing the number of elements reduces the cost of the feed array and RF electronics significantly. The NFR antenna is suitable for several applications at L-, S-, C-, Ku-, and Ka-band applications using a smaller solid reflector or larger mesh reflector. Some of the practical applications of the NFR antenna include: 1) contoured beam antenna, where the satellite can be reconfigured on-orbit to provide coverage over multiple orbit locations based on operator requirements to replace an ailing satellite or provide ability to reconfigure beam shape; 2) continuous reconfiguration of the beam as required by the satellites in the highly inclined elliptical orbit (HIEO) for digital radio satellite applications at low frequencies; and 3) multiple overlapping beams for mobile satellite and personal communications satellite applications.

A reconfigurable antenna providing flexible coverage patterns over CONUS employing a 12-m reflector antenna using NFR with 37 elements in the feed array is illustrated in Fig. 17. The transmit feed array is active and employs "phase-only" synthesis for beam reconfiguration of the beam. Computed contoured beam plots over CONUS showing 90° yaw compensation for an extreme case are illustrated in Fig. 16. The beam shape and the minimum directivity is maintained over the large yaw angle compensation. Minimum edge-of-coverage gain of 30 dBi is achieved for both yaw angles of 0° and 90°.

Axially displaced ellipsoidal (ADE) reflector has been developed in the recent past [18] for satcom on the move (SOTM) terminal applications and other high-frequency applications demanding compact antennas. The advantages of ADE are its ability to produce spot beam with relatively high efficiency using electrically small main reflectors and smaller subreflectors. It also has advantages of eliminating the geometrical blockage from the feed and subreflector support and potentially eliminating the struts to support subreflector. It also requires a smaller feed compared to conventional Gregorian or Cassegrain antennas. It employs a focal-ring Gregorian or Cassegrain antennas. It employs a focal-ring instead of a focal point for the rays reflected by the ellipsoid and hence named as ADE.

A novel and cost-effective method of high-power thermal vacuum (HPTVAC) of satellite payloads has been developed recently using pickup horn (PUH) absorber loads [19]. The PUH loads are placed in close proximity of high-power horns and are designed to absorb all the power with minimal reflections going back to the horn and the repeater chain. Other constraints are minimizing the RF leakage, cooling of the PUH, and the ceramic loads through LN2/GN2 inlet and outlet channels. This method allows testing of all payloads at the same time without opening and closing the TVAC chamber for each payload test. Group delay, temperature sensing, and return loss can be measured simultaneously using this method. Several commercial and military satellites have successfully used this PUH method over the last 8 years with benefits of cost and schedule reductions compared to conventional methods. Other areas of antenna recent developments include large deployable mesh reflectors capable of reflecting RF signals at high frequencies (K/Ka) with low losses, wideband phased array antennas with multioctave bandwidth capability, wide scan phased arrays, multiband and multi-pol feed assemblies, tracking antennas high frequencies K/Ka/Q/V-bands, with low losses, wideband for inter-satellite links, reconfigurable antennas allowing beam shape change on-orbit, high power test methods, increased power handling of the antennas, low-loss sunshield materials, PIM-free feed components and reflectors, antennas supporting multiple bands to serve different services from the same antenna, and light-weight materials for feed assemblies and reflectors. Mutual coupling impacts have to be analyzed carefully with array antennas having electrically small feed elements in order to characterize the radiation more accurately. Extensive research is ongoing in the areas of metamaterials, but its application and suitability to space antennas remains to be seen. Nanotubes and EBG are other development areas that researchers are currently working.

## VII. CONCLUSION

A review of antenna systems used on current satellite communications payloads for different services has been given. Recent advances in the satellite antenna payload have been outlined. With the addition of military services to commercial services, the so-called “hosted payloads,” demand more for improvements in the areas of multiband antenna systems, such as more efficient antenna designs, high power spacecrafts, improved pointing methods such as higher order RF tracking, better methods for PIM predictions including spacecraft effects, reconfigurable antennas, and improved feed assemblies with low losses, better power handing, and multiband capabilities. Some details of developments in many of these areas have been provided.

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