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Large Multibeam Antennas for Space

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A number of space missions (communication, Earth observation, and power transfer) are surveyed that involve the use of large spacecraft antennas. All of these antennas require sophisticated radiation control. Ways to achieve these controls and associated problems are presented and some details are given about the factors affecting the gain, beam isolation, and polarization isolation of the antennas.

Nomenclature

B_T	= total effective communication spectrum
BFN	= beamforming network
d	= diameter of feed horn
D	= diameter of antenna aperture
f_0	= center of up or downlink frequency band
F	= focal length of the antenna reflector
G	= gain of a shaped beam of the multibeam antenna
I_B	= beam isolation, e.g., level difference between desired beam and interfering sidelobe of another beam in the same frequency band and polarization
p	= power level in the peripheral horns relative to the center horn in a seven-element feed
n	= number of horns or component beams
N	= number of reuse of the allocation bandwidth ΔF
S	= slope of the pattern as a function of angle
VPD	= variable power divider
VPS	= variable phase shifter
α	= component beam center-to-center separation
Δ	= rms surface accuracy of reflector
Ω	= solid angle of coverage (deg^2)
ψ	= angle between axis of paraboloid and a ray directed from feed toward paraboloid
θ_3	= 3 dB beamwidth

Introduction

WITH the advent of the Shuttle, space antenna systems for communications, radiometry, and power transmission are no longer severely constrained in weight and volume, and antenna concepts of 10-100 m diameter have been vigorously proposed. Large multibeam antennas requiring sophisticated beamforming networks, accurate reflector shape control, and reconfigurability to accommodate changing data flow and to provide beam control are envisioned as commonplace in the next ten years. These emerging antennas will be examined for electrical and mechanical implications. It will be shown that multibeam antenna systems require technology development in the areas of large offset-fed parabolic reflectors to reduce beam blockage, accurate reflector surface contours to maintain beam isolation, low thermal gradient to reduce defocusing errors, and active real-time beam shape control.

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Index categories: Spacecraft Configurational and Structural Design (including Loads); Satellite Communication Systems (including Terrestrial Stations).

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Typical Mission Requirements

The most important present and near-future beneficial uses of space include communication, Earth observation, and electric power generation. For these missions, one key element is the antenna.

Table 1 lists a few missions which require antennas with large diameter or large beam number. All these antennas have a common feature: they utilize an array of radiating elements to produce the desired shape of radiation. In the case of the Solar Power Satellite (SPS), the array is the final radiating element and the radiation forms a single beam. The other listed cases use a feed array (primary radiator) which illuminates a secondary reflector. The feed array and reflector forms one or more shaped beams, which are composed from a number of component beams. One component beam is associated with each radiating element in the feed. The shaped beams are available either in a time-sequenced manner, as for a scanning soil moisture radiometer, or in a simultaneous manner, as for a multiple-shaped beam communication satellite.

The first five missions listed in Table 1 are communication related; the remaining involve Earth observation or power transfer. Note that the listed missions entail successively increasing component beam numbers, antenna sizes, pointing accuracy requirements, and D/Δ ratios.

The antennas for communication missions require the coverage of specified traffic areas. These areas may be noncontiguous (e.g., metropolitan areas) between which heavy route communication requirements exist, or contiguous with varying traffic density.

The overall traffic area as it appears from synchronous orbit may be the complete Earth (~ 235 deg^2 solid angle) or part of an individual country (for instance, the lower 48 states of the U.S. occupy 13.5 deg^2 solid angle).

The shape of the traffic area may follow the national boundaries of a country and can be approximated by one or more cluster of circles. In other applications—coastal surveillance, air traffic corridor, or pipeline—the shape of the coverage area may be long and narrow and can be approximated by a linear sequence of circles.

Tailoring the coverage of the antenna helps in optimally utilizing the available radiated power. However, the most important use of multiple component beam antennas is to allow subdivision of the traffic region into subregions. Each of these subregions can be covered by a shaped beam, which is generally synthesized from several component beams. If the shaped beams are ideal in the sense that they illuminate only

Table 1 Examples for planned multibeam antennas

Mission	Frequency band, GHz	D linear antenna dimension, m	3 dB beam-width of component beam, deg	No. of component beams	No. of shaped beams or f reuse	Pointing accuracy, deg	Δ rms surface accuracy, mm	D/Δ
			Large beam numbers (synchronous orbit)					
AT and T	3.7-4.2	3.55	1.6	33	4-5	±0.05	1.3	2.73×10^3
second generation	5.925-6.425	3.55	1.6	33	4-5	±0.05	1.0	3.55×10^3
INTELSAT VI	3.7-4.2	5.5	1.27	144	7	±0.05	1.3	4.23×10^3
	5.925-6.425	3.5	1.27	144	7	±0.05	1.0	3.5×10^3
	3.4-4.99	2.4	1.7	89	4	±0.07	1.3	1.85×10^3
	5.625-7.015	1.6	1.7	89	4	±0.07	1.0	1.6×10^3
INTELSAT	3.7-4.2	5.5	1.27	70	12	±0.05	1.3	4.23×10^3
regional	5.925-6.425	3.5	1.27	70	12	±0.05	1.0	3.5×10^3
	10.7-11.2	5.52	0.5	108	29	±0.03	0.5	1.1×10^4
	14.0-14.5	4.24	0.5	108	29	±0.03	0.4	1.06×10^4
NASA K_a band	18-20	3.35	0.5	108	29	±0.03	0.25	1.34×10^4
COMSAT exp.	28-30	2.20	0.5	108	29	±0.03	0.16	1.37×10^4
			Large antenna structures					
Public service satellite	0.8-0.9	60	0.63	46	9	±0.05	5.6	1.0×10^4
(Mobile communication	1.6-1.75	32.7	0.58	69	10.5	±0.045	2.8	1.17×10^4
synchronous orbit)	2.0-2.2	28.8	0.50	108	14.5	±0.03	2.4	1.2×10^4
Soil moisture	0.6-.628	230	0.15	500		±0.05	10	2.3×10^4
	1.4-1.428	20						
	1.4-1.428	20	0.75	100		±0.10	3	6.6×10^3
	1.4-1.428	100	0.15	500		±0.05	3	6.6×10^3
Solar power satellite:								
Development	2.4-2.45	40	0.2			±0.10	2	2×10^4
test article							(for 10×10 m subarray)	
(400 km orbit)								
SPS operational system	2.4-2.45	1000	6×10^{-3}	10^5		0.3×10^{-3}	2	2×10^4
(synchronous orbit)				(subarray)			(for 10×10 m subarray)	

the desired subregion, then the frequency band can be reused as many times as there are shaped beams in the overall system. These multiple-shaped beam, frequency reuse systems allow efficient utilization of spectrum and orbit space and represent the most important mission requirement for communication satellites.

Table 2 and Fig. 1 exhibit the main topology characteristics of eight candidate multibeam communication antenna plans designed to cover the lower 48 states of the U.S. Such systems are characterized by the number of spectrum reuses and the available isolation between beams serving different regions at the same frequency. (Since systems with many spectrum reuses are interference and not thermal noise limited, the number of spectrum reuses and isolation are equally important measures in determining the total traffic carrying capability of the system.)

The beam plans shown in Table 2 and Fig. 1 are based on providing isolation (orthogonality) between beam cells by subdividing the total available spectrum ΔF into m subbands (channels) and/or by using two orthogonal polarizations. The numbers in the cells show the serial number of available channels (up to 8). The uncircled and circled channel numbers signify the two orthogonal polarizations, respectively.

The complexity of a typical system may be characterized by the component beam center to component beam center separation, α, which for constant crossover level is inversely proportional to the diameter of the antenna in wavelength and by the number of component beams n in the antenna. This increased complexity typically improves the spectrum reuses possible with the system.

For $0.17\text{ deg} \leq \alpha \leq 0.5$ deg and $69 \leq n \leq 683$, spectrum reuses of 5.5 to 23 and adjacent beam isolation values between 23 and 31 dB result. However, the coupling between more distant beams generally is not negligible, and the total combined interference can be significant when the number of spectrum reuse is large. Consequently, with increasing spectrum reuse the isolation requirement has to be increased also. For modest spectrum reuse (4-7), a typical adjacent beam isolation requirement is 25-27 dB. For larger (~ 20) spectrum reuse the adjacent beam isolation has to be in the 27-31 dB range.

Table 3 shows the practical antenna sizes in various frequency bands for a 27 dB isolation system.

In Table 3 the United States is defined as the lower 48 states plus Alaska, Hawaii, and Puerto Rico. The beam plan is based on a nine main horn cluster (plan 2 of Table 2).

It can be seen that the total available communication bandwidth increases with the antenna diameter for a given frequency band.

Typical Antenna Requirements

For a system with Earth and space segments, the minimum yearly operating cost is typically realized when the cost in space is comparable to that on Earth.

The cost in space is significantly influenced by the cost of the transportation system. In the past this cost was determined largely by nonreusable launch vehicles. For instance, for the early Intelsat communication system, the high cost of space delivery coupled with a relatively small number of Earth terminals, determined that a small space antenna and a large Earth station antenna were optimal. As Earth stations proliferate and traffic increases, optimum cost favors larger space and smaller Earth station antennas.

High resolution multiple beam antennas for satellite communication and Earth observation purposes are therefore necessary for the reduction of Earth station complexity, thus lowering the cost of the communication channels and for the purpose of better spectrum utilization. This type of antenna is also useful for improving information gathering capability of Earth observation systems.

The desired features of such future high capability communication antennas are as follows:

1) Contiguous coverage of the specified traffic area with a single antenna aperture and a large number of highly efficient

Table 2 Characteristics of eight beam plans

Plan no.	Beam plan	Main beam configuration	ϵ/α, main polarization	ϵ/α, cross polarization	Number of main component beams	Number of auxiliary component beams in first outer ring beams	Band sub-division	Overlap	D/λ	α, deg	N
1	Triangular layout singlets, single polarization	Singlet	1.232	NA	1	6	3	No	243	0.75	10.7
2	East-west overlapping novets, dual polarization, reuse strips	Sextet or novet	1.5	0.5	6 or 9	12 or 14	2	One-dimensional	609	0.3	2.2
3	East-west overlapping triplets, dual polarization, reuse strips	Line triplet	1.7	0.5	3	10	2	One-dimensional	609	0.3	10.7
4	Triangular layout septets, single polarization	Septet	2.145	NA	7	12	3	No	609	0.3	10.7
5	Overlapping quadruplets, dual polarization	Rhombic quadruplet	2.345	1.232	4	10	8	Yes	366	0.5	10.7
6	Triangular layout doublets, dual polarization, reuse spots	Doublet	2.145	0.5	2	8	3	No	366	0.5	0.5
7	Rhomboidal layout singlets, single polarization	Singlet	2.5	NA	1	6	9	No	305	0.6	5.1
8	Rhomboidal layout triplets, dual polarization	Triplet	3.105	1.5	3	9	4	No	609	0.3	16.7

Table 3 Basic characteristics of multibeam antennas for U.S. coverage

			$f_0=0.8$ GHz $B=100$ MHz		$f_0=3.95$ GHz $B=500$ MHz		$f_0=11.95$ GHz $B=500$ MHz		$f_0=18$ GHz $B=1500$ MHz	
α	n	N	D, m	B_T, GHz	D, m	B_T, GHz	D, m	B_T, GHz	D, m	B_T, GHz
0.50	108	14.5	75.54	1.45	15.30	7.25	5.057	7.25	3.357	21.75
0.58	69	10.5	65.36	1.05	13.24	5.25	4.376	5.25	2.905	15.75
0.63	46	9	59.89	0.9	12.13	4.50	4.01	4.25	2.663	12.75

isolated beams. Contiguity is defined by adjacent-shaped beam crossover around the -3 dB contour. The adjacent-shaped beams are operated in different channels. For smaller antennas, contiguity can be achieved economically by multiple reflectors. However, for large systems the cost of multiple reflectors may be prohibitive.

2) Maximum spectrum reuse compatible with antenna size, frequency band, and geographical area. Antenna size must be Shuttle launch optimized. Frequency bands of interest include UHF (800 MHz), S, C, X, K_u, and K_a bands.

3) Polarization plan which reduces or eliminates propagation induced loss of polarization isolation by avoiding the use of the same cell (component beam) for dual polarization, therefore allowing the use of simple, non-critically aligned Earth station antennas.

4) Reconfigurability for in-orbit change of antenna patterns to adapt the system to orbit location, antenna tolerance, or traffic pattern changes.

It can be shown that necessary, but not sufficient, requirements to achieve the above features are: antenna gain of $G \geq 13{,}500/\Omega$, gain slope of $S \leq 6$ dB/deg and beam and polarization isolation of more than 27 dB.

Beam Topology Considerations

The design of a multibeam antenna begins with the selection of beam topology, including the number, configuration, and angular size of the beams, the assignment of frequency band, and polarization for each beam.

In broad terms there are noncontiguous and contiguous coverage multibeam antennas. In a noncontiguous system, the overall coverage area is blanketed by a set of generally shaped beams in the same frequency band using the same polarization, but the sum of these shaped-beam footprints does not cover a contiguous overall traffic area.

In a contiguous system, a given shaped beam uses only part of the overall frequency band and/or available polarizations, but the sum of all shaped-beam footprints contiguously covers the overall traffic areas.

Much study has gone into the development of beam topology schemes and corresponding antenna systems which produce the maximum possible channel capacity for a given overall traffic area.[1,2] Here only an example will be given to illustrate the approach.

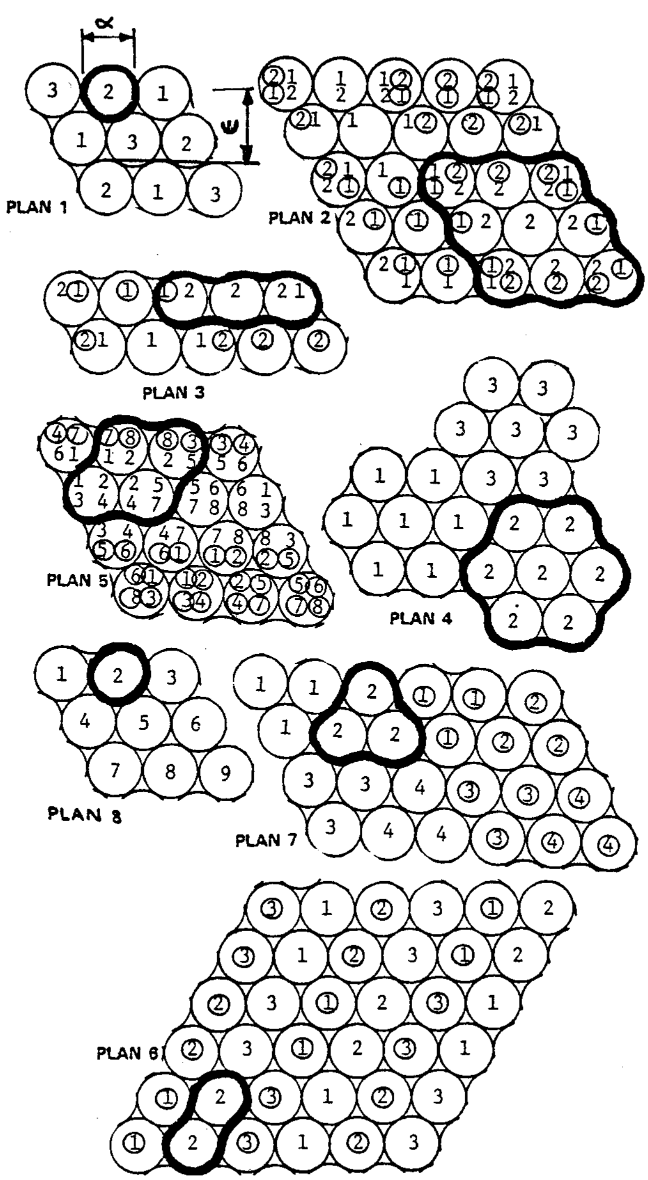

Fig. 1 Examples for various beam topology plans.

Beam plan 5 in Table 2 is one concept for providing contiguous coverage. In this plan the available frequency band is divided into eight sub-bands (channels). Additionally, two orthogonal polarizations are used; thus 16 decoupled channels are created. With the availability of 16 such channels, shaped beams comprised of four component beams each can be generated with a given channel always available in four adjacent component beams.

This results in a 16 component beam cluster which can be repeated indefinitely. Except for the peripheral beams, four channels are available in each of the component beams. Thus if the allocation bandwidth is, for instance, $\Delta F = 1390$ MHz, on the average four 173.75 MHz wide channels are available in each cell. The maximum bandwidth capability of a single cell is 695 MHz.

Figure 2 exhibits this plan. Note that the identical channel combinations form a rhombic grid in which the elements repeat at four component cell periodicity. When such a grid is superimposed on the U.S., for $\alpha = 0.5$ deg, then for the lower 48 states 11 reuses of the spectrum are possible. In this scheme the polarization is not reused in any cell or adjacent cells; thus no polarization isolation is needed for any Earth station antenna. Consequently, such a system is independent of propagation conditions for polarization isolation which is of great value at very high frequencies (e.g., 12 GHz) where rain depolarization is present and at low frequencies (3.4 GHz) where the Faraday effect is large. Further, identically polarized spectrum reuse regions are separated by at least two guard cells which allows either increased beam isolation and/or simplification of the beamforming circuit. Four-way power dividers are required to form the shaped beams, and larger beamforming networks (BFN) for producing increased beam isolation. The power amplifiers in such a system can be directly connected to the input of the radiating elements to minimize losses or placed before the beamforming network to eliminate the need for linear amplifiers. Disadvantages of the scheme are that the overall band is fragmented into relatively narrow frequency band channels and the communication capacity is uniformly distributed over the coverage area. This latter limitation can be removed by making the eight channels appropriately nonequal in bandwidth or omitting the use of certain channels in certain cells.

Candidate Microwave Optics

The microwave optics transform the aperture distribution produced by the feed to a larger aperture, thus realizing a larger gain and pattern resolution than is possible by the feed array itself. This transformation must be achieved such that the accuracy and purity of the field in the larger aperture remain within the desired limits over the specified frequency band. From a mechanical point of view, the optics must be simple and lightweight and, together with the feed, must occupy the smallest feasible volume and projected aperture area.

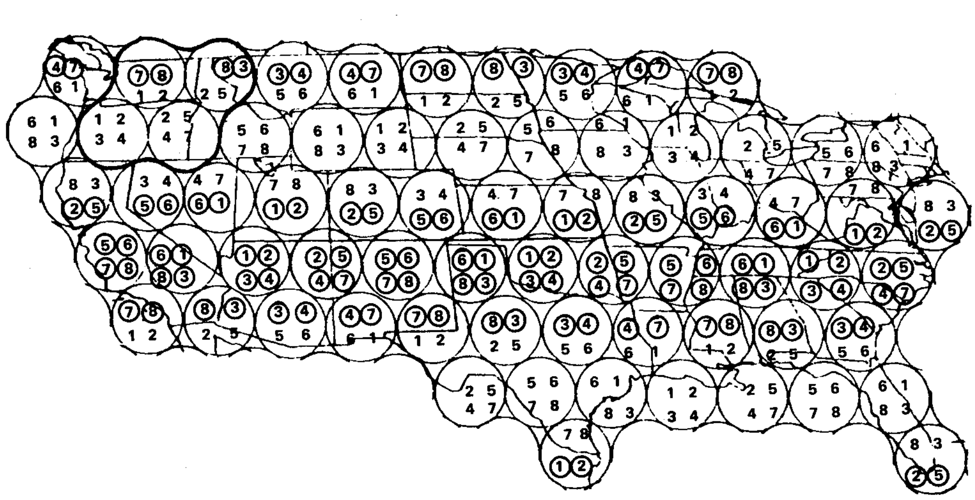

Fig. 2 Application of beam plan 5 to cover the 48 states of the U.S. Plan uses overlapping layout of rhombic quadruplets, dual polarizations, $\alpha = 0.5$ deg, $n = 68$, $N_B = 87$, $N = 10.9$.

Ideally the optics should compensate for imperfections associated with the feed or at least not further deteriorate its characteristics. Imperfections introduced by the optics (e.g., frequency dependency or polarization impurity) should be within acceptable limits.

A reconfigurable multibeam antenna design should meet or exceed specifications with the maximum number of spectrum reuses and minimum complexity. The key system trades relate the coverable traffic regions, achievable total spectrum space, gain, gain slope, beam and polarization isolation and overall complexity. The coverage may not be exactly specified; however, even in so-called noncontiguous coverage systems it is desirable to reach most of the anticipated Earth station sites. In practice, 95% coverage is adequate. Complexity is defined mainly by the number of component beams and the type and size of the optical aperture.

The optics change the amplitude, phase, and polarization distributions relative to that on the feed aperture. These changes can be compensated for in the design of the feed aperture distribution and can be used advantageously. For instance, amplitude distributions can be affected by the F/D ratio, by using dual reflector optics, and/or by allowing some degree of transparency over parts of the reflector. Polarization distributions can be modified by filtering or rotating polarizations in the optics.

For communications satellites, the candidate optical systems can be divided into reflectors and lenses. Within these broad categories the offset-fed paraboloid and the wideband lens are of greatest interest.

For the beam numbers and component beam directivities, considered antenna apertures in the 50-80 λ diam range, and feed array diameters from 18 to 24 λ are anticipated. If such a large array is placed in the center of a paraboloid reflector, at least 13% of the aperture will be blocked, producing intolerable sidelobes and poor gain performance. This eliminates the use of the center-fed paraboloid and favors offset reflectors. This results in simple optics, but introduces electrical and mechanical problems associated with asymmetries.

Lens-type optics ideally do not suffer feed blockage, but instead may have zoning and feed-support-related blockage, frequency dependency, reflections, and weight problems. Their main attractions are compactness and symmetry. Both types of optics are currently in use. For a lens, the occupied area in the plane perpendicular to its axis is equal to the aperture of the lens. For an offset-fed paraboloid the sum of the feed and reflector projection to the aperture plane is applicable.

System Trades for Gain and Beam Isolation

Performance requirements can be contradictory, e.g., an increase in the number of shaped beams (spectrum reuse) requires a decrease in the width of the guard regions between beams, which in turn requires a decrease in component beam separation α, and thus a larger number of beamforming networks, components, and complexity. If the number of desired frequency reuses is fixed, then the problem is reduced to selecting the largest possible number of shaped beams which meet the specified coverage percentage, gain, gain slope, and isolation requirements for noncontiguous coverage. For contiguous coverage, the number of frequency reuses for a given isolation is the function of α and the beam plans as shown in Table 2.

An elementary tradeoff analysis using a component beam built from one main and six auxiliary beams around it provides insight into the relationship between design parameters.

Figures 3 and 4 illustrate the nature of the problem and show the variation of gain and beam isolation for antenna diameters $D=1.78$ and 1.89 m, $F/D=1$, and 11.95 GHz. The upper curves in Fig. 3 show peak antenna gain G_M; the lower curves show the contour gain $G(0.5$ deg) at 0.5 deg from beam

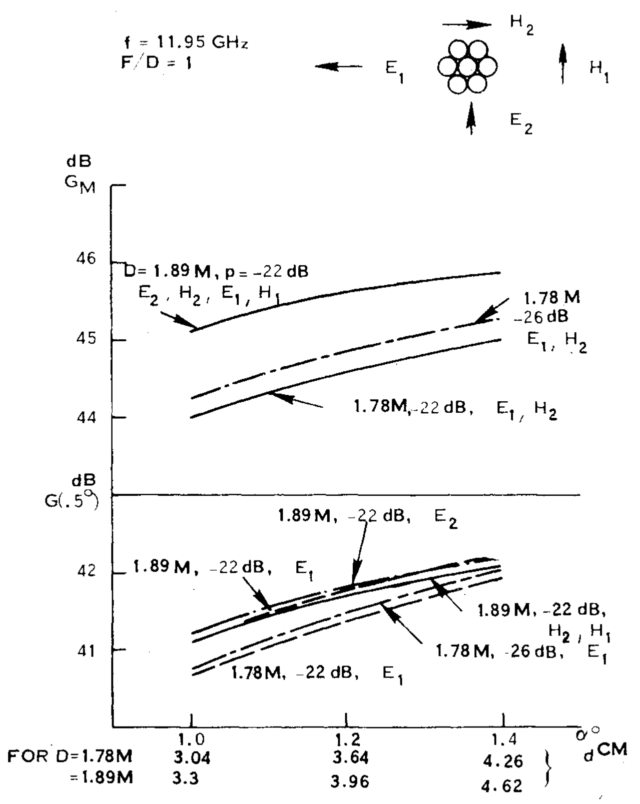

Fig. 3 Peak antenna gain G_M, and contour gain $G(0.5$ deg), (0.5 deg from beam center), as a function of antenna diameter, radiating element diameter, and component beam separation. The curves show G_M when polarization is in plane 1 and 2 of the cluster and $G(0.5$ deg) in the E and H planes. Beam is on axis of paraboloid.

center vs beam separation α and radiating element diameter d. The feed is a seven-element horn cluster with unity power in the center-horn and $p=-22$ and -26 dB relative power in the outer (auxiliary) horns.

System Trades for Polarization Isolation

The achievable polarization isolation is a function of the polarization characteristics of the feed and optical system. The required polarization purity for linear or circular polarization can be achieved either by the optics, by the feeds, or by a combination of both. Large F/D, low sidelobe systems are typically not optics limited, although the depolarization introduced by the optics is part of the overall cross-polarized power budget. For instance, if $F/D=1$, $D=1.89$ m, $f=11.95$ GHz, a seven-element TE_{11} mode-excited circular horn cluster with $p=-22$ dB, $\alpha=1.4$ deg is used and the optical system is a fully offset-fed paraboloid, then the peak cross-polarized lobe is more than 33 dB down relative to the main polarized power within the coverage zone for circular polarization. For this example the horn diameter in wavelength cannot exceed 1.4.

When $d_\lambda \sim 1.8$ is desirable to reduce the number of feed elements for a given coverage area, then the achievable polarization isolation drops to about 29 dB with a TE_{11} mode horn. For this case, the use of a multimode horn is mandatory to improve polarization isolation to 30 dB or better.

Generally, it is easier to achieve good polarization isolation with offset-fed paraboloids for circular polarization. Polarizers with better than 0.25 dB axial ratio in 47% relative frequency band have been built. This allows 37 dB polarization isolation on account of the feed. When such a polarizer is used in conjunction with a higher-order mode feed, the resultant antenna system can have circularly polarized polarization isolations in the 32-40 dB range.

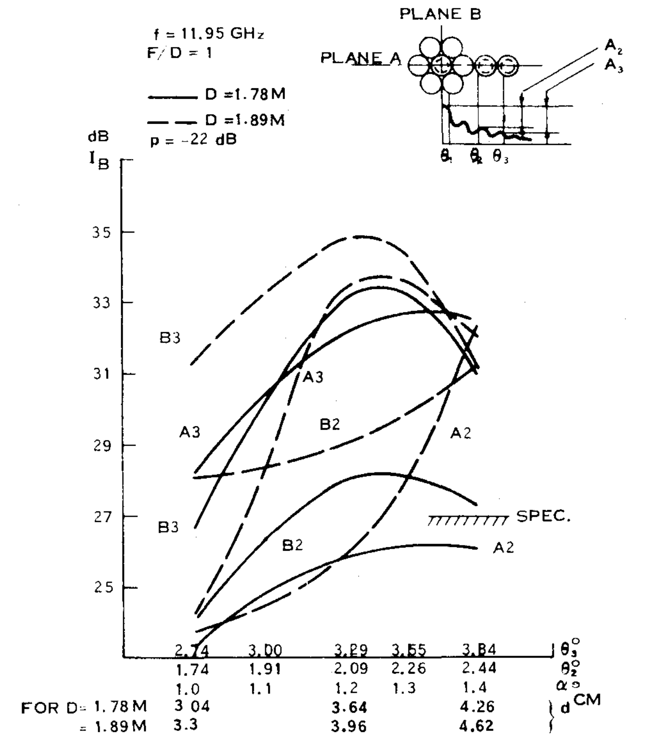

Fig. 4 Variation of beam isolation for the same conditions as in Fig. 3. Indices 2 and 3 refer to beam isolations at angles θ_2 and θ_3 from axis of the main beam.

System Trades for Gain Slope

The gain slope is the main characteristic that defines the contour of a coverage zone. Figure 5 displays the relationship between gain slope S and the usable angle from the peak of component beam. The chart also shows the relationship between S, the half-power beamwidth θ_3, and the contour level A. For instance, the figure shows that for a component beamwidth of $\theta_3 = 1$ deg, a slope specification of 6 dB/deg defines an $A = 1.4$ dB contour level relative to the beam peak as the usable limit corresponding to a full cone angle of only 0.68 deg. However, when the component beams form an overall shaped beam, the same contour level typically becomes the approximately -3 dB contour of the shaped beam, which allows for more economical use of the available beam power.

In contiguous coverage systems, the gain and gain slope must be acceptable at the contour of adjacent shaped beams, which generally are operated in different frequency bands (channels). This can be achieved by multiple reflectors, which allow the use of larger feed horns with simple BFN's or by a single reflector with overlapping feed apertures and associated more complex BFN's.

Radiating Elements

The radiating elements for multibeam antennas can be divided into the following groups: 1) single mode (LP), 2) dual mode (CP), 3) multimode (LP or CP), and 4) multielement (LP or CP). The main requirements of the radiating elements are: axial symmetry of the main beam, low sidelobes, low cross-polarization level, low cross-coupling to adjacent radiating elements, and capability to compensate for optical asymmetries present in offset-fed paraboloids. Additionally, the radiating element must provide adequate impedance match and power handling capability.

Only multimode radiating elements approach these desirable characteristics. These elements are typically derived from circular aperture conical horns and their main asset is excellent axial symmetry and very low sidelobe level in the radiation pattern.

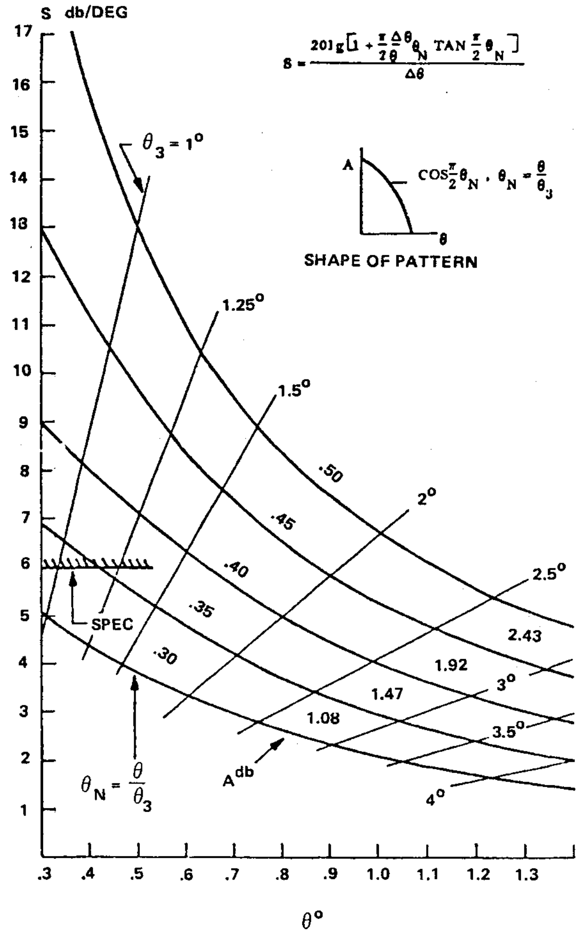

Fig. 5 Gain slope vs angle from beam maximum.

If a circular aperture horn is excited with both a TE_{11} waveguide mode and a TM_{11} mode and the peak of the TM_{11} mode associated pattern is at 17.7 dB lower level and in phase, the resultant aperture distribution is an axially symmetrical pattern; e.g., at the -5 dB level of this beam, symmetry is better than ± 0.1 dB and cross-polarized power is more than 47 dB below the main polarized peak. Such a horn can be constructed in about a 3% frequency band. For wider (14%) frequency bands, beam symmetry is nearly unchanged and the cross-polarized level can still be kept at more than 29 dB below the main polarized peak at the edge of the illuminated optics. The use of such multimode horns in multibeam antennas is vital to minimize mutual coupling between horns and to suppress cross-polarized sidelobes as required for polarization reuse. (Such a horn was developed by the authors under an Intelsat sponsored study program.)

For an offset-fed paraboloid with the indicated single radiating element, the secondary pattern peak cross-polarized levels can be kept theoretically below the -24.5 and -51 dB levels for LP and CP, respectively. The LP case can be further improved with additional higher-order modes (TM_{01} or TE_{21}), or by gridded paraboloid reflectors.

Beamforming Networks

The BFN provides the necessary amplitude and phase distribution over the aperture of the radiating elements to form the desired beams. This distribution has to be provided to a given accuracy in the frequency, power, and temperature range over the specified lifetime of the antenna. Further, the loss, weight, volume, and complexity of the network must be minimized. Generally, the BFN is reconfigurable to allow flexible use of the multibeam antenna.

Figure 6 shows a typical BFN layout, which consists of a set of variable power dividers (VPD), radiating elements, and

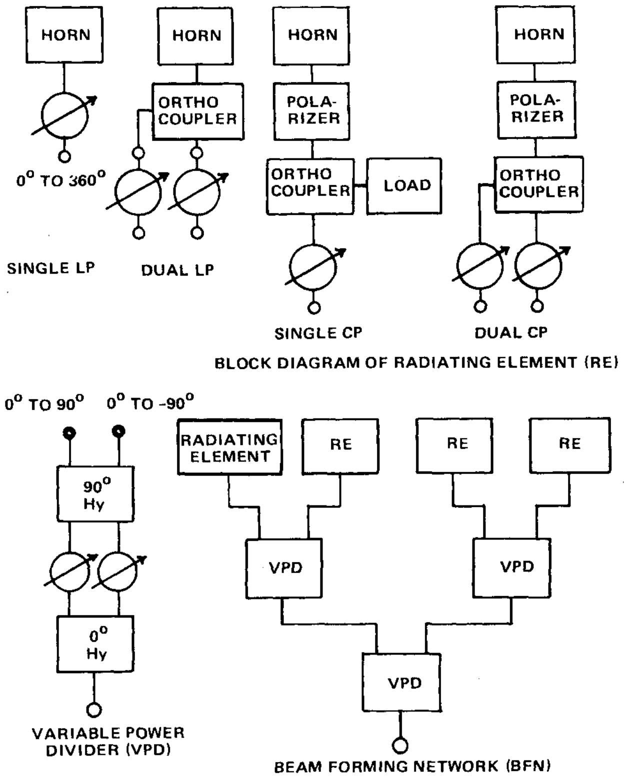

Fig. 6 Typical beamforming network layout.

connecting lines. The radiating element as a minimum consists of a VPD and a horn for linearly polarized (LP) single polarization systems. Also included are an orthocoupler, for dual polarized LP systems, and an orthocoupler and polarizer, for circularly polarized systems.

The radiating element above S-band typically employs waveguide components. The VPD up to C-band may employ stripline construction, but for X-band and higher frequencies, it typically uses waveguide components. The most convenient VPD consists of two hybrids between which a pair of VPS (ferrite) is inserted. For a given input and nominal VPS setting, all the input power leaves at one of the two output ports, say port 1. When the VPD's are changed by ± 90 deg, the output power appears at port 2. In practice, deviations occur from these ideal situations due to imbalances in the hybrids, nonlinearity and inequality of the ferrites, and mismatches. For a 6.0-6.8 GHz stripline VPD insertion loss is typically less than 0.6 dB, maximum attenuation error less than 0.1 dB up to a 4 dB power division and less than 3 dB up to 20 dB power division. For a 4 GHz band implementation, insertion loss can be reduced to 0.45 dB.

For higher frequency bands, waveguide VPD's are recommended. In X-band, about 0.35 dB insertion loss is achievable with waveguide construction.

Mechanical Design Considerations for Reflector Size and Type of Construction

For the missions listed in Table 1, mechanical considerations related to size, surface tolerances, thermal stability, pointing, and environmental disturbance attenuations represent the central difficulties.

For deployable and erectable accurate structures within the weight and volume boundaries of the Shuttle, three multibeam antenna reflector types are being considered: the solid, mesh-deployable, and precision-erectable. The solid reflector is limited by the Shuttle cargo bay dimension to 4.3 m in diameter, but for this case, high antenna diameter to rms surface accuracy ratio (D/Δ) is feasible.

For the deployables and erectables, the designs are governed by the control of surface tolerances and high packaging densities. Reference 3 defines two regimes separated by a reflector diameter to surface tolerance ratio of $D/\Delta = 10^5$. The best ground-based installations are $2 \sim 3$ times above that limit, while for present space deployables (TDRSS, ATS), $D/\Delta \sim 0.3 \times 10^5$ was achieved. An improvement up to $D/\Delta \sim 1 \times 10^5$ is expected by tailored thermal expansion mesh design, low thermal expansion materials, and partially active reflector shape control. The size of these mesh deployables, which can be transported by the Shuttle in a furled condition and subsequently unfurled to operting shape, range from 4-100 m. Antenna sizes beyond 100 m in diameter are referred to as precision erectables. These reflectors are erected in space by sequential payload deliveries. Their surface tolerance capabilities approach $D/\Delta = 10^6$ using active real-time shape control.

Reflector Surface Tolerances

The main effects of reflector inaccuracies in a multibeam antenna are the reduction of available gain and beam isolation. The conventional gain reduction is given by Ruze's formula ($\Delta G = 157.8\ \Delta_\lambda^2 \%$). The beam isolation reduction is related to the increase of total sidelobe power and is governed by the same formula. For instance, if $\Delta = 2$ mm, then at 2 GHz $\Delta G = 2.8\% = 0.12$ dB. Table 4 illustrates the effect of such increase in sidelobe power on beam isolation if the antenna is not reconfigurable.

For a reconfigurable type of multibeam antenna, the adverse effect of surface inaccuracies can be reduced relative to the conventionally predicted values. The distorted reflector does not focus all the incoming power of a plane wave in its aperture to a single focal point, but rather distributes it over a larger area in the focal plane. This power distribution fluctuates rapidly in amplitude and phase and also varies with time as the shape of the reflector changes with environmental conditions. When a large number of feeds are placed over this focal surface with controllable amplitude and phase, the resultant feed can adapt itself to the distorted field and deliver all the collected power in phase to the receiver terminal. The larger the number of feeds used, the better this adaptation can be.

Table 4 Relationship between reflector surface accuracy and achievable beam isolation at 2 GHz

Amplitude of periodic surface error component, mm	Amplitude of aperture phase error, deg	Beam isolation without error, dB	Beam isolation deterioration, dB	Resultant beam isolation, dB
2.5	12	27	2.73	24.3
		29	3.52	25.6
1.25	6	27	1.84	25.2
		29	1.83	27.2
0.62	3	27	0.78	26.2
		29	0.78	28.2

The error between the desired and actual surface can be expressed in terms of periodic components, and the isolation degradation can be calculated for each periodic surface inaccuracy component.

Table 4 shows the results of such calculations at 2 GHz for the first surface error harmonic, which affects essentially the first sidelobe. When the beam isolation is limited by the first sidelobe and no beam reconfiguration is used in the antenna, then the isolation degradation will be 0.8-3.5 dB as shown. However, the degradation can be reduced by reconfiguring the BFN. To control the first sidelobe region, a single-element feed has to be replaced by a cluster of seven feeds. Under these conditions, the beam isolation (first sidelobe) remains almost the original value and the limitation is shifted to the second sidelobe region. To improve sidelobes in this region requires 19 feeds. The procedure can be continued until an economic compromise is established between complexity of the BFN and cost of the reflector.

Axial Defocusing Tolerances

Axial defocusing, caused by differential thermal expansion between reflector and feed support, generates a phase error in the aperture of the reflector and a consequent change in the pattern. For symmetrical paraboloid, the phase error is essentially quadratic and causes a reduction of gain. For an offset-fed paraboloid with large F/D, the quadratic phase error is small but the axial defocusing δ_A causes a shift of the main beam direction and a path length error of $P_A = \delta_A(1-\cos\psi)$. Table 5 shows typical gain degradation and beam shift values for $\delta_A = 0.1\lambda$, $D_\lambda = 130$ as a function of F/D.

Beamforming Network Tolerances

The two principal tolerance-caused effects in this area are gain degradation and beam isolation reduction.

The gain degradation caused by BFN power division errors can be calculated from the accuracy capability of the phase shifters (ferrites or diodes) in the variable power dividers (VPD). The achievable accuracy with ferrite VPD's is typically ± 0.1 dB for nearly equal power division. Assuming a typical five-layer VPD network, the resulting root sum square (rss) gain degradation for a given angular direction is less than 0.23 dB.

The BFN tolerances also contribute to a degradation in beam isolation. A computer simulation indicates that at a 27 dB isolation level, realizable BFN tolerances do not generate isolation variations exceeding 0.2 dB at 6 GHz.

Antenna Pointing Tolerances

Beam pointing errors in high-resolution multibeam antennas can be caused by attitude control errors, thermally introduced asymmetrical deformations of the reflector, movement of the feed and reflector relative to each other, and amplitude and phase errors generated in the BFN. It can be assumed that most of the pointing error associated with the antenna will be caused by relative movement between feed and reflector. For such a case, the total mechanical pointing error is the root sum square of the attitude error and the boresight error due to this movement. If the component beam has large gain slope, say 10 dB/deg at the contour, then a 0.05 deg pointing error causes 0.5 dB gain degradation. This total rss error may be budgeted into 0.035 deg of peak attitude error and 0.035 deg of peak boresight error in the antenna. It can be seen from Table 5 that for a $D_\lambda = 130$, $F/D = 1.4$ offset-fed paraboloid at 2 GHz, a 13-mm axial defocusing error produces a 0.035 deg boresight shift.

Reconfigurability of the antenna can compensate for pointing errors whether they are caused by attitude errors or thermally introduced defocusing. A ground beacon can be electrically tracked to provide an error signal from which information for antenna reconfiguration can be derived. As long as the relative angular motion of the antenna beam is slow with respect to the transmission delay (0.3 s at synchronous altitude), ambiguities can be avoided and required reconfiguration time can be relatively long. Both open- and closed-loop techniques can be considered.

Example for a Multibeam Antenna Mechanical Design

The mechanical design of a multibeam reflector antenna may be illustrated by a wrap rib deployable mesh reflector described in Ref. 3. For this example, a center-fed paraboloid with a 19 feed linear array is considered. The blockage can be less than 2.1%, resulting in a sidelobe level of better than -22 dB. This wrap rib antenna consists of a hollow doughnut-shaped hub to which a series of radial ribs are attached. A lightweight reflective mesh is stretched between the parabola-shaped ribs to form the reflecting surface. The accuracy of the approximated paraboloidal surface is a function of the number of ribs. The feed system is supported at the focus of the paraboloid by a deployable telescoping boom. To furl the reflector, the ribs are wrapped around the hollow hub with the mesh folded between them. The ribs of the antenna are 1.4 deg apart. Such an antenna ideally has a gain of 36.2 dB and beam isolation of 27 dB with a 75-m reflector at 870 MHz.

At 870 MHz, a surface tolerance of 3 mm is required to restrict beam isolation degradation to a maximum of 1.8 dB from 27 dB. Gain degradation can be limited to 0.1 dB in the presence of a 5-mm rms surface error and 6.75-mm axial defocusing error. Reference 4 shows that with the selected number of ribs, a 5-mm rms surface accuracy can be achieved. Adequate beam isolation may require the use of more ribs, contoured mesh between ribs, or reconfigurability of the feed.

At 870 MHz for $F = D = 75$ m, an 18 mm, thermally induced lateral movement of the feed causes 0.014 deg beam pointing error and 0.1 dB gain degradation in the original direction. If the rib length-to-diameter ratio is large to discourage thermal conduction and the effect of shading is nearly constant, then the thermal balances are governed by radiation fluxes. The rib- and feed-related axial thermal deflections at the focus are acceptable assuming a coefficient of thermal expansion of 1×10^{-6} in./in./°F.

One multibeam antenna mission is the soil moisture radiometer. This system operates at low orbit altitude, where aerodynamic disturbances must be faced. The impact of drag on orbit maintenance has been ignored for most previous

Table 5 Effect of axial defocusing for $\delta_A = \lambda/10$ and $D/\lambda = 130$

		Symmetrical paraboloid		Offset-fed paraboloid	
F/D	ψ_M, deg	P_A/δ_A	P_A, deg	Degradation gain, dB	Beam shift, deg
1.418	20	0.0603	2.17	0.025	0.023
1.128	25	0.0936	3.37	0.061	0.033
0.933	30	0.1339	4.82	0.126	0.041
0.7928	35	0.1808	6.51	0.232	0.047
0.6869	40	0.2339	8.42	0.396	0.052

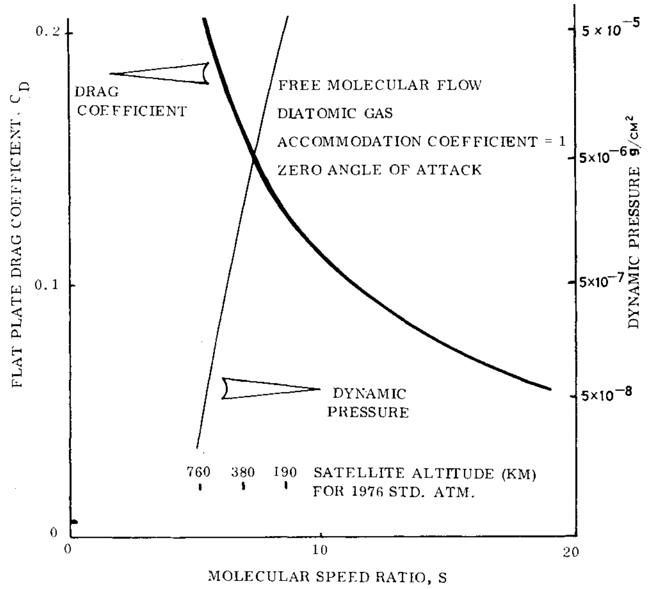

Fig. 7 Dynamic pressure and flat-plate pressure vs molecular drag coefficient.

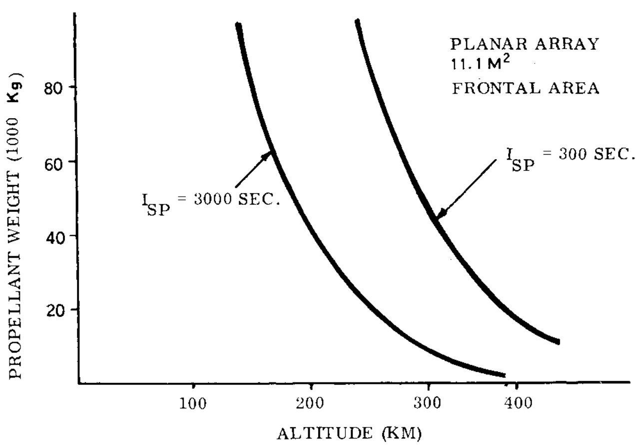

Fig. 8 Propulsion requirements of five-year drag makeup.

applications due to the low atmospheric densities and high weight-to-area ratios.

Figure 7 shows flat plate drag coefficients and associated dynamic pressures. Utilizing these data, the effect of drag on a 75×75 m planar radiometer with 11.1 m^2 of frontal area was evaluated. For five-year-life drag compensation requires a propulsion weight which is significant even though the drag force is small.

Two examples of this effect are shown in Fig. 8—one for liquid propulsion at 300 s specific impulse and one for 3000 s specific impulse for systems utilizing advanced propulsion concepts. At altitudes less than 350 km, the required propulsion weight for orbit maintenance is excessive. Reflector antennas, even with mesh surface represent difficulties at these large sizes. A possible solution is to restrict operations to higher altitudes where effective freestream molecular flow temperature to surface temperature ratio can be modified to reduce the drag coefficient.

Technology Requirements

For large multibeam antennas, various electrical and mechanical technology developments are required. A few of these are now summarized:

1) Large Offset Paraboloids. These are for blockage-free operation with acceptable sidelobe performance. For lower frequencies, the development of mesh deployables are needed to maintain compatibility with the physical constraints of the Shuttle.

2) Beam Reconfigurability. This should be used for reduction of tolerance effects, pointing complexity, and accommodation of coverage variability.

3) Thermal Control. Lightweight structural materials possessing low thermal expansion properties should be developed. Thermal control approaches, such as reflective coatings, should be examined to provide passive thermal control.

4) Reflector Shape Control . Real-time active shape control systems compatible with large mesh reflector antennas should be explored.

5) Drag Coefficient Control. Techniques must be developed for large antennas in low Earth orbit in order to achieve manageable orbit maintenance.

Conclusions

Large multibeam antennas for low and synchronous orbits offer a variety of communication and Earth observation applications. These applications require a number of sequentially or simultaneously available component beams from which low sidelobe level-shaped beams can be formed. A set of such shaped beams allows the coverage of non-contiguous or contiguous areas and multiple use of the spectrum. The reuse of the spectrum can be affected by the beam topology and by the electromechanical design of the antenna. The central problems of the antenna design is Shuttle compatibility, acceptable erection and orbit maintenance methods, surface and pointing accuracy, elimination of blockage and electrical reconfigurability to allow adaptation to changing operational use, and reduction of some of the tolerance problems.

The solution of these problems needs a vigorous, broad-based technology development program, which should be considered in close coordination with the ultimate mission requirements.

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