REPORT ITU-R BO.810-4*

TRANSMITTING AND RECEIVING ANTENNA TECHNOLOGY AND REFERENCE PATTERNS FOR THE BSS

Broadcasting-satellite service
(sound and television)

(Question ITU-R 84/10, Question ITU-R 93/11)

(1978-1982-1986-1990-1994)

1. Introduction

The WARC-BS-77 agreed to reference patterns for satellite transmitting and earth-station receiving antennas for planning the 12 GHz broadcasting-satellite service in Regions 1 and 3. The adopted patterns are contained in Annex 8 to the Final Acts of the WARC-BS-77. Similarly, antenna reference patterns were adopted at the RARC SAT-83 for planning the 12 GHz broadcasting-satellite service in Region 2. These patterns are found in Annex 5, § 3 of Part I of the Final Acts of the RARC SAT-83. (See also § 3 of Annex 5 of Appendix 30 (ORB-85) of the Radio Regulations.)

The purpose of this Report is to introduce new reference antenna patterns for spacecraft transmitting and ground receiving equipment. This information can be used in system planning. The reference patterns are presented in § 2 and a description of the present state of technology, including experimental data which justifies the reference patterns, is presented in § 3.

2. Reference patterns

For planning the broadcasting-satellite service, it is necessary to make certain assumptions concerning the maximum gain of the antenna (both for transmitting and receiving), and the way in which the gain decreases as a function of the angle measured from the axis of the beam. This information is essential for calculating interference between the transmissions for different service areas.

This section proposes reference patterns which can be used for this purpose. They are not intended to represent specifications of the best performance which may be possible, but they are reasonable practical targets which should be feasible when good design techniques are used.

The patterns are given as functions of the relative angle φ/φ_0, where φ is the angle measured from the axis of the beam, and φ_0 is the angular width of the beam measured between the -3 dB levels. The levels are expressed in dB relative to the maximum (on-axis) gain of the antenna.

Patterns are specified separately for the co-polar and the cross-polar component. They apply equally to linear and circular polarization. It is intended that they should be applicable throughout the whole of the broadcasting band under consideration, and for all angles of azimuth.

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[*] This Report should be brought to the attention of the IEC.

2.1 *Satellite transmitting antenna*

It is likely that initial planning will be based on the assumption that the beams emitted from the satellite have elliptical or circular cross-sections, and the reference patterns in this Report are based on this case.

Note. – Nevertheless, antennas with specially-shaped beams may be very useful for broadcasting satellites, because they would facilitate the suppression of undesirable spillover to neighbouring countries, while maintaining an effective coverage in the intended area. Information on one such antenna is given in § 3 and in ITU-R SA Report 676.

2.1.1 *Co-polar component*

It is convenient to consider the reference pattern as comprising three sections, namely:

- the main lobe, corresponding approximately to $0 < \varphi/\varphi_0 < 1.6$;
- the near sidelobes, corresponding approximately to $1.6 < \varphi/\varphi_0 < 3.2$;
- the far sidelobes, corresponding approximately to $\varphi/\varphi_0 > 3.2$.

As discussed in Recommendation ITU-R S.672-2, the envelope of the main lobe can be satisfactorily approximated by a curve of the form $-12(\varphi/\varphi_0)^2$ (dB). This is confirmed by measurements on a number of antennas already produced in the USA [CCIR, 1974-78a].

The level of radiation in the region of the near sidelobes is particularly important for broadcasting satellites, because it will have a significant effect upon the interference between different service areas. For this reason, it will be essential to employ antennas which are designed to reduce the level of the near sidelobes.

Through the use of offset-feed configurations, such as a Cassegrain horn, sidelobe levels less than -30 dB can be achieved [Janky and Barewald, 1977].

For the far sidelobes, the measurements made in the USA show that, with current technology, the level can be kept within an envelope defined by the curve:

$$-[17.5 + 25 \log (\varphi/\varphi_0)] \qquad \text{dB}$$

The studies made by ESA show that, if necessary, it would be possible to design antennas in which the level of the far sidelobes falls off more rapidly, with respect to φ/φ_0, than indicated by the above expression.

It is recognized that, in practice, there must be some lower limit to which the level asymptotes. For the reference pattern, this is taken as being equal to minus the on-axis gain of the antenna.

Taking account of the above discussion, the proposed reference pattern for the co-polar component of the satellite transmitting antenna is defined in Fig. 1. In practice, the values near $\varphi/\varphi_0 = 1.5$ may be difficult to achieve [CCIR, 1978-82a]. One method to improve this situation is to use a larger reflector with tapered illumination.

2.1.2 *Cross-polar component*

A study by the European Broadcasting Union [CCIR, 1974-78b] suggests that the upper limit for the cross-polar component can be expressed in the form:

$$-(a + b \log |(\varphi/\varphi_0) - 1|) \qquad \text{dB} \tag{1}$$

where a and b are constants.

Account is taken of the discontinuity which occurs at $\varphi/\varphi_0 = 1$ by applying a limit to the permitted values of the envelope.

Theoretically, the level can be kept arbitrarily low at all angles, and some studies have indicated that this could be as low as -40 dB [CCIR, 1974-78c]. However, until more practical experience is obtained in the design and construction of antennas with a very low cross-polar radiation, it is prudent to adopt, for a reference pattern, a somewhat less stringent specification.

In practice, the level of cross-polar response depends primarily on the characteristics of the feed. If the feed for the transmitting antenna is used exclusively for transmission and does not have to be part of a multi-function feed assembly, then excellent cross-polar responses can be obtained in the range of -35 to -40 dB over the main beam [Janky and Barewald, 1977].

Taking account of the limited amount of information on measured results which is so far available, it is proposed to make *a* and *b* equal to 40, in expression (1), with an upper limit of -33 at $\varphi/\varphi_0 < 1.5$, and a limit equal to minus the on-axis gain at $\varphi/\varphi_0 > 1.5$.

This proposed pattern is shown in Fig. 1. In practice, the values around boresight may be difficult to achieve [CCIR, 1978-82a].

If the feed assembly is used for both transmitting and receiving, or if a multiple-feed assembly is used to generate an irregularly-shaped beam, then it may not be possible to achieve the cross-polar performance indicated in Fig. 1.

2.2 *Earth-station receiving antenna*

2.2.1 *Co-polar component*

Because broadcasting systems involve the use of numerous receiving antennas (whether for individual or community reception), the standards of performance that are reasonable on economic grounds will tend to be poorer than for transmitting antennas. Moreover, when specifying the reference pattern, account must be taken of the probable inaccuracy of pointing the antenna towards the wanted satellite.

It is suggested that, to take account of the pointing error, the reference pattern should correspond to a relative gain of 0 dB for relative angles up to $\varphi/\varphi_0 = 0.25$. Thereafter, the curve may be expected to follow a square-law (that is, the relative level is equal to $-12\ (\varphi/\varphi_0)^2$ dB), in the same way as in the case of the transmitting antenna discussed above in § 2.1, to a level of -6 dB.

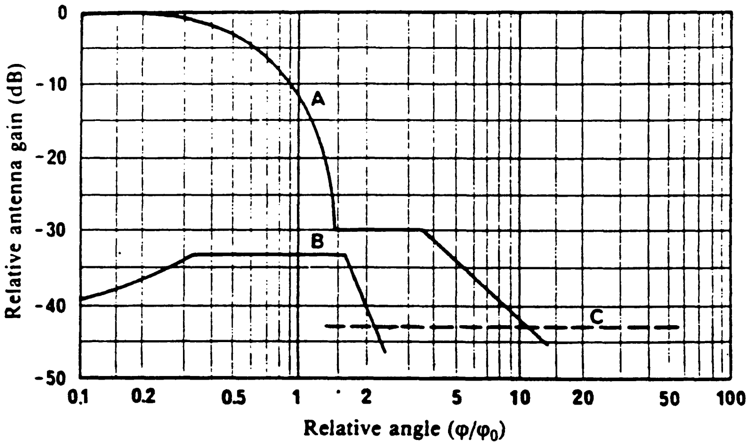
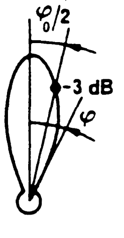


FIGURE 1 – ***Reference patterns for co-polar and cross-polar components for a single-feed satellite transmitting antenna producing a beam of circular or elliptical cross-section***

Curve A: Co-polar component (dB)
– $12\ (\varphi/\varphi_0)^2$ for $0 \leq \varphi \leq 1.58\ \varphi_0$
– 30 for $1.58\ \varphi_0 < \varphi \leq 3.16\ \varphi_0$
– $[17.5 + 25 \log (\varphi/\varphi_0)]$ for $3.16\ \varphi_0 < \varphi$
After intersection with Curve C: as Curve C

B: Cross-polar component (dB)
– $(40 + 40 \log |(\varphi/\varphi_0) - 1|)$ for $0 \leq \varphi \leq 0.33\ \varphi_0$
– 33 for $0.33\ \varphi_0 \leq \varphi \leq 1.67\ \varphi_0$
– $(40 + 40 \log |(\varphi/\varphi_0) - 1|)$ for $1.67\ \varphi_0 < \varphi$
After intersection with Curve C: as Curve C

C: minus the on-axis gain (dB)



At larger angles, the relative level will depend on the degree to which sidelobe reduction techniques are used.

For individual-reception antennas, without the use of such techniques, the upper limit of the relative level decreases from the -6 dB point at a rate given by the expression

$$-[9 + 20 \log (\varphi/\varphi_0)] \qquad \text{dB}$$

up to $\varphi/\varphi_0 = 1.26$, and from this point decreases at a faster rate given by

$$-[8.5 + 25 \log (\varphi/\varphi_0)] \qquad \text{dB}$$

up to $\varphi/\varphi_0 = 9.55$. Beyond this point, a constant level of -33 dB is taken for the remainder of the envelope.

According to the WARC-BS-77, Curve A of Fig. 2 for individual reception (in Region 2) is extended up to a value of $\varphi/\varphi_0 = 15.14$ and has a constant value of -38 dB beyond that (see Annex 8 to the Final Acts of the WARC-BS-77).

For community reception, without sidelobe-suppression techniques, the relative level is given by the expression

$$-[10.5 + 25 \log (\varphi/\varphi_0)] \qquad \text{dB}$$

starting from $\varphi/\varphi_0 = 0.86$, and continuing until the level corresponding to minus the on-axis gain is reached. The pattern corresponding to a community receiver without sidelobe-suppression is given in Curve A′ of Fig. 2.

If sidelobe-suppression techniques are employed, the curve $-12 (\varphi/\varphi_0)^2$ could be continued to a relative angle of $\varphi/\varphi_0 = 1.44$, corresponding to a relative level of -25 dB. The sidelobes could be contained at less than this level to a relative angle of $\varphi/\varphi_0 = 3.8$, and thereafter the level falls according to a curve defined by

$$-[10.5 + 25 \log (\varphi/\varphi_0)] \qquad \text{dB}$$

The pattern corresponding to the use of sidelobe-suppression is shown as curve A″ in Fig. 2. This curve may be feasible for both individual and community reception when sidelobe-suppression techniques are used.

2.2.2 *Cross-polar component*

The level of the cross-polar component can be defined in the same way as in the case of the transmitting antenna, but a less stringent performance must be expected. Moreover, account must be taken of the probable pointing inaccuracy of the antenna. Thus, it is proposed that the level should be -25 dB to a relative angle $\varphi/\varphi_0 = 0.25$. It then rises according to the curve

$$-(30 + 40 \log |(\varphi/\varphi_0) - 1|) \qquad \text{dB}$$

to a maximum of -20 dB, which is maintained to a relative angle $\varphi/\varphi_0 = 1.4$. It then decreases according to the curve

$$-(30 + 25 \log |(\varphi/\varphi_0) - 1|) \qquad \text{dB}$$

to a level of -30 dB. It maintains the -30 dB level until it intersects with the co-polar component curve which it then follows. The resultant pattern is shown in Fig. 2 as Curve B. It may be taken as applying to both individual and community reception.

2.3 *Suggested values of* φ_0

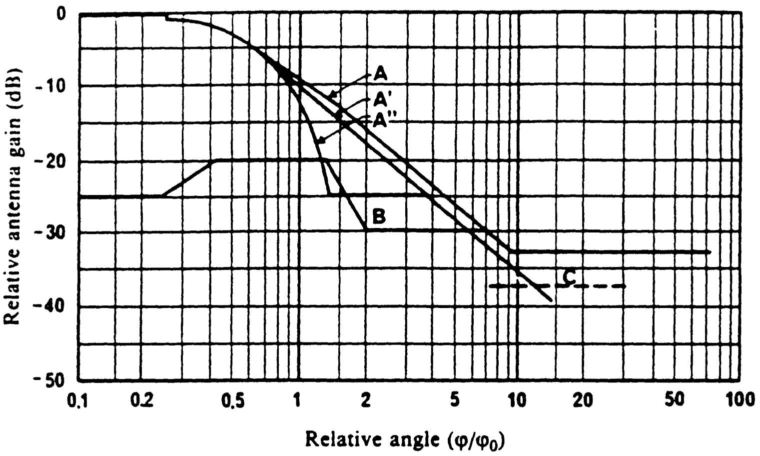
The suggested values of φ_0 to be assumed for different types of broadcasting service are given in Table 1.

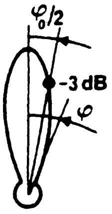
Higher-gain antennas may be used in some receiving installations, for example, to obtain a better signal-to-noise ratio, but the Table is intended to indicate the values of φ_0 for the types of antenna expected to be used in the majority of receiving installations.

Attention is drawn to the fact that antennas with smaller beamwidths will require careful alignment and careful mounting to prevent degradation in reception, and that they may also call for a specification of maximum satellite motion more demanding than that of satellites for other services.

3. Antenna technology and experimental data

This section presents a summary of the documents submitted on spacecraft and ground-station antenna technology. New sidelobe envelopes have been presented in § 2, and the salient experimental data justifying these envelopes are also included.





Relative antenna gain (dB):

Co-polar component

A: individual reception without sidelobe suppression

0 for $0 \leq \varphi \leq 0.25\ \varphi_0$

- $12\ (\varphi/\varphi_0)^2$ for $0.25\ \varphi_0 < \varphi \leq 0.707\ \varphi_0$
- $[9.0 + 20 \log (\varphi/\varphi_0)]$ for $0.707\ \varphi_0 < \varphi \leq 1.26\ \varphi_0$
- $[8.5 + 25 \log (\varphi/\varphi_0)]$ for $1.26\ \varphi_0 < \varphi \leq 9.55\ \varphi_0$
- 33 for $9.55\ \varphi_0 < \varphi$

A′: community reception without sidelobe suppression

0 for $0 \leq \varphi \leq 0.25\ \varphi_0$

- $12\ (\varphi/\varphi_0)^2$ for $0.25\ \varphi_0 < \varphi \leq 0.86\ \varphi_0$
- $[10.5 + 25 \log (\varphi/\varphi_0)]$ for $0.86\ \varphi_0 < \varphi$

After intersection with curve C: as curve C

A″: feasible for community and possibly for individual reception when sidelobe-suppression techniques are used

0 for $0 \leq \varphi \leq 0.25\ \varphi_0$

- $12\ (\varphi/\varphi_0)^2$ for $0.25\ \varphi_0 < \varphi \leq 1.44\ \varphi_0$
- 25 for $1.44\ \varphi_0 < \varphi \leq 3.8\ \varphi_0$
- $[10.5 + 25 \log (\varphi/\varphi_0)]$ for $3.8\ \varphi_0 < \varphi$

B: *Cross-polar component (both types of reception)*

- 25 for $0 \leq \varphi \leq 0.25\ \varphi_0$
- $(30 + 40 \log |(\varphi/\varphi_0) - 1|)$ for $0.25\ \varphi_0 < \varphi \leq 0.44\ \varphi_0$
- 20 for $0.44\ \varphi_0 < \varphi \leq 1.4\ \varphi_0$
- $(30 + 25 \log |(\varphi/\varphi_0) - 1|)$ for $1.4\ \varphi_0 < \varphi \leq 2\varphi_0$
- 30 until intersection with co-polar component curve; then as for co-polar component

C: *Minus the on-axis gain*

FIGURE 2 – *Reference patterns for co-polar and cross-polar components for receiving antenna*

Note. – The flat portion of the curves up to $\varphi/\varphi_0 = 0.25$ takes account of the pointing error of the antenna.

TABLE I – *Half-power beamwidths*, φ_0 *of ground receiving antennas*
(typical diameters are given in brackets)

Frequency	Broadcasting-satellite service		Terrestrial broadcasting service
	Community reception	Individual reception	
12 GHz(1)	1.0° (1.8 m) (Regions 1 and 3)	2.0° (Regions 1 and 3) (0.9 m) 1.7° (Region 2) (1 m)	3.0°(2) (0.6 m)
2600 MHz	2.7° (3 m)	8° (1 m)	
700 MHz	9° (3.4 m)	15° (2 m parabola) 30° (Yagi)	See Recommendation 419

(1) These are the values of φ_0 adopted at the WARC-BS-77 for planning of the 12 GHz broadcasting-satellite service in Regions 1 and 3 and at the RARC SAT-83 for planning of the 12 GHz broadcasting-satellite service in Region 2.

(2) Some Administrations propose a different value for this parameter.

3.1 *Spacecraft transmitting antennas*

3.1.1 *Sidelobe levels*

Effective spectrum utilization of the geostationary orbit for broadcasting satellite transmission depends to a large extent upon directional control of the antenna radiation. The most effective means of serving a desired broadcasting service area with the required e.i.r.p. while maintaining low levels of radiation outside of this area is through active or passive control of the satellite antenna radiation pattern, particularly in the areas of the near-in sidelobes. This applies to both the co-polar and cross-polar patterns. (The Earth's disc as seen from the geostationary orbit subtends approximately 17.5 degrees, and it is in this region that the reduction of sidelobes is most advantageous.) Much effort has been directed toward this vital aspect of effective spectrum usage.

3.1.2 *Reflectors and lenses*

It is a standard practice to taper the illumination of parabolic reflectors to increase sidelobe suppression. Extension of this technique in conjunction with other techniques has shown [Thomas *et al.*, 1970] that with deliberate design, first sidelobe levels can be held to the −40 dB level relative to the main beam through application of aperture blockage compensation and active zone suppression techniques.

Passive techniques are also used to control sidelobe levels in reflectors. A common technique uses a stepped zone in the reflector, usually at the centre or outer edge. The height of the step produces the desired phase change and determines the width and position of the desired cancellation pattern.

In principle, any desired degree of lobe suppression can be obtained with these techniques. Practically, however, cumulative errors in amplitude, phase and position, limit the degree of lobe suppression to approximately −40 dB referred to the peak of the main beam. This degree of suppression, however, has not been demonstrated in space qualified hardware. For this reason, a higher level has been adopted in the reference pattern.

An effective design technique for a horn-reflector antenna of arbitrary beam cross-section has been recently presented [Katagi and Takeichi, 1975]. The technique is simple in nature. The shape of the wave-front near the aperture is first determined, for a desired beam shape, and the reflector shape is then based on optical path considerations. Such antennas may be useful in the design of broadcasting satellites.

3.1.3 Beam shaping

Three approaches to beam shaping have been studied: phased arrays, multiple-feed circular or elliptical reflectors, and single-feed shaped reflectors. Each of these approaches is discussed in turn. These discussions are followed by a consideration of the impact on the shape of satellite-receiving antenna beam, of using the same reflector for both transmission and reception, and the impact on beam shape of changing the orbital position of the satellite.

3.1.3.1 Phased array antennas

Several studies have been performed concerning the applicability of satellite-borne multi-element arrays to the solution of broadcast and communication coverage requirements.

Active arrays appear to offer a capability of providing greatly reduced interference effects and increased spectrum re-usability because of the greater flexibility and efficiency with which they can be made to operate.

Phased arrays allow virtually unlimited control over the amplitude and phase of aperture illumination, and a single aperture can be used to provide any desired number of parallel beams (assuming a separate phasing matrix for each beam to be generated). Arbitrarily shaped portions of the aperture can be selected to provide arbitrarily shaped beam cross sections such that a geographical boundary may be closely approximated. Arrays appear to be capable of providing first sidelobe isolation to the −40 dB level from the main beam [Hult *et al.*, 1968].

Adaptive phased-array antennas present the possibility of providing light-weight apertures with high directivity and precise beam shape control coupled with the ability to selectively place array pattern nulls in specified directions; for example, towards significant interference sources, or in directions where reception is not desired. In particular, the use of a self-calibration algorithm permits the relaxation of both mechanical and electrical tolerances, thereby preserving extremely high isolation and gain control for direct satellite broadcasting while reducing the cost and weight of the antenna array [1990-1994]a.

The concept of self-calibration has been successfully demonstrated in a laboratory setting using irregularly spaced antenna elements with no attempt to match element channel electrical characteristics. The proponents of this approach estimate that about three years of development time will be required before engineers determine how cost-effective the technique is.

3.1.3.2 Multiple-feed reflector antennas

Other approaches to the shaped beam antenna involve the use of multiple-feed reflectors and lenses. In these devices, each feed element of a multiple-element feed array separately illuminates the reflector or lens to generate a component beam in the far field. By properly adjusting the main aperture distribution phase and amplitude from each feed and summing the feed inputs in hybrids, the secondary pattern can be shaped to provide arbitrary area coverage. Several engineering models of these antennas have been built, and satellite antennas now in orbit (Intelsat IV-A) and planned (DSCS-III) make use of such techniques. There are a number of sophisticated computer programs available for calculating phase and amplitude distribution for the feed element array. Additional information on development of these techniques in the USA is given in Report 676.

An antenna with specially-shaped beams developed in Japan for the Broadcasting Satellite for Experimental Purposes (BSE) consists of an elliptical reflector and three primary feed horns to conform to the shape of the service area in which the mainland and the remote islands of Japan are included [CCIR, 1974-78d]. The frequency of the down link is 12 GHz. The measured patterns were in good agreement with the theoretical calculations. Such an antenna would facilitate the suppression of undesirable spillover to neighbouring countries, while maintaining an effective coverage in the intended area.

Another study indicates that an improvement in sidelobe suppression can be obtained by the use of offset feed horns for this type of antenna [CCIR, 1974-78e]. A circularly polarized shaped beam antenna which is similar to the above configuration has also been developed. Measured results show that cross-polar discrimination of better than 33 dB (referenced to the boresight co-polar gain) could be maintained in most directions.

However, it was found that a requirement of 40 dB discrimination around the boresight is difficult considering current technology for medium scale broadcasting satellites [CCIR, 1978-82b]. Further study of this matter is desirable.

3.1.3.3 Shaped-reflector antennas

In contrast to the arrayed feed horn designs just discussed, a new technology employing a single feed horn with a shaped reflector has been developed and tested in the United States. As with the arrayed feed horn designs, the shaped reflector approach utilizes offset feed geometry to obtain high aperture efficiency. The shaped reflector serves to shape the e.i.r.p. distribution over the service area. This new technology has lower output losses, generally creates better beam shaping, and has reduced weight compared to reflectors with phased feed horn arrays.

One of the first applications of this shaped reflector approach to achieve a shaped-beam satellite antenna was to a 12 GHz broadcasting satellite scheduled for launch in December 1993. The service area to be covered was the contiguous United States (CONUS) [1990-1994]b, and Williams et al. 1993.

The design objectives for this antenna included not only matching the beam shape to that of CONUS, but also: 1) providing variations of gain within the main beam to compensate for differences in the expected rain attenuation, and 2) control of side-lobe radiation to meet the interference requirements of other Region 2 countries in the 12 GHz plan.

The design of the shaped reflector was carried out in two stages. In the first stage, no special consideration was given to side lobe performance. Instead, the reflector shape was optimized to match the beam shape to CONUS and to provide about 1.5 dB more gain to the eastern part of CONUS, with local gain peaks towards major population centres.

In the second stage of the design, the reflector shape was refined to control side-lobe gain towards other Region 2 countries so that the overall equivalent protection margins (oepms) of these countries would not be reduced. To do this, the IFRB version of the SOUP software, augmented with a shaped-beam subroutine, was first used to calculate the oepms at over 15 000 receiving test points throughout Region 2 assuming the side lobe-pattern corresponding to the first stage antenna design.

Using these results for reference, the reflector shape was reoptimized to reduce side-lobe gain towards those countries whose oemps had been adversely affected. Using a reflector with a nominal diameter of about 2.2 m and a single offset corrugated feed horn, it was found possible to achieve the desired side-lobe suppression without degrading the derived gain performance at any point within the main lobe by more than 0.3 dB.

3.1.3.4 Other factors affecting satellite antenna beam shape

It is possible to use beam-shaping techniques with multiple feeds to achieve a main lobe pattern which is different from the conventional Gaussian shape. Specifically, it is possible to maintain a more uniform amplitude level over the intended service area. Such equalization of the radiation pattern may have distinct advantages under some circumstances. The principal advantage is that less spacecraft prime power is needed to provide the minimum e.i.r.p. required at the edge of the service area. This means that a smaller transmitter and smaller solar cell panels could be used, with consequent economic savings. For some applications, these savings could be significant.

A disadvantage of this technique is that the more uniform pattern may slightly exceed the present Gaussian envelope within the desired service area, but not outside the intended −3 dB contour. In this event, an administration which desired to use such beam-shaping techniques would have to co-ordinate with its neighbour in advance. Further study of this technique is desirable.

Analytical and measured results at 12 GHz [Chen and Franklin, 1980] were obtained for a shaped beam coverage of the US Eastern Time Zone (ETZ) using linear polarization. The 25-horn feed reflects the use of additional horns at the zone periphery for sidelobe cancellation. Comparisons of calculated and measured results for transmit frequencies at 11.7 and 11.95 GHz showed excellent agreement.

The antenna implementations covering the 11.7 to 14.5 GHz band provided quite uniform performance. For the 12.2/18.1 GHz receive/transmit band, use of the same antenna would result in some performance compromise. Although the reflector could be compensated by making the outer 1/3 portion dichroic (i.e., transparent) to the frequencies near 18 GHz, the bandwidth limitation of the feeds and polarizer would result in degraded performance.

Broadcast systems generally are not amenable to relocation of satellites to new orbital locations because of the change of coverage area in size and shape. If the longitude shift is small, say less than 5°, and specified during antenna development, then the coverage can be designed for the composite pattern (which is larger than either one) at a small loss in gain of 0.3 to 0.5 dB. The spacecraft can easily be repointed in the east-west direction to provide additional flexibility.

If the change in orbital longitude is large, say a shift from 100° W to 115° W, it may be impractical to design using the composite pattern because of the loss in gain. The difference in gain for an antenna designed for 115° and used at 100° could be as large as 3 dB for selected areas. This effect will generally be less severe for a broader coverage shaped-beam antenna, i.e., where coverage is provided at the -2 dB contour rather than at the -3 to -4 dB contour or with a shaped beam not as closely matched to the coverage contour.

If two discrete longitudes are specified, a design could be synthesized using some combination of variable power dividers or switchable horns to reconfigure the antenna feed in orbit. This is generally undesirable from the standpoint of complexity and reliability.

3.1.4 *Multiple beams*

The use of multiple beams to provide multiple independent coverages within a desired service area has been shown to increase the total spectrum capacity through frequency re-use.

Multiple beams can be produced from a single aperture by employing reflector, lens or array technologies.

Multiple off-set horn feeds operating in conjunction with a reflector or a lens provide a viable solution to the broadcasting-satellite service's performance requirements, for spacecraft as well as earth station antennas. Allowing a separate beam to be devoted to each group of users permits the desirable re-use of frequency bands. A proposed multi-beam microwave antenna [Ohm, 1974] using an off-set multiple horn feed system and Cassegrain reflector has been shown to essentially eliminate aperture blockage, reduce coma aberrations and provide good isolation between beams (40-45 dB).

Much effort has been devoted to studies of the zoned lens for producing multiple independent beams. Analytical techniques and some experimental results of a wave guide lens antenna have been presented [Dion and Ricardi, 1971] indicating the capability of providing a variable coverage radiation pattern. This variable coverage is obtained through selective excitation of derived feeds to produce the proper aperture illumination and phase distribution.

Phased arrays offer good potential for future satellite antennas in the higher frequency ranges. Multiple independent beams can be produced through selective element excitations.

Phased array antennas of the lens type have been developed for ECM and telemetry applications, and designs producing several independently steerable beams over octave bandwidths have been demonstrated. Selective summing of groups of beams produces even narrower beams which are independently "steerable".

3.1.5 *In-orbit satellite antenna reconfiguration* [CCIR, 1982-86a]

Most communication satellite systems in operation today employ spacecraft antennas which provide footprints which straddle the service area, and the generation of their footprints is orbit-location dependent. In the future a need will arise to change the footprint shape or size while the satellite is in orbit and at a fixed location. Another more complicated footprint change would be required if the satellite is to be relocated (while in orbit) to another location, or a spare built whose location in orbit may not be known since it would replace one of several satellites already there. Both of these situations would require an in-orbit antenna reconfiguration in order to match the footprint to the service area.

In the discussion which follows, it is assumed that a shaped beam(s) will be used and the antenna aperture is driven by a cluster of feed horns.

The first form of reconfigurable antenna would be to service several areas from a single orbital position. For example, the sketch in Fig. 3a shows three possible service areas which can be served from a single orbital position. That is, the antenna power can go to footprint A or footprint B or the composite footprint C. The power division between area A and area B is generally not equal, with the larger area receiving more power to equalize the pfd. Another scenario would be that one area receives more power to reduce the earth station requirements in that area.

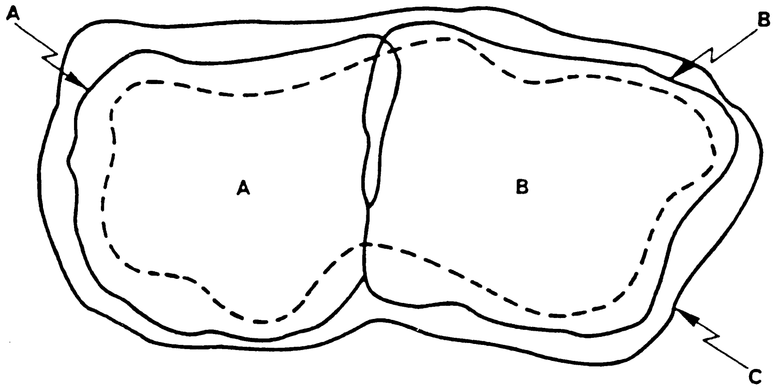
Implementation of these ground illumination patterns can be made by the beam forming networks and feed clusters shown in Fig. 3b. The ground-controlled variable power divider (VPD) partitions the power to the two sub-arrays which individually produce footprints A and B. Suitable power division between the two sub-arrays produces footprint C. There may be additional circuitry in the labyrinth such as phasing devices to ensure uniform phasing across the aperture. A schematic diagram of a VPD is shown in Fig. 3c. The phase shifters have a maximum phase shift of $\pi/2$ radians and are incrementally stepped to this value with a resolution of 4 bits. This corresponds to $\pi/32$ radians. The output power at each port will be the same when the phaser states are identical. The output of either port will be zero when the phase difference is 90°. Therefore, all divisions are possible within the increments set by the number of bits.

Another form of reconfigurable antenna, which presents more practical problems than the structure above, is for use in the case in which reconfiguration is required when a satellite is relocated from its present longitude, or a spare is required which can assume several possible orbital positions. The final orbital position is not known *a priori*, since which satellite will fail first is unknown.

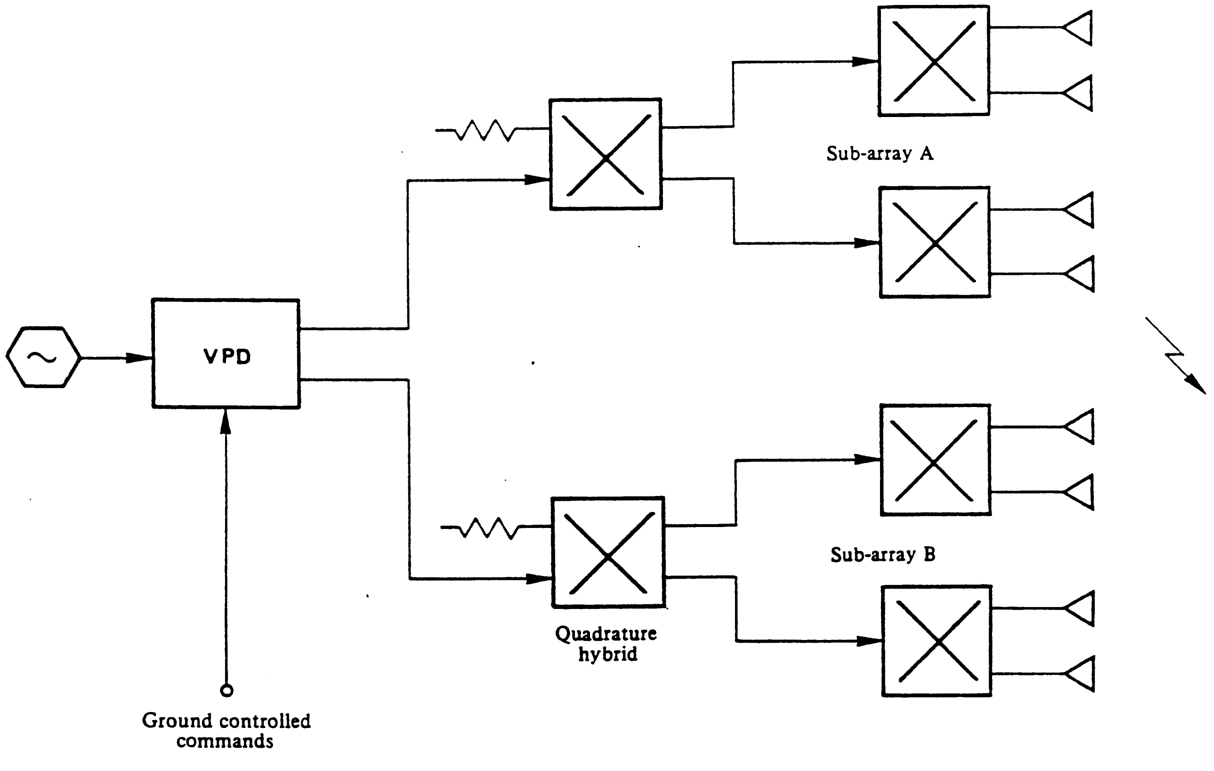
For antennas which are designed to follow the contour of the service area and produce little radiation outside this area, the migration of the satellite will no longer produce an optimum shaped footprint for that area. This is because the satellite "sees" the service area from a different perspective. Especially for shaped beams, the service area coverage at the beam periphery is satellite location sensitive. It would therefore be necessary to reconfigure the antenna feed arrangement to return it to the optimum illumination of the service area. It is clear that dividing up the power amongst the feeds is not adequate since the original footprints would prevail, as indicated in the previously-described antenna reconfiguration. It is therefore necessary to have a multiplicity of feeds in the feed cluster which can be driven by varying amounts of power. Some feeds, depending on the satellite location and area to be contoured, may receive more power or less power or none at all.

A reconfigurable antenna system is being investigated in the United States which can be programmed to provide optimum footprints to the 50 states for a satellite location in the range of 66° W to 129° W longitude. Typical footprints which can be generated for three different locations are depicted in Fig. 4.

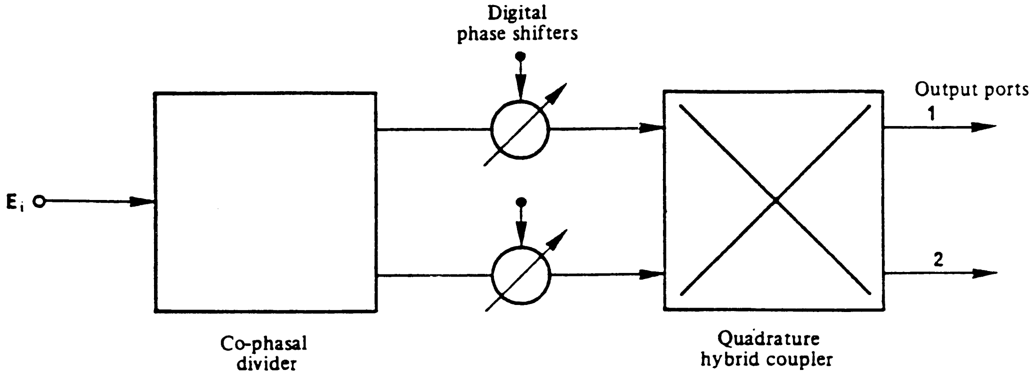
It is noticed that the reconfigurable antenna network will generally be more complicated and may contribute more weight than a simpler beam shaping network. Another factor to consider is that the added circuitry will introduce more losses in parts of the transponder where losses are critical. In addition, one would expect an additional cost to the spacecraft, but this is less important than the weight and performance factors.



a) Assumed service areas

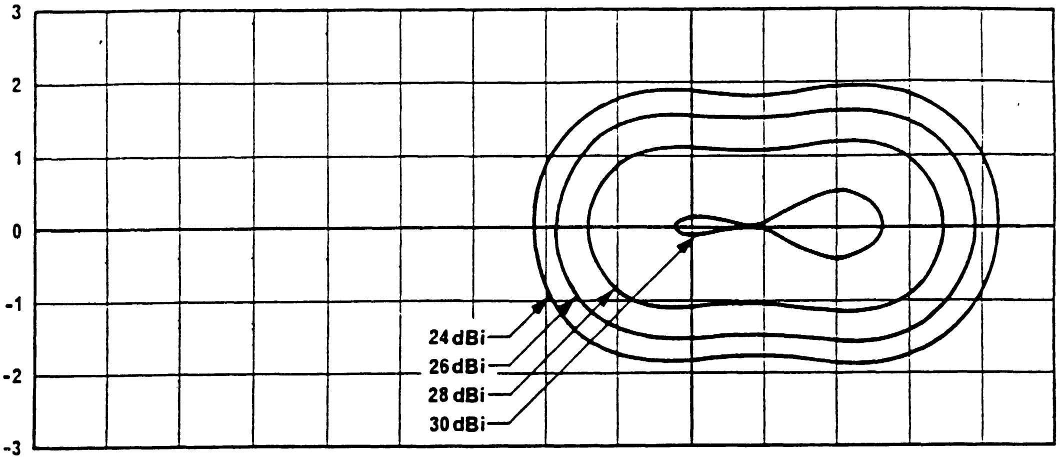


b) Beam-forming network

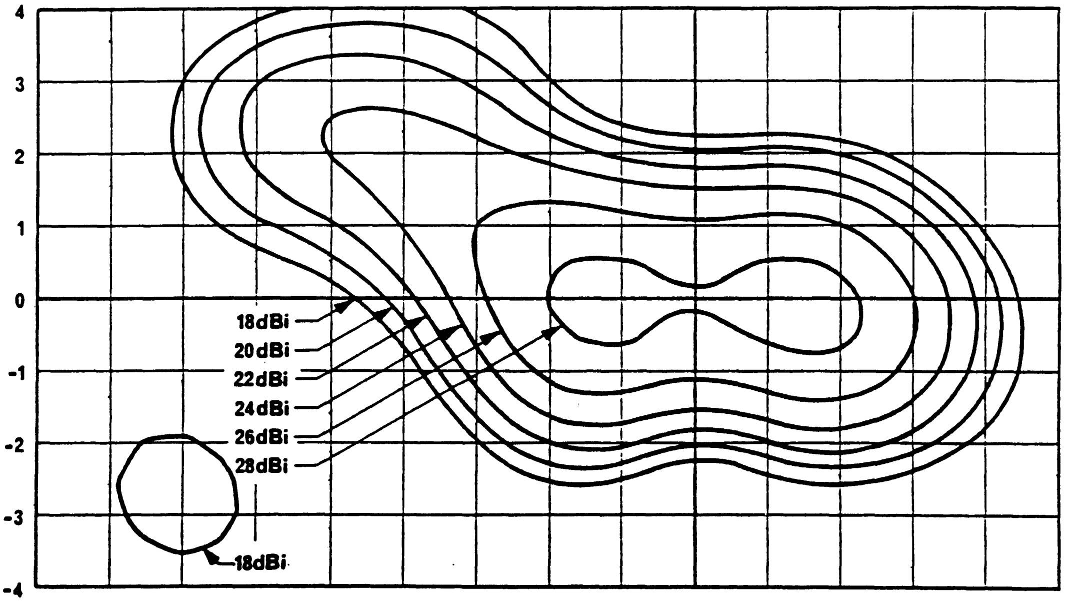


c) Variable power divider (VPD)

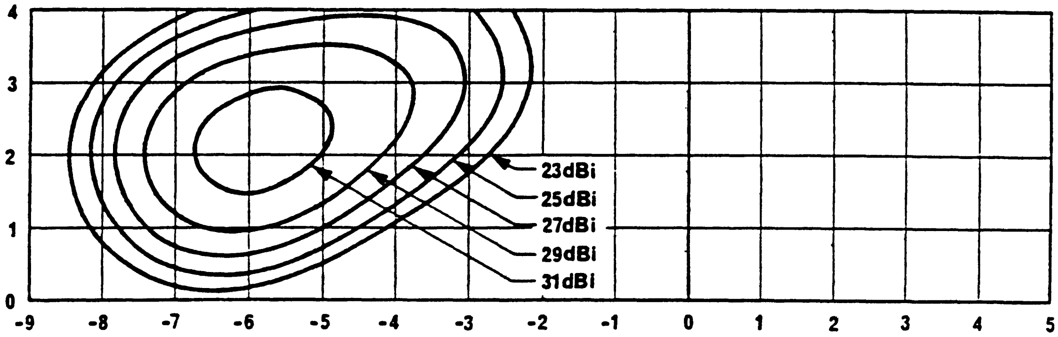
FIGURE 3 – *Reconfigurable antenna to service several service areas from a single orbital position*



a) 96° W (CONUS)



b) 119° W (CONUS/Alaska/Hawaii)



c) 139° W (Alaska only)

FIGURE 4 – *Typical footprints for different orbital positions*

CONUS: contiguous United States

3.2 Antennas for earth receiving equipment

This section gives the results of some measurements on antennas of a type suitable for individual or community reception. In addition, the results of some side-lobe suppression experiments are presented to justify the recommended -25 dB level for community-reception in the reference pattern.

3.2.1 Antenna sizes and types

In the 12 GHz band, a common form of antenna for individual reception is one with a conventional or offset parabolic reflector 0.3 to 1 m in diameter. Larger diameters may, however, be used for community reception. Two feed arrangements are possible; either an antenna with direct illumination, or a dual reflector assembly. The choice of diameter and of feed device may depend on economic considerations since for a given figure of merit (G/T), a lower antenna gain would necessitate a lower noise temperature for the receiving equipment. The antenna may be either of aluminium or a composite moulding, e.g., of plastics with a conductive coating or an embedded wire mesh. An effective surface accuracy of about 1 mm r.m.s. under all weather conditions is adequate, and the mounting must be sufficiently rigid to maintain correct pointing, e.g., better than 0.5° or 0.6° for the antenna dimensions envisaged (0.3 to 1 m).

"Flat-plate" antennas are also now of interest. They may have broadside or steerable beams. The advantage of such antennas is that they may be easier to support and maintain correctly pointed in high winds, and less susceptible to loss of gain from snow deposits on the antenna face. This would be particularly true of an antenna with a steered beam to provide the required elevation angle while the antenna is mounted in a vertical plane. A further refinement, whereby a phased-array antenna has a beam which may be steered away from broadside, permits the antenna to be mounted flat against the most suitable wall or roof of a building having arbitrary orientation. This arrangement would be less obtrusive and simple to install.

Broadside-beam flat-plate antennas have reached the stage whereby they are likely to be an economic alternative to dish antennas, and, in the smaller sizes at least, can offer an antenna efficiency comparable to that of a dish of similar size. At present the efficiency of larger arrays and steerable arrays tends to be lower than that of comparable dishes. In the future the low-noise amplifier may be incorporated into the antenna, with the first amplifier stages distributed through the feed structure to improve the loss performance.

The broadside-beam flat-plate antenna can offer gain and side-lobe performance equivalent to that of a parabola of comparable size. For many home installations, it also provides advantages over a parabolic antenna in terms of unobtrusive appearance, lightweight and ease of installation.

Recent development work in the United States, the United Kingdom and Japan has led to BSS receiving antenna designs using planar phased arrays [Sorbello, *et al.*, 1988; Wells, 1989; Sorbello and Zaghloul, 1989; Griffiths *et al.*, 1989; Maddocks, 1988]. The characteristics of these "flat antennas", including measured data on their co-polar and cross-polar patterns are described in § 3.2.3.

Along with various types of offset parabolic antennas, some flat-plate antennas have appeared in the market in Japan. The flat antenna offers advantages in shape and in convenience of installation to the wall of the houses, preventing snow accumulation, although there are many items to be studied, such as efficiency.

3.2.2 Measured data for parabolic antennas

Data extracted from measured antenna patterns for the co-polar component of parabolic antennas are shown in Fig. 5a. All the antennas were linearly polarized. The list of antennas from which the data was taken is given in Table II. The data is presented in groups. Each group is represented by a vertical bar spanning the range of gain variation of the sample of data points in that group. Such partitioning into groups is done with due caution to ensure that sufficient data is encompassed by each group. The upper circle on each vertical bar represents that point above which 20% of the data lies. The lower circle is the corresponding lower 20% point. The median is shown as an open circle. In addition to the measured data, Fig. 5a also includes a plot of the reference antenna pattern given in § 2.

Similar data extracted from a group of 3.3 m antennas at 12 GHz are shown in Fig. 5b. The antennas were linearly polarized. Median values fall well below curve A of Fig. 2 at all angles measured, and peak values fall below the reference pattern out to six or eight times the half-power beamwidth. These data were generated with no efforts made toward sidelobe suppression.

For antennas in the size and cost range considered suitable for broadcasting-satellite applications, it is unlikely that gains below isotropic will be consistently achieved in the far sidelobes and backlobes.

Measurement of radiation patterns of linearly polarized receiving antennas with a diameter of 40 cm to 1.6 m were carried out in Japan [CCIR, 1974-78f]. Figure 6 shows some measured data for a parabolic antenna with a diameter of 60 cm.

These results, and the test results obtained by the measurements of the patterns of antennas with 1.0 and 1.6 m diameters, which were manufactured with the objectives of high efficiency, light weight and low cost, show that the patterns for the co-polar components fall within the reference pattern for individual reception.

Measurements of the cross-polarized component were made on various kinds of parabolic antennas for D/λ between 40 and 100. The results are shown in Fig. 7. The data are presented in the same way as in Figs. 5a and 5b.

Measurements were performed in Canada on a centre-fed parabolic antenna. The antenna had a diameter of 1.2 m and was linearly polarized. The side-lobe patterns were measured in 1982 for the frequency band 11.7 - 12.2 GHz. The mid-band efficiency was found to be 72% and a scatter plot of the side-lobe peaks is shown in Fig. 8. The antenna side-lobe patterns were taken at three frequencies (edge and centre of the frequency band) and for two azimuthal profiles (E-plane and H-plane). The reference pattern adopted for Region 2 at the RARC SAT-83 is also shown for purposes of comparison [CCIR, 1982-1986b].

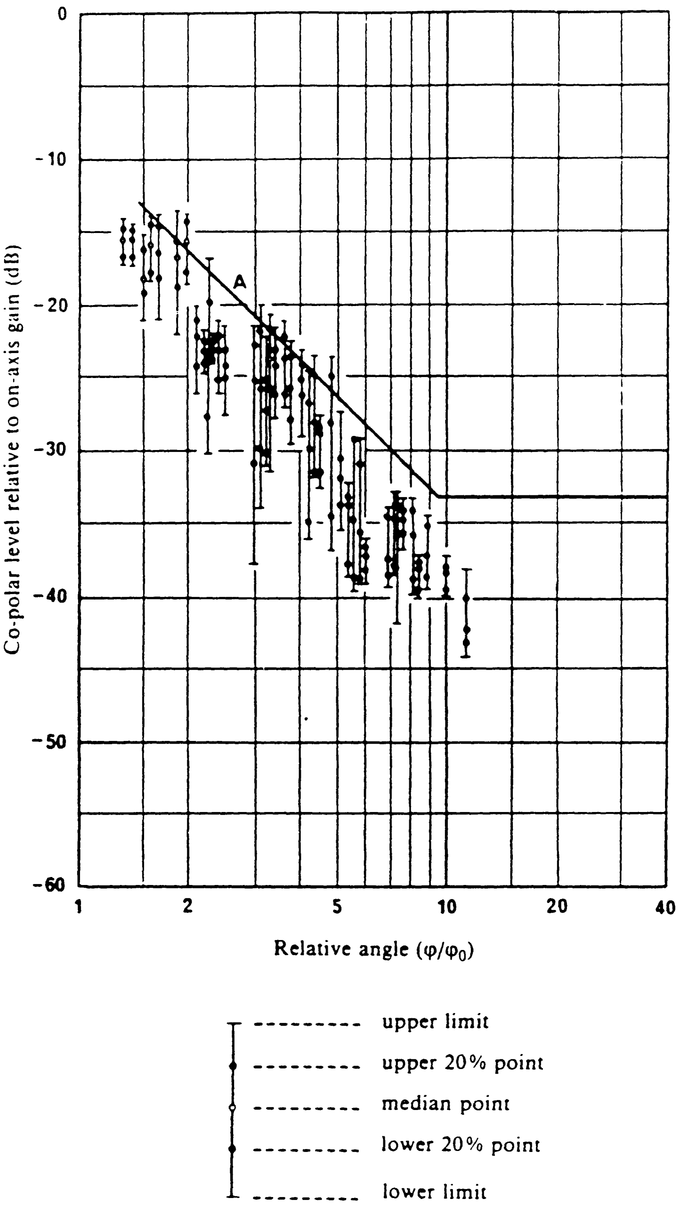
Analysis of limited data on the cross-polarized response of small-aperture antennas, where no special attention was paid to side-lobe levels, indicates that a minimum discrimination level of 20 dB is attainable, and the maximum level is 32 dB both on-axis and elsewhere. In the case where side-lobe suppression techniques are employed, the minimum level of discrimination can be reduced to 25 dB.

3.2.3 Characteristics and measured data for flat-plate antennas

The basic, single-polarized flat-plate antenna is constructed from three layers, as shown schematically in Fig. 9. There are two etched layers, one containing the receiving elements and the other the power divider or combining network. These layers are separated by plastic foam spacers, and a foam spacer also separates the power divider network layer from the ground plane.

FIGURE 5a

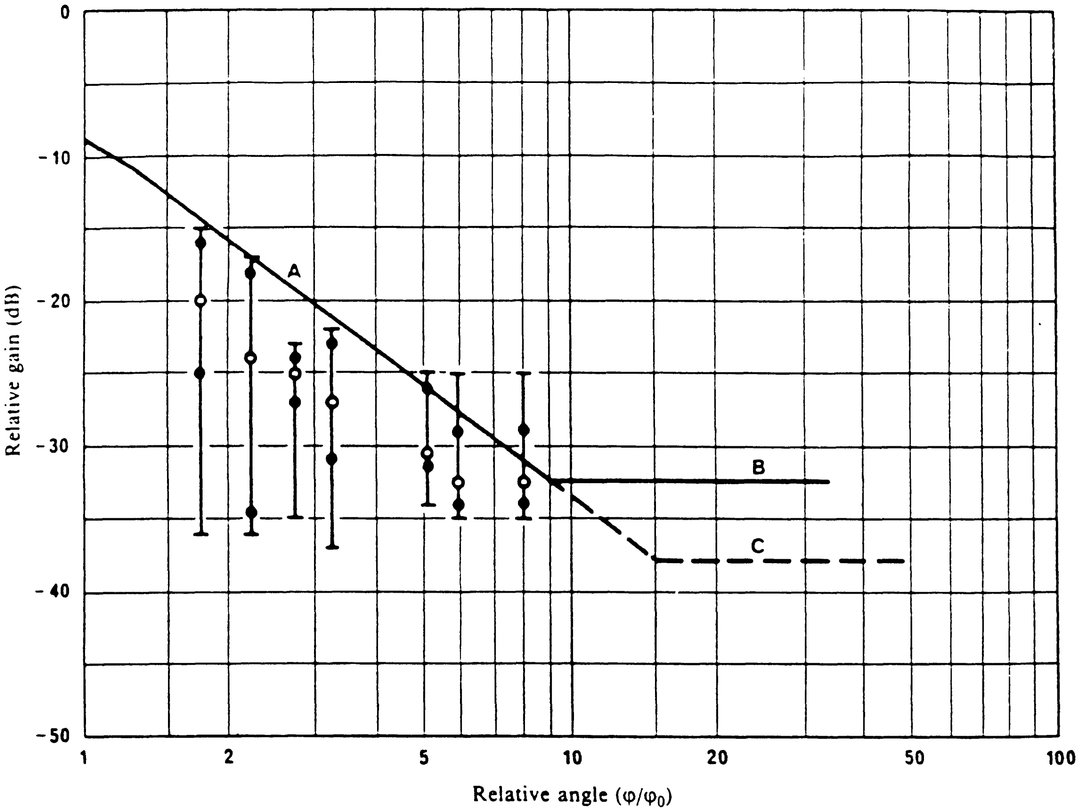
Measured co-polar peak side-lobe levels and reference antenna pattern



Curve A: reference pattern for individual reception

FIGURE 5b

Measured co-polar peak side-lobe levels and reference earth station antenna pattern at 12 GHz

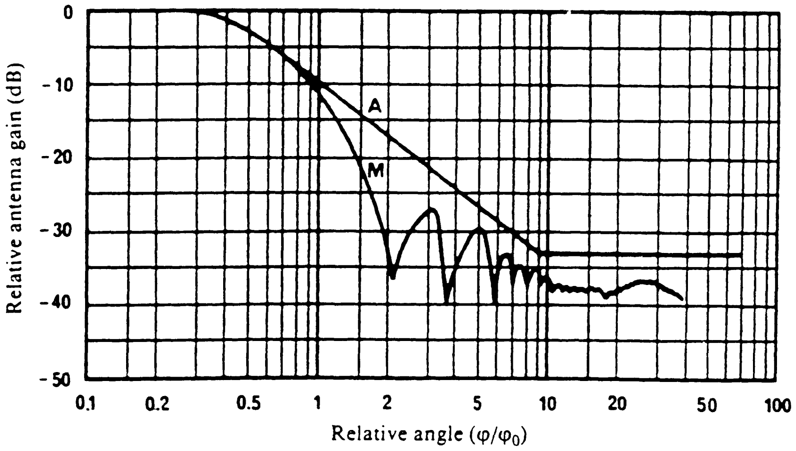


Curves A: reference pattern for individual reception
B: Regions 1 and 3
C: Region 2

┬ — upper limit
● — upper 20% point
○ — median point
● — lower 20% point
┴ — lower limit

FIGURE 6

An example of co-polar pattern of a terrestrial parabolic antenna (12 GHz)

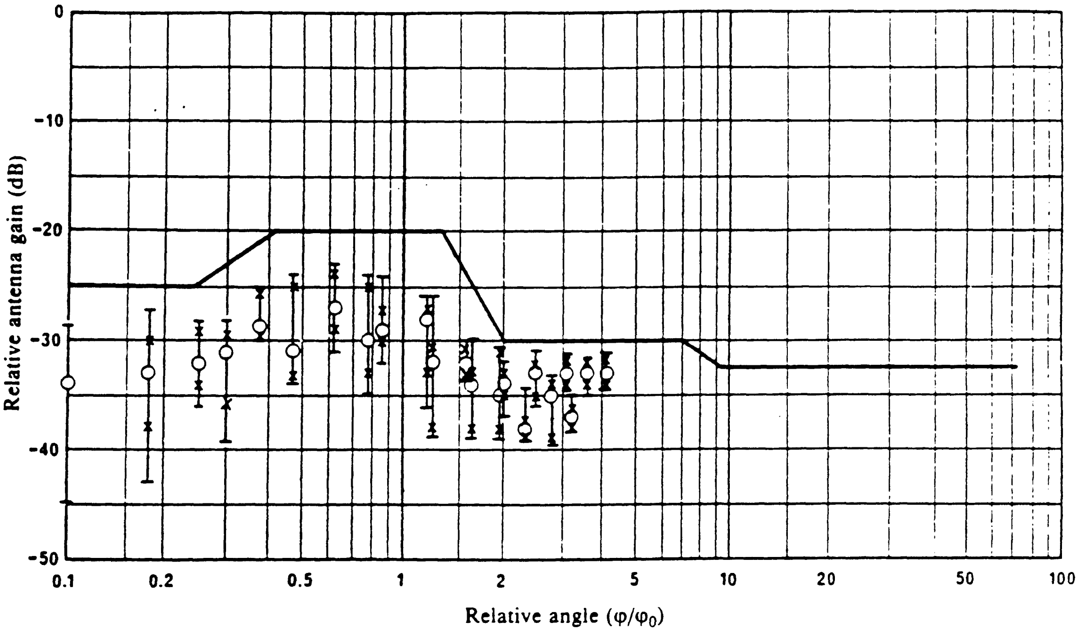


Curves A: reference pattern for individual reception

M: measured results for a 60 cm parabolic antenna

FIGURE 7

Measured data for cross-polar response



———— reference pattern

----- upper limit

----- upper 20% point

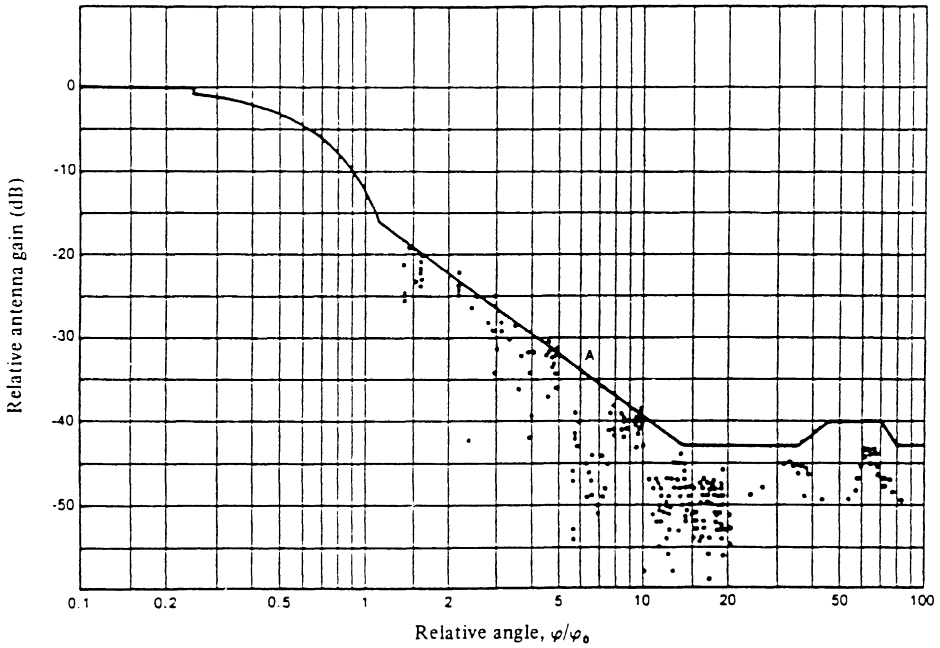
----- median point

----- lower 20% point

----- lower limit

FIGURE 8

Co-polar side-lobe levels measured on a 1.2 m centre-fed antenna at 12 GHz (φ_0 = 1.46°)



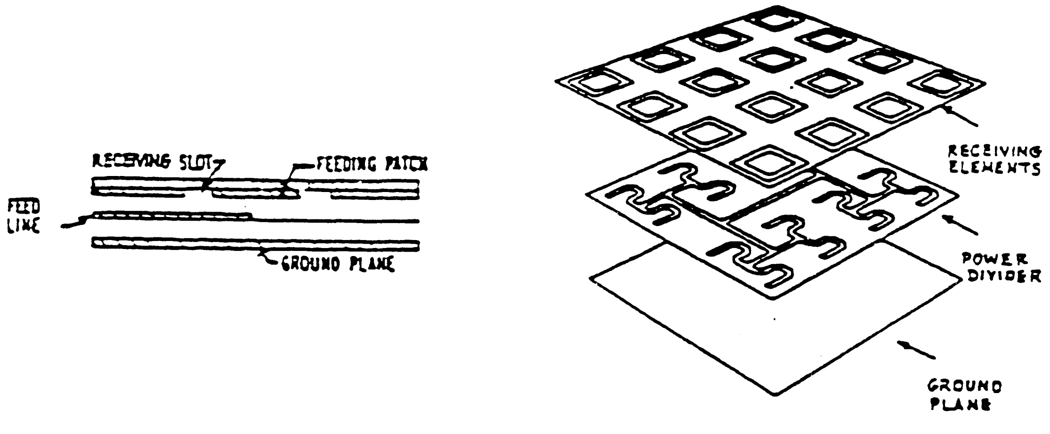
Curve A: co-polar component of the antenna reference pattern adopted at the RARC SAT-83 for Region 2

Two aspects of this construction lend themselves to the low manufacturing costs that are essential for a consumer electronics product. One is the etched layers, which are easily mass produced. The other is the capacitive coupling between the receiving elements and the power divider, which avoids the requirement of physical connections.

The physical and principal electrical characteristics of a family of commercially available models of the flat-plate antenna are given in Table 2. It will be noted that the gain and efficiency of these antennas are comparable to those of parabolic antennas of the same cross-section. Side-lobe performance is also comparable to that of parabolic antennas as discussed below.

FIGURE 9

Schematic representation of the construction of a flat antenna array for reception of satellite broadcasts



Measured data on the co-polar and cross-polar patterns of production models of the 256-element, 41 cm square array are shown and compared with the reference patterns of Recommendation 652 in Fig. 10. The 256-element antenna is chosen for illustration because, as the smallest of the family of flat-plate arrays, it is the one most vulnerable to interference from adjacent satellites.

The patterns in Fig. 10 are measured in a plane that contains the beam axis and is 45° to the principal planes of the array. They are representative of the patterns measured in all planes containing the beam axis that are more than 15° away from the principal planes. These are the patterns of most interest from an interference standpoint because, with circular polarization as prescribed in the Plans for the BSS at 12 GHz, the antenna can always be mounted so that all significant sources of satellite interference lie at least 15° from the principal planes. Indeed, this will normally be the case if the antenna is mounted with its edges horizontal and vertical, because the orbital position assigned to each country in the BSS Plans lies from 15° to 40° west of the longitude of the service area for that country.

TABLE 2

Characteristics of a family of flat-plate antennas

Characteristic	Number of radiating elements 256	384	256	1 024
Frequency range (GHz)	11.7 - 12.2	11.7 - 12.0	11.7 - 12.5	11.2 - 11.45
Dimensions of panel (cm)**	41 x 41	42 x 60	41 x 41	78 x 78
Thickness (cm)	2	2.5	2	2.5
Weight (kg)	2.3	5	2.3	9
Gain (dBi)	32.5	34.5	31	37
Efficiency (%)	>65	>60	>55	>50
Polarization*	R or L	R or L	R or L	V and H
On-axis cross-pol. discrim. (dB)	-20	-20	-25	-25
Beam squint angle (°)	0	0 or 12	0	0
Half-power beamwidths (°)	4 x 4	4 x 2.7	4 x 4	2 x 2
Noise figure of LNB (dB)	1.6	1.6	1.6	1.6
G/T ant (dB(K)$^{-1}$)	9.8	11.4	8.5	13.2

* R = right-hand circular;
L = left-hand circular;
V = vertical linear;
H = horizontal linear.

** These are the overall dimensions of the panel including the supporting frame; the dimensions of the active area of the array are about 4 cm less.

FIGURE 10

Measured side-lobe patterns of 256-element flat antenna in a plane which contains the beam axis but is 45° to the principal planes of array

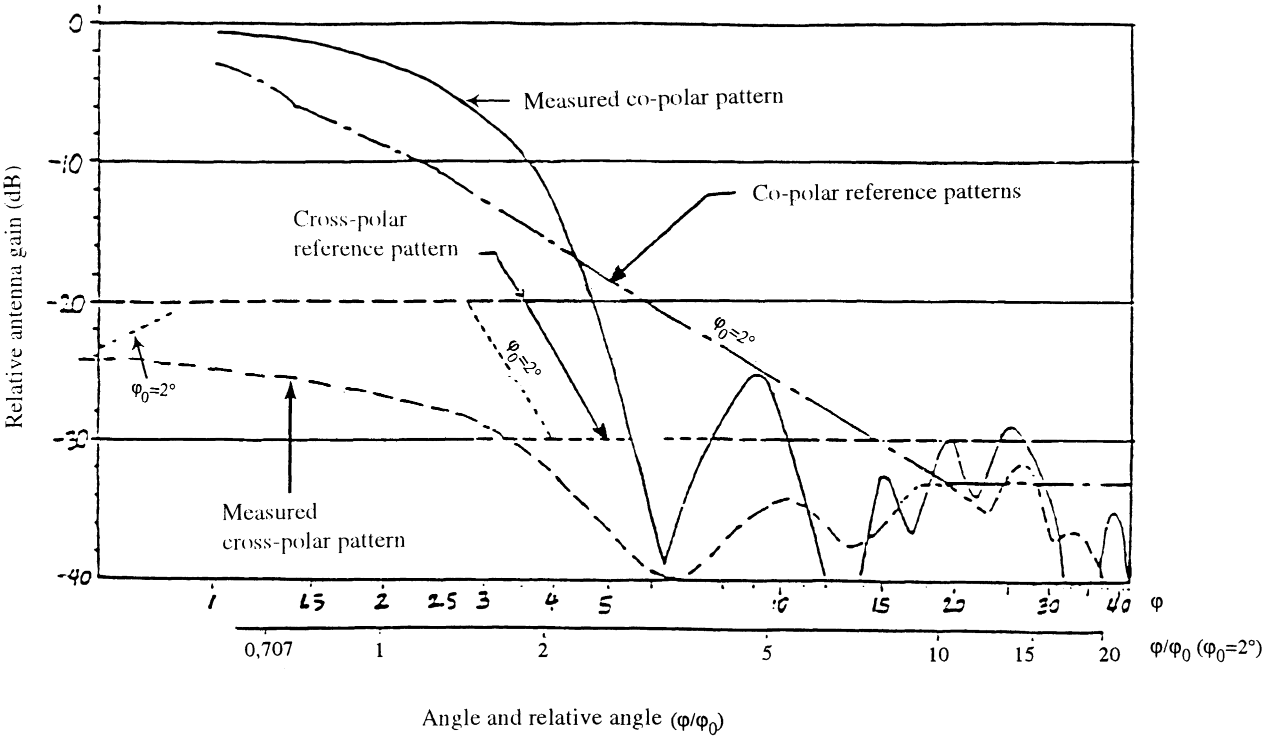


Figure 10 also displays the co-polar and cross-polar reference patterns for individual reception earth station antennas in Regions 1 and 3 as given in Recommendation ITU-R BO.652 and § 3.7.2 of Appendix 30 (ORB-85) of the Radio Regulations.

These reference patterns assume a half-power beamwidth φ_0 = 2°, the half-power beamwidth assumed for interference calculations in constructing the Regions 1 and 3 Plan at WARC-77.

It is seen that, even though the 256-element flat-plate antenna has a half-power beamwidth of 4°, its cross-polar side-lobe pattern conforms to the φ_0 = 2° reference at all off-axis angles greater than 0.5° (except at 27° where it exceeds the reference by 1.6 dB), and the co-polar pattern conforms out to an off-axis angle of 18°. Even beyond this angle, where adjacent satellite power-flux densities are expected to be low, the flat-plate antenna exceeds the reference by only about 3 dB.

3.2.4 Side-lobe suppression techniques for parabolic antennas

There are numerous ways to reduce side lobes, ranging from extremely simple to extremely complicated [Han, 1972].

A reduction can be achieved by increasing the taper of the feed pattern across the aperture of the reflector [Han, 1972; Silver, 1949]. The penalty paid is a loss of on-axis gain, but overall efficiencies of 50% are still achievable. With simple under-illumination, the side-lobe levels are reduced in all planes of rotation about the boresight.

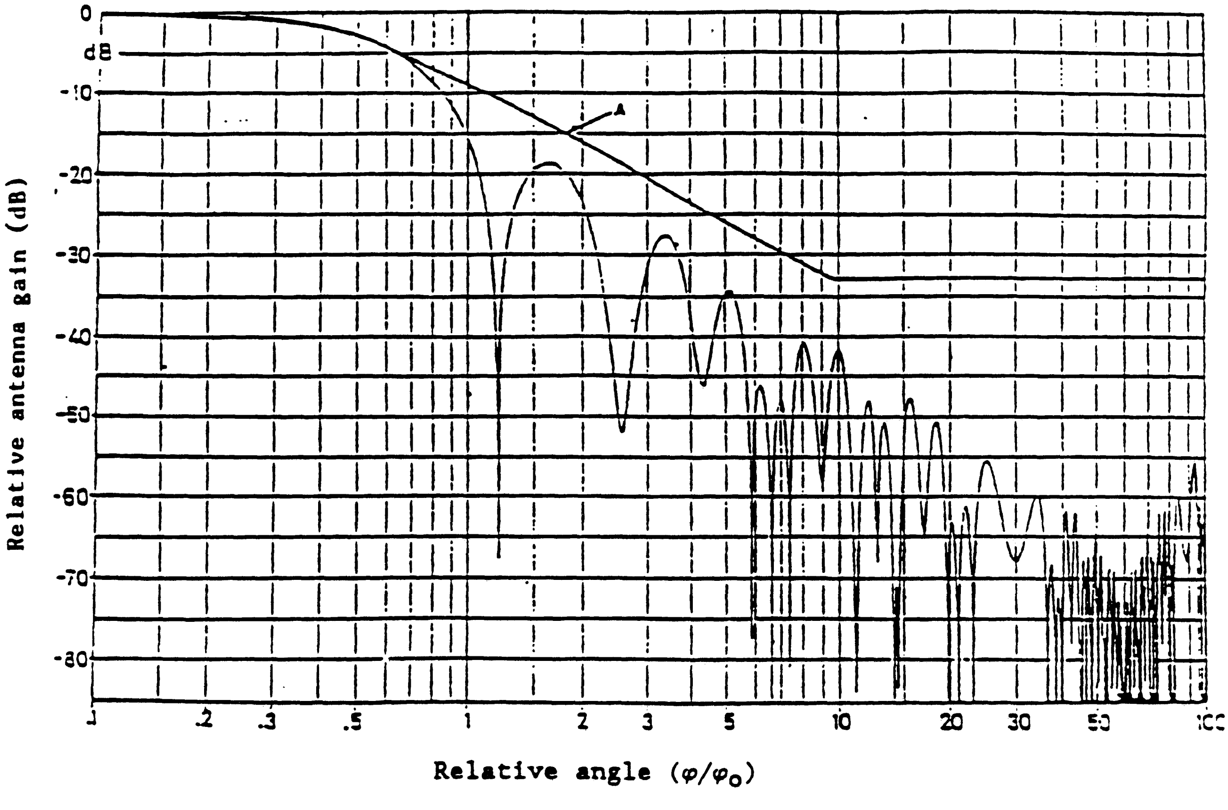
Recent analyses in Italy have demonstrated the effect of using corrugated surfaces on the performance of parabolic antennas. With such surfaces, it is possible to obtain radiation patterns equal in the two main planes, high cross-polar isolation, reduced side lobes, low spillover, and correspondingly lower antenna noise temperatures and higher aperture efficiencies (sometimes higher than 70%).

The computed co-polar radiation pattern for a 60 cm parabolic antenna with a corrugated flange is shown in Fig. 11. This pattern is seen to lie at least 3.5 dB below the corresponding WARC-77 reference for all relative angles φ/φ_0 greater than 1 [Pacini, 1985].

In theory, a circular aperture with uniform illumination results in side lobes some 15 dB below the peak of the secondary pattern. With an aperture distribution proportional to $(1 - \gamma/2)$, where γ is the radial function normalized to the aperture radius, the side lobes drop to 24.5 dB below the pattern peak. Patterns at 6 GHz using a 1.22 m dish with an aperture edge illumination of -12 dB, show first side lobes 26 dB below the main lobe peak [Silver, 1949]. If the feed remains at the focus of the reflector and a portion of the reflector is removed, thereby creating an offset-fed reflector, the side lobes can be lowered an additional several dB because the aperture blockage is reduced. However, the aperture is also reduced so that the main beam is broadened and reduction in gain occurs. This can be compensated for by increasing the size of the reflector. Side-lobe data measured on several offset-fed reflectors is shown in Fig. 12. The curves represent the peak side-lobe envelope for each antenna. All of the data lies substantially below Curve A' of Fig. 2. The antennas had efficiencies ranging from 63% to 70% [CCIR, 1982-1986c].

FIGURE 11

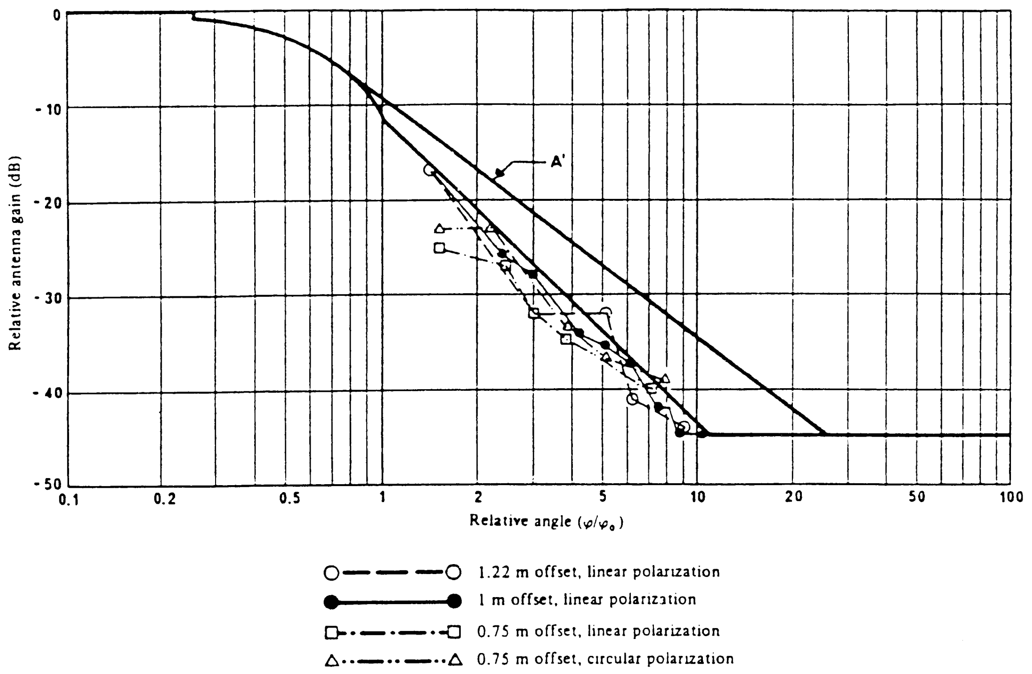
Radiation pattern computed for a 60 cm diameter parabolic dish implemented with corrugated flange



Note 1 - Curve A is the WARC-77 co-polar reference pattern for individual reception.

FIGURE 12

Composite side-lobe envelopes for offset-fed reflectors



Another method of side-lobe reduction in one plane is through the use of a duopod feed support. The duopod is a two-armed rigid feed support oriented in one plane with guy-wire support in the orthogonal plane. In operation, the low side-lobe plane is aligned with the equatorial plane, thus reducing side-lobe levels in the direction of neighbouring satellites. This duopod construction provides low side lobes in the plane of the supports because the blockage discontinuity in the aperture plane is smallest in this plane [EDUTEL, 1977]. Envelope A" of Fig. 2 can be met easily in the equatorial plane with a duopod-supported feed antenna.

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