

RECOMMENDATION ITU-R S.672-4*

**Satellite antenna radiation pattern for use as
a design objective in the fixed-satellite service
employing geostationary satellites**

(1990-1992-1993-1995-1997)

The ITU Radiocommunication Assembly,

considering

- a) that the use of space-station antennas with the best available radiation patterns will lead to the most efficient use of the radio-frequency spectrum and the geostationary orbit;
- b) that both single feed elliptical (or circular) and multiple feed shaped beam antennas are used on operational space stations;
- c) that although improvements are being made in the design of space-station antennas, further information is still required before a reference radiation pattern can be adopted for coordination purposes;
- d) that the adoption of a design objective radiation pattern for space-station antennas will encourage the fabrication and use of orbit-efficient antennas;
- e) that it is only necessary to specify space-station antenna radiation characteristics in directions of potential interference for coordination purposes;
- f) that for wide applicability the mathematical expressions should be as simple as possible consistent with effective predictions;
- g) that nevertheless, the expressions should account for the characteristics of practical antenna systems and be adaptable to emerging technologies;
- h) that measurement difficulties lead to inaccuracies in the modelling of spacecraft antennas at large off-axis angles;
- j) that the size constraints of launch vehicles lead to limitations in the D/λ values of spacecraft antennas, particularly at lower frequencies such as the 6/4 GHz band;
- k) that space-station antenna pattern parameters such as reference point, coverage area, equivalent peak gain, that may be used to define a space-station reference antenna pattern, are found in Annex 1;
- l) that two computer programs have been developed to generate coverage contours (see Annex 2),

* Radiocommunication Study Group 4 made editorial amendments to this Recommendation in 2001 in accordance with Resolution ITU-R 44 (RA-2000).

recommends

1 that for single feed circular or elliptical beam spacecraft antennas in the fixed-satellite service (FSS), the following radiation pattern should be used as a design objective, outside the coverage area:

$$G(\psi) = G_m - 3 (\psi / \psi_b)^\alpha \quad \text{dBi} \quad \text{for} \quad \psi_b \leq \psi \leq a \psi_b \quad (1)$$

$$G(\psi) = G_m + L_N + 20 \log z \quad \text{dBi} \quad \text{for} \quad a \psi_b < \psi \leq 0.5 b \psi_b \quad (2a)$$

$$G(\psi) = G_m + L_N \quad \text{dBi} \quad \text{for} \quad 0.5 b \psi_b < \psi \leq b \psi_b \quad (2b)$$

$$G(\psi) = X - 25 \log \psi \quad \text{dBi} \quad \text{for} \quad b \psi_b < \psi \leq Y \quad (3)$$

$$G(\psi) = L_F \quad \text{dBi} \quad \text{for} \quad Y < \psi \leq 90^\circ \quad (4a)$$

$$G(\psi) = L_B \quad \text{dBi} \quad \text{for} \quad 90^\circ < \psi \leq 180^\circ \quad (4b)$$

where:

$$X = G_m + L_N + 25 \log (b \psi_b) \quad \text{and} \quad Y = b \psi_b 10^{0.04(G_m + L_N - L_F)}$$

$G(\psi)$: gain at the angle ψ from the main beam direction (dBi)

G_m : maximum gain in the main lobe (dBi)

ψ_b : one-half the 3 dB beamwidth in the plane of interest (3 dB below G_m) (degrees)

L_N : near-in-side-lobe level in dB relative to the peak gain required by the system design

$L_F = 0$ dBi far side-lobe level (dBi)

z : (major axis/minor axis) for the radiated beam

L_B : $15 + L_N + 0.25 G_m + 5 \log z$ dBi or 0 dBi whichever is higher.

NOTE 1 – Patterns applicable to elliptical beams require experimental verification. The values of a in Table 1 are provisional.

TABLE 1

L_N (dB)	a	b	α
-20	$2.58 \sqrt{(1 - \log z)}$	6.32	2
-25	$2.58 \sqrt{(1 - 0.8 \log z)}$	6.32	2
-30	–	6.32	–

The numeric values of a , b , and α for $L_N = -20$ dB and -25 dB side-lobe levels are given in Table 1. The values of a and α for $L_N = -30$ dB require further study. Administrations are invited to provide data to enable the values of a and α for $L_N = -30$ dB to be determined;

2 that for multiple-feed, shaped beam, spacecraft antennas in the FSS, the radiation pattern to be used as a design objective shall be selected from the following formulae depending upon the class of antenna and the range of the scan ratio.

Definition of class of antennas

- Definition of class A antennas:

Class A antennas are those with the boresight location within the coverage area.

- Definition of class B antennas:

Class B antennas are those with the boresight location outside the coverage areas for one or more of the beams.

Definition of scan ratio

There are two definitions of the scan ratio:

The scan ratio δ in § 2.1 is defined as the angular distance between the centre of coverage (defined as the centre of the minimum area ellipse) and a point on the edge-of-coverage, divided by the beamwidth of the component beam.

Scan ratio S used in § 2.2 and 2.3 is defined as the angular distance between the antenna boresight and a point on the edge-of-coverage, divided by the beamwidth of the component beam.

In the initial determination of which *recommends* is applicable to a specific class A antenna, the δ scan ratio definition should be used;

2.1 for class A antennas with scan ratio values $\delta \leq 3.5$:

$$G_{\text{dBi}}(\Delta\psi) = \begin{cases} G_{ep} + 0.256 - 13.065 \left(\frac{\Delta\psi}{Q \psi_0} + 0.5 \right)^2 & \text{for } 0 \leq \frac{\Delta\psi}{\psi_0} \leq 0.8904 Q \\ G_{ep} - 25 & \text{for } 0.8904 Q < \frac{\Delta\psi}{\psi_0} \leq 1.9244 Q \\ G_{ep} - 25 + 20 \log \left(\frac{1.9244 Q \psi_0}{\Delta\psi} \right) & \text{for } 1.9244 Q < \frac{\Delta\psi}{\psi_0} \leq 18/\psi_0 \end{cases}$$

where:

$\Delta\psi$: angle (degrees) from the convex coverage contour to a point outside the coverage region in a direction normal to the sides of the contour

G_{ep} : equivalent peak gain (dBi)

$$= G_e + 3.0$$

ψ_0 : the half-power beamwidth of component beams (degrees)

$$= 72 (\lambda/D)$$

λ : wavelength (m)

D : physical diameter of the reflector (m)

$$Q = 10^{\left(\frac{0.000075 (\delta - 1/2)^2}{[(F/D_p)^2 + 0.02]^2} \right)}$$

δ : scan ratio as defined in § 2

F/D_p : ratio of the reflector focal length F to parent parabola diameter D_p

$$D_p = 2(d + h)$$

d : projected aperture diameter of the offset paraboloid

h : offset height to the edge of the reflector;

2.2 that for class A antennas with scan ratio values $S \geq 5$:

$$G_{\text{dBi}}(\Delta\psi) = \begin{cases} G_e - B \left[\left(1 + \frac{\Delta\psi}{\psi_b} \right)^2 - 1 \right] & \text{for } 0^\circ \leq \Delta\psi \leq C \psi_b \\ G_e - 22 & \text{for } C \psi_b < \Delta\psi \leq (C + 4.5) \psi_b \\ G_e - 22 + 20 \log_{10} \left[\frac{(C + 4.5) \psi_b}{\Delta\psi} \right] & \text{for } (C + 4.5) \psi_b < \Delta\psi \leq 18^\circ \end{cases}$$

where:

$\Delta\psi$: angle (degrees) from the convex coverage contour in a direction normal to the sides of the contour

G_e : gain at the edge-of-coverage (dBi)

$$B = B_0 - (S - 1.25) \Delta B \text{ for } S \geq 5$$

$$B_0 = 2.05 + 0.5 (F/D - 1) + 0.0025 D/\lambda$$

$$\Delta B = 1.65 (D/\lambda)^{-0.55}$$

ψ_b : beamlet radius

$$= 36 \lambda/D$$

λ : wavelength (m)

D : physical diameter of the reflector (m)

$$C = \sqrt{1 + \frac{22}{B}} - 1$$

S : scan ratio as defined in § 2

F/D : ratio of focal length over the physical diameter of the antenna;

2.3 that for class B antennas, which only use scan ratio S (for $S \geq 0$):

$$G_{\text{dBi}}(\Delta\psi) = \begin{cases} G_e - B \left[\left(1 + \frac{\Delta\psi}{\psi_b} \right)^2 - 1 \right] & \text{for } 0^\circ \leq \Delta\psi \leq C \psi_b \\ G_e - 17 + 18.7012 \log_{10} \left(\cos \left[\frac{\Delta\psi - C \psi_b}{\psi_b} \right] \right) & \text{for } C \psi_b < \Delta\psi \leq (C + 1) \psi_b \\ G_e - 22 & \text{for } (C + 1) \psi_b < \Delta\psi \leq (C + 4.5) \psi_b \\ G_e - 22 + 20 \log_{10} \left[\frac{(C + 4.5) \psi_b}{\Delta\psi} \right] & \text{for } (C + 4.5) \psi_b < \Delta\psi \leq 18^\circ \end{cases}$$

where:

$\Delta\psi$: angle (degrees) from the convex coverage contour in a direction normal to the sides of the contour

G_e : gain at the edge-of-coverage (dBi)

$$B = B_0 - (S - 1.25) \Delta B \text{ for } S \geq 0$$

$$B_0 = 2.05 + 0.5 (F/D - 1) + 0.0025 D/\lambda$$

$$\Delta B = 1.65 (D/\lambda)^{-0.55}$$

ψ_b : beamlet radius

$$= 36 \lambda/D$$

λ : wavelength (m)

D : physical diameter of the reflector (m)

$$C = \sqrt{1 + \frac{17}{B}} - 1$$

S : scan ratio as defined in § 2

F/D : ratio of focal length over the physical diameter of the antenna;

2.4 that for class A antennas with scan ratio values $\delta > 3.5$ and $S < 5$, the design objective is still under study. In particular, studies are required on the extension of the equations given in § 2.1 and 2.2 into this region. One possible method of extending the design objective into this region is described in Annex 1. For the definition of scan ratios δ and S and their application, see § 2;

2.5 that the following Notes shall be considered part of § 2.1 and 2.2:

NOTE 1 – The coverage area shall be defined as the contour constructed from the polygon points surrounding the service area, using the method given in Annex 2.

NOTE 2 – For the cuts, where the –3 dB gain contour is outside of the constructed coverage contour, the design objective pattern should originate from the –3 dB contour.

NOTE 3 – This Recommendation should be applied only in the direction of an interference sensitive system. That is, it need not be applied in directions where the potential for interference to other networks does not exist (e.g. off the edge of the Earth, unpopulated ocean regions). 10% of the cuts may exceed the design objective pattern.

NOTE 4 – This Recommendation does not apply to dual frequency band antennas. Antennas using the reflector induced phase error for beam broadening belong to this category and require further study.

ANNEX 1

Satellite antenna patterns in the fixed-satellite service

1 Satellite antenna reference radiation patterns

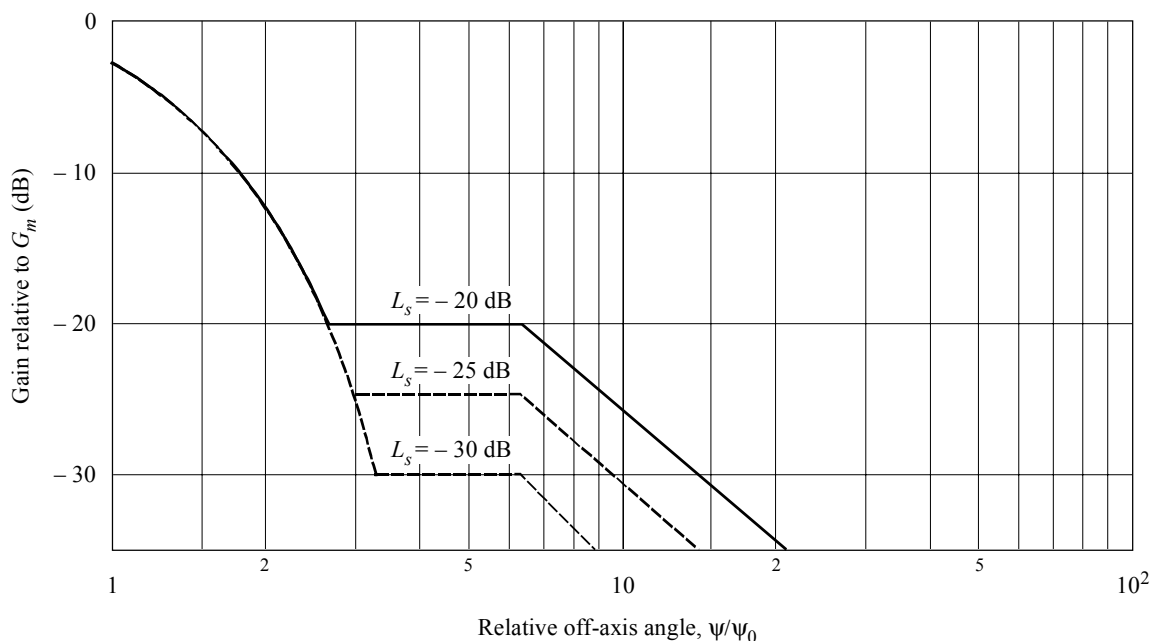
1.1 Single feed circular beams

The radiation pattern of the satellite antenna is important in the region of the main lobe as well as the farther side lobes. Thus, the possible patterns commencing at the –3 dB contour of the main lobe are divided into four regions. These are illustrated in Fig. 1.

Difficulties arise, however, in attempting to apply the postulated pattern to a non-circular beam. Administrations are therefore requested to submit measured radiation patterns for antennas with other than simple circular beams.

FIGURE 1

Radiation pattern envelope functions



$$G(\psi) = G_m - 3 (\psi/\psi_0)^2 \quad \text{dBi} \quad \text{for} \quad \psi_0 \leq \psi \leq a \psi_0 \quad \text{(I)}$$

$$G(\psi) = G_m + L_s \quad \text{dBi} \quad \text{for} \quad a \psi_0 < \psi \leq b \psi_0 \quad \text{(II)}$$

$$G(\psi) = G_m + L_s + 20 - 25 \log (\psi/\psi_0) \quad \text{dBi} \quad \text{for} \quad b \psi_0 < \psi \leq \psi_1 \quad \text{(III)}$$

$$G(\psi) = 0 \quad \text{dBi} \quad \text{for} \quad \psi_1 < \psi \quad \text{(IV)}$$

where:

$G(\psi)$: gain at the angle (ψ) from the axis (dBi)

G_m : maximum gain in the main lobe (dBi)

ψ_0 : one-half the 3 dB beamwidth in the plane of interest (3 dB below G_m) (degrees)

ψ_1 : value of (ψ) when $G(\psi)$ in equation (III) is equal to 0 dBi

L_s : the required near-in-side-lobe level (dB) relative to peak gain

a, b : the numeric values are given below:

L_s	a	b
-20	2.58	6.32
-25	2.88	6.32
-30	3.16	6.32

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1.2 Single feed elliptical beams

The functions in Fig. 1 define a maximum envelope for the first side lobes at a level of -20 dB relative to peak gain and this pattern applies to antennas of fairly simple designs. However, in the interest of a better utilization of the orbit capacity, it may be desirable to reduce this level to -30 dB and to use antennas of more sophisticated design. The pattern adopted by the World Administrative Radio Conference for the Planning of the Broadcasting-Satellite Service, Geneva, 1977 (WARC BS-77) for broadcasting satellite antennas meets this requirement and is now being achieved and

should therefore apply in that case. Additional studies may be desirable to ascertain the feasibility of achieving these reduced side-lobe levels in common practice, particularly with respect to the 6/4 GHz bands.

1.3 Multiple feed shaped beams

A similar pattern applicable to shaped beams must be based on analysis of several shaped beams and also on theoretical considerations. Additional parameters must be specified, such as the diameter of the elemental beamlet and the level of the first side lobe. In addition the cross-section and means of measuring angles form part of the pattern definition.

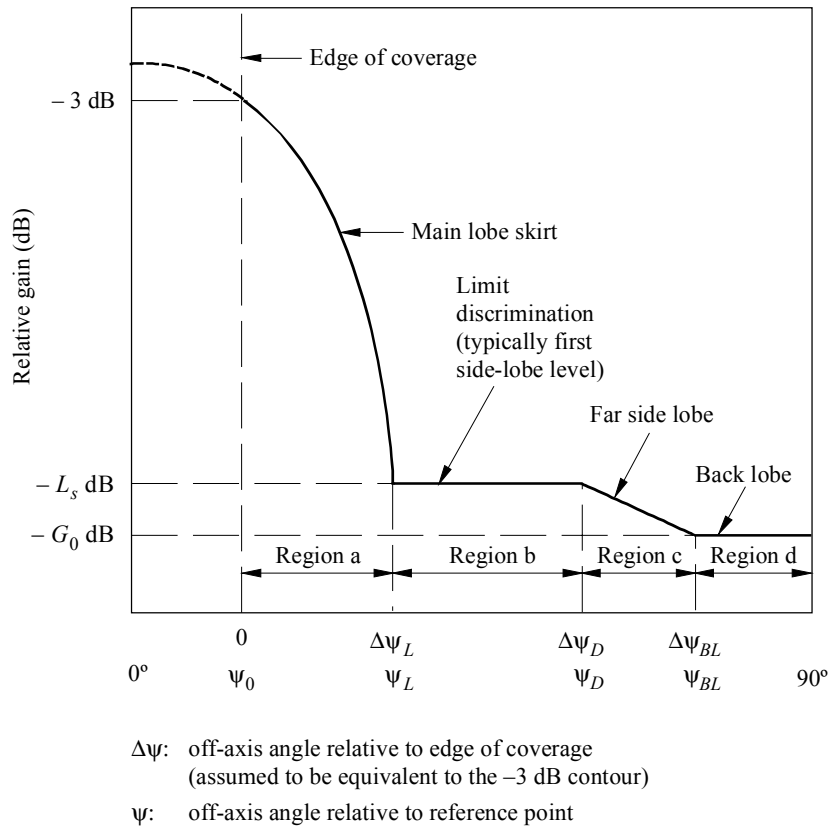
The important consideration in producing such a reference is the discrimination to be achieved from the edge of coverage of all types of antenna, including the most complex shaped beam antenna, as a function of angular separation of the coverage areas as seen from the orbit. The radiation pattern of a shaped beam antenna is unique and it is mainly determined by the following operational and technical factors:

- shape of the coverage area;
- satellite longitude;
- maximum antenna aperture;
- feed design and illumination taper;
- normalized reflector aperture diameter (D/λ);
- focal length to aperture diameter ratio (F/D);
- number of frequency re-use and independent beam ports;
- number of feed elements utilized;
- bandwidths;
- polarization orthogonality requirements;
- total angular coverage region provided;
- stability of feed element phase and amplitude excitations;
- reconfigurability requirements;
- number of orbital positions from which beam coverages must be provided;
- reflector surface tolerances achieved;
- beam pointing (i.e. derived from satellite or independent beam positioning via earth-based tracking beacons);
- component beam degradations due to scan aberrations that are related to the specific reflector or antenna configuration (i.e. single reflector, dual reflector, shaped reflector systems without a focal axis, direct radiating array, etc.).

In view of this, there may be some difficulties in developing a single reference radiation pattern for shaped beam antennas.

The reference pattern of Fig. 1 is unsatisfactory for shaped beam antennas, since a key parameter to the reference pattern is ψ_0 , the -3 dB half-beamwidth, whereas the beam centre of a shaped beam is ill-defined and largely irrelevant to the out-of-beam response. A simple reference pattern consisting of four segments, as illustrated in Fig. 2 might be more satisfactory for the basis of a reference pattern. The slope of the skirt of this pattern would be a function of the angular distance outside the average contour.

FIGURE 2
Possible form of reference radiation pattern



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The particular direction in which to measure this angular distance is also a parameter which needs definition. One method is to measure this angle orthogonally from the constant gain contour which corresponds most closely to the coverage area. Difficulties arise with this method where portions of the gain contours are concave such as occurs with crescent-shaped patterns. For this type of pattern, the orthogonal direction away from a contour could intersect the coverage area again. From an antenna design standpoint, the difficulty in achieving good discrimination in the concave portion of a pattern increases with the degree of concavity. An alternative method which could circumvent these problems is to circumscribe the coverage area by a contour which has no concavity and then measure the angles orthogonally from this contour; this contour being considered as edge of coverage. Other methods of defining the direction of measurement are possible, e.g. the centre of a circumscribing ellipse could be used as a reference point (see § 2.1 and 2.2), but an unambiguous definition is needed for any reference pattern.

Once the direction is defined, the radiation pattern can be separated into four regions of interest:

Region a: Main lobe skirt (edge of coverage to angle of limit discrimination)

This region is assumed to cover what is considered to be adjacent coverage regions. The required isolation between satellite networks would be obtained from a combination of satellite antenna discrimination and orbital separation.

A simple function which could be applied to this region could be in a form similar to that given in equation (I) of Fig. 1.

Region b: Non-adjacent coverage region

This region begins where the radiation pattern yields sufficient discrimination to allow nearly co-located satellites to serve non-adjacent areas ($\Delta\psi_L$ in Fig. 2). The limit discrimination (L_s) may be between -20 and -30 dB.

Region c: Far side-lobe region**Region d:** Back-lobe region

Each of these regions covers the higher order side lobes and is applicable to very widely spaced service areas and, in those frequency bands used bidirectionally, to parts of the orbit. In the latter case, care must be exercised when considering very large off-axis angles since unpredictable reflections from the spacecraft bus and spill-over from the main reflector might have significant effect. A minimum gain envelope of 0 dBi is suggested pending more information (Region d in Fig. 2).

2 Shaped beam radiation pattern models

For shaped beam modelling purposes, prior to the actual design of an antenna, a simplified reference pattern might be used. Two models which can generate such patterns and their associated parameters are presented below. Both models are suitable for computer-aided interference studies and, in conjunction with satellite centred maps, for manual application. The models form the basis of a recommended pattern or patterns. However, it would be advisable to only apply the resultant pattern “profiles” in the direction of an interference sensitive system. That is, they should not be applied in directions where the potential for interference to other networks does not exist (i.e. off the edge of the Earth, unpopulated ocean regions, etc.).

2.1 Representation of coverage area

Various methods have been proposed in the past for the service area representation of FSS antennas. In one method, the angular distance outside the coverage area is measured in a direction normal to the service area geography (constant gain contour) as seen from the satellite. In practice, the gain contour is designed to fit the service area as closely as possible and therefore the difference between using the service area and the constant gain contour is expected to be very small. However, difficulties will arise with this method in certain cases where portions of gain contours are concave such as with crescent shaped patterns. For such patterns, the orthogonal direction away from the contour could intersect the coverage area again thereby causing ambiguity (see Fig. 3a)). Another difficulty with this representation is that for a given location outside the coverage area, there could be more than one point on the service area at which the line joining the observation location to the point on the service area is normal to the service area contour at that point (see Fig. 3a)).

However, a method has been developed which circumvents the difficulties cited above using angular measurements normal to the coverage area and patterns containing concavities. This method involves a number of graphical constructions and is described in a set of step-by-step procedures in Annex 2.

In addition, these step-by-step procedures can be simplified by use of a convex-only coverage contour. To produce a convex-only coverage contour, the same procedure as described in Annex 2 is undertaken, except that only convex corners, i.e. those in which the circle lies inside the coverage contour are considered. The resultant coverage contour is illustrated in Fig. 3b).

Another way of representing the shaped beam patterns is by circumscribing the actual coverage area by a minimum area ellipse. The angular distance is measured from the edge of the ellipse in a direction normal to the periphery of the ellipse. This has the advantage that it is relatively easy to write highly efficient computer programs to define such an angular measurement procedure. However, this representation tends to considerably overestimate the area defined by the actual service area.

Another method is a hybrid approach which gives an unambiguous definition for representing the shaped beam coverage area. In this method a minimum area ellipse circumscribing the geographic coverage is used to define the centre of coverage area. The centre of coverage area does not necessarily represent the beam centre and is used only to define the axis of pattern cuts. Once the centre of coverage area is defined, the minimum area ellipse has no further significance.

A convex polygon is then used to define the coverage area boundary. The number of sides forming the polygon are determined based on the criteria that it should circumscribe the coverage area as closely as possible and should be of convex shape. A typical example is shown in Fig. 3c) for the service area representation. The angular directions are radial from the centre of the coverage area.

For an observation location outside the coverage area, the direction of applying the template and the angular distances are unambiguously defined with reference to the centre of coverage area. However, this method tends to underestimate the angular spacing between the gain contours outside the coverage area when the angle of the radial with respect to the coverage contour significantly departs from normal.

In summary, it would appear that the most acceptable method, both in accuracy and ease of construction, is the use of the convex-only coverage contour with the angular distances measured along directions normal to the sides of the contour, as shown in Fig. 3b).

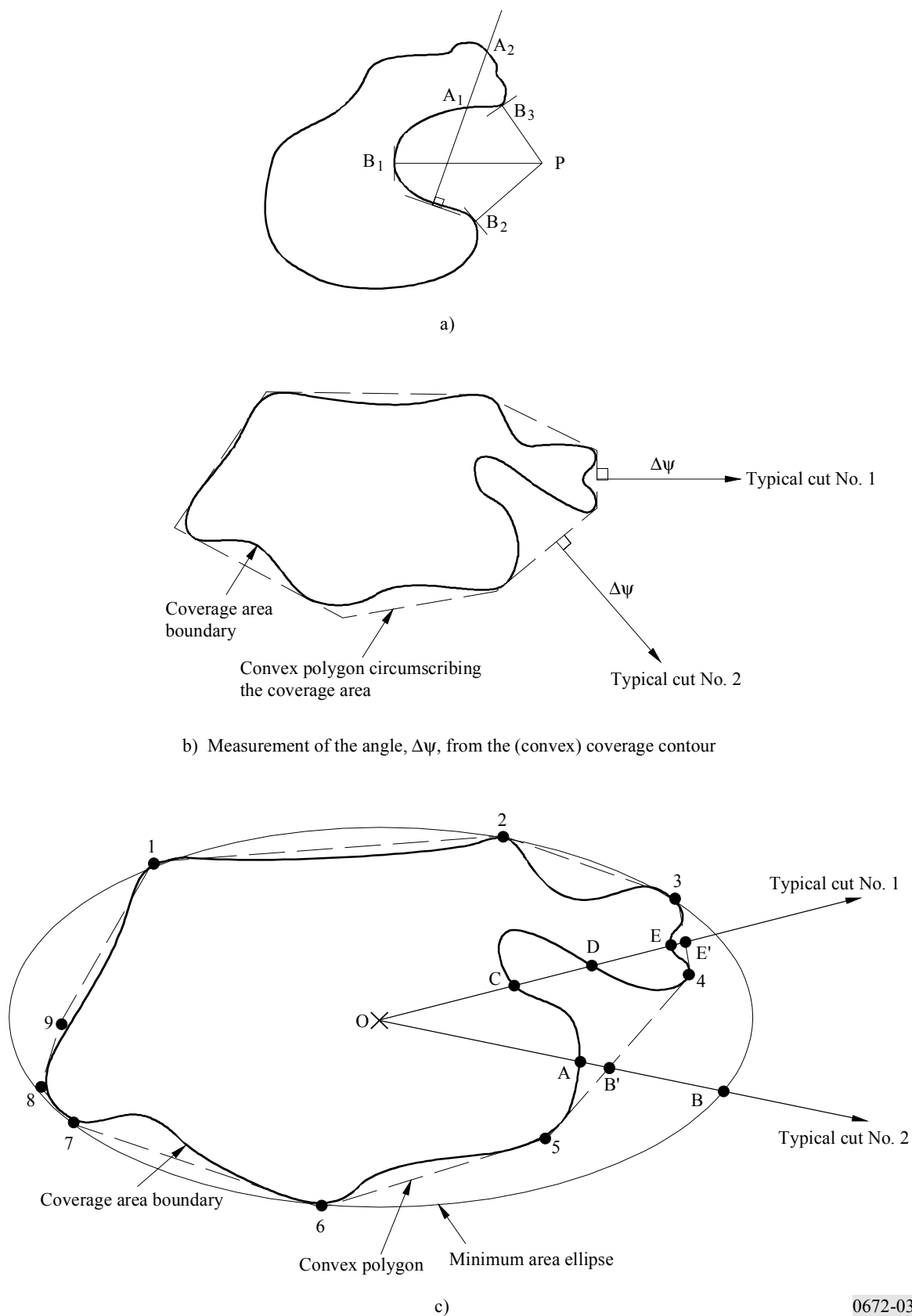
2.2 Equivalent peak gain

In situations where it is not necessary to tailor the beam to compensate for the variation in propagation conditions across the service area, the minimum coverage area gain achieved at the coverage area contour is considered to be 3 dB less than the equivalent peak gain (G_{ep}). In practice the actual peak gain may be higher or lower than the equivalent peak gain and may not necessarily occur on-axis.

In some situations there could be a large variation of propagation conditions over the service area or service requirements may warrant special beam tailoring within the service area. In these cases the minimum required relative gain (relative to the average gain on the coverage area contour) at each polygon vertex is computed and linear interpolation based on the azimuth from the beam axis may then be used to determine the relative gain at intermediate azimuths. Under this scenario the gain at the coverage area contour is direction dependent.

Note that for a shaped beam, the gain variation within the coverage area is not related to the roll-off of gain beyond the edge of coverage. The antenna performance within the coverage area, including the gain, is not related to the interference introduced into adjacent systems. The gain variation within the coverage area, therefore, need not be characterized in shaped beam reference patterns.

FIGURE 3
Different representation of coverage area



2.3 Elemental beamlet size

The side-lobe levels are determined by the aperture illumination function. Considering an illumination function of the form:

$$f(x) = \cos^N \left(\frac{\pi}{2} \cdot x \right) \quad |x| \leq 1 \quad (5)$$

which is zero at the aperture edge for $N > 0$. The elemental beamlet radius, as a function of the side-lobe level (dB) and the D/λ ratio, is, over the range of interest, approximately given by:

$$\psi_b = (16.56 - 0.775 L_s) \lambda/D \quad \text{degrees} \quad (6)$$

where L_s is the relative level of the first side lobe (dB).

This expression illustrates the trade-off between antenna diameter, side-lobe level and steepness of the main lobe skirt regions. It is derived by curve fitting the results obtained from calculations for different side-lobe levels. This relationship has been used as a starting point in the models described below.

2.4 Development of co-polar pattern models

Generalized co-polar patterns for future shaped beam antennas based on measurements on several operational shaped beam antennas (Brazilsat, Anik-C, Anik-E, TDRSS, Intelsat-V, G-Star, Intelsat-VI, Intelsat-VII, Cobra) and on theoretical considerations are given in this section.

Previous modelling did not appear to quantify the beam broadening effects. The following models include two separate approaches which deal with these effects, which are essential to predicting shaped beam antenna performance accurately.

2.4.1 First model

The shaped beam pattern given in this section is in terms of the primary as well as the secondary parameters. The primary parameters are the beamlet size, coverage area width in the direction of interest and the peak side-lobe level. Secondary parameters are the blockage parameter, surface deviation and the number of beamwidths scanned. The effect of secondary parameters on the antenna radiation is to broaden the main beam and increase the side-lobe level. Although the dominant parameter in the beam broadening is the number of beamwidths scanned, the effects of the other two parameters are given here for completeness. However, the effect of blockage on side-lobe level should not be overlooked. Though it is true that, due to practical limitations, even for a satellite antenna design which calls for maintaining the blockage free criteria, there is normally a small amount of edge blockage. In particular, edge blockage is quite likely to occur for linear dual-polarization antennas employing a common aperture as is the case of dual gridded reflectors used for Anik-E, G-Star, Anik-C, Brazilsat, etc. This is because of the required separation between the foci of the two overlapped reflectors for the isolation requirements and for the volume needed for accommodating two sets of horns.

In the far side-lobe regions there is very little measured information available on which to base a model. Reflections from the spacecraft structure, feed array spill-over, and direct radiation from the feed cluster can introduce uncertainties at large off-axis angles and may invalidate theoretical

projections. Measurement in this region is also extremely difficult and therefore further study is required to gain confidence in the model in this region. In the interim, a minimum gain plateau of 0 dBi is suggested.

It should be noted that the suggested pattern is only intended to apply in directions where side-lobe levels are of concern. In uncritical directions, e.g. towards ocean regions or beyond the limb of the Earth or in any direction in which interference is not of concern, this pattern need not be a representative model.

General co-polar Model 1

The following three-segment model representing the envelope of a satellite shaped beam antenna radiation pattern outside of the coverage area, is proposed:

Main lobe skirt region:

$$G_{\text{dBi}}(\Delta\psi) = G_{ep} + U - 4V \left(\frac{\Delta\psi}{Q\psi_0} + 0.5 \right)^2 \quad \text{for} \quad 0 \leq \Delta\psi \leq W \cdot Q \cdot \psi_0$$

Near-in side-lobe region:

$$G_{\text{dBi}}(\Delta\psi) = G_{ep} + SL \quad \text{for} \quad W \cdot Q \cdot \psi_0 \leq \Delta\psi \leq Z \cdot Q \cdot \psi_0$$

Far side-lobe region:

$$G_{\text{dBi}}(\Delta\psi) = G_{ep} + SL + 20 \log(Z \cdot Q \cdot \psi_0 / \Delta\psi) \quad \text{for} \quad Z \leq \Delta\psi \leq 18$$

where:

$\Delta\psi$: angle from the edge of coverage (degrees)

$G_{\text{dBi}}(\Delta\psi)$: gain at $\Delta\psi$ (dBi)

G_{ep} : equivalent peak gain

$$G_{ep} = G_e + 3.0 \text{ (dBi)}$$

ψ_0 : half-power diameter of the beamlet (degrees)

$$\psi_0 \approx (33.12 - 1.55 SL) \lambda/D$$

λ : wavelength (m)

D : diameter of the reflector (m)

SL : side-lobe level relative to the peak (dB)

$U = 10 \log A$, $V = 4.3429 B$ are the main beam parameters

$$B = [\ln(0.5/10^{0.1SL})] / [(16.30 - 3.345 SL) / (16.56 - 0.775 SL)]^2 - 1]$$

$$A = 0.5 \exp(B)$$

$$W = (-0.26 - 2.57 SL) / (33.12 - 1.55 SL)$$

$$Z = (77.18 - 2.445 SL) / (33.12 - 1.55 SL)$$

Q : beam broadening factor due to the secondary effects:

$$Q = \exp[(8\pi^2(\epsilon/\lambda)^2) \cdot [\eta_i(\Delta)]^{-0.5} \cdot 10^{\left(\frac{0.000075(\delta - 1/2)^2}{[(F/D_p)^2 + 0.02]^2}\right)}] \quad (7)$$

The variables in equation (7) are defined as:

ϵ : r.m.s. surface error

Δ : blockage parameter (square root of the ratio between the area blocked and the aperture area)

δ : number of beamwidths scanned away from the axial direction

$$= \theta_0 / \psi_0$$

θ_0 : angular separation between the centre of coverage, defined as the centre of the minimum area ellipse, to the edge of the coverage area

$$\begin{aligned} \eta_i(\Delta) &= 1 - \Delta^2 && \text{for central blockage} \\ &= [1 - [1 - A(1 - \Delta)^2] \Delta^2]^2 && \text{for edge blockage} \end{aligned} \quad (8)$$

A in equation (8) is the pedestal height in the primary illumination function $(1 - Ar^2)$ on the reflector and r is the normalized distance from the centre in the aperture plane of the reflector ($r = 1$ at the edge). F/D_p in equation (7) is the ratio of the focal length to the parent parabola diameter. For a practical satellite antenna design this ratio varies between 0.35 and 0.45.

The far-out side-lobe gain depends on the feed-array spillover, reflection and diffraction effects from the spacecraft structure. These effects depend on individual designs and are therefore difficult to generalize.

As given in equation (7), the beam broadening factor Q depends on the r.m.s. surface error ϵ , the blockage parameter Δ , number of beams scanned δ , and F/D_p ratio. In practice, however, the effect of ϵ and Δ on beam broadening is normally small and can be neglected. Thus, equation (7) can be simplified to:

$$Q = 10^{\left(\frac{0.000075 (\delta - 1/2)^2}{[(F/D_p)^2 + 0.02]^2} \right)} \quad (9)$$

where:

$$D_p = 2(d + h)$$

d : projected aperture diameter of the offset paraboloid

h : offset height to the edge of the reflector.

Equation (9) clearly demonstrates the dependence of beam broadening on number of beams scanned and the satellite antenna F/D_p ratio. This expression is valid for δ as high as nine beamwidths, which is more than sufficient for global coverage even at 14/11 GHz band; for service areas as large as Canada, United States or China the value of δ is generally one to two beams at 6/4 GHz band and about four beams at 14/11 GHz band, in the application of this model. Thus, for most of the systems the value of Q is normally less than 1.1. That is, the beam broadening effect is generally about 10% of the width of the elemental beamlet of the shaped-beam antenna.

Neglecting the main beam broadening due to blockage and reflector surface error, and assuming a worst-case value of 0.35 for F/D_p ratio of the reflector, the beam broadening factor Q can be simplified as:

$$Q = 10^{0.0037 (\delta - 1/2)^2}$$

In the 6/4 GHz band, a -25 dB side-lobe level can be achieved with little difficulty using a multi-horn solid reflector antenna of about 2 m in diameter, consistent with a PAM-D type launch. To achieve 30 dB discrimination, a larger antenna diameter could be required if a sizeable angular

range is to be protected or controlled. In the 14/11 GHz fixed-satellite bands, 30 dB discrimination can generally be achieved with the 2 m antenna and the use of a more elaborate feed design.

The above equations for the reference pattern are dependent upon the scan angle of the component beam at the edge of coverage in the direction of each individual cut for which the pattern is to be applied. For a reference pattern to be used as a design objective, a simple pattern with minimum parametric dependence is desirable. Hence, a value or values of Q which cover typically satellite coverages should be selected and incorporated in the above equations.

A steeper main beam fall-off rate can be achieved for a typical domestic satellite service area as compared to very large regional coverage areas; and conversely a reference pattern satisfying a regional coverage will be too relaxed for domestic satellite coverages.

Therefore it is proposed to simplify Model 1 into the following two cases for the FSS antennas. For these cases a -25 dB side-lobe plateau level is assumed.

a) Small coverage regions ($\delta < 3.5$)

Most of the domestic satellite coverage areas fall under this category. The beam broadening factor Q is taken as 1.10 to represent reference patterns of modest scan degradations for small coverage regions as:

$$G_{\text{dBi}}(\Delta\psi) = \begin{cases} G_{ep} + 0.256 - \frac{10.797}{\psi_0^2} (\Delta\psi + 0.55 \psi_0)^2 & \text{for } 0 \leq \Delta\psi \leq 0.9794 \psi_0 \\ G_{ep} - 25 & \text{for } 0.9794 \psi_0 < \Delta\psi \leq 2.1168 \psi_0 \\ G_{ep} - 25 + 20 \log(2.1168 \psi_0 / \Delta\psi) & \text{for } 2.1168 \psi_0 < \Delta\psi \leq 18 \end{cases}$$

b) Wide coverage regions ($\delta > 3.5$)

Examples for wide coverage regions are the hemi-beam and global coverages of INTELSAT and INMARSAT. In order to represent the pattern degradation due to large scan, a value of 1.3 is taken for the Q factor. The reference patterns applicable to these coverages ($\delta > 3.5$) are defined as:

$$G_{\text{dBi}}(\Delta\psi) = \begin{cases} G_{ep} + 0.256 - \frac{7.73}{\psi_0^2} (\Delta\psi + 0.65 \psi_0)^2 & \text{for } 0 \leq \Delta\psi \leq 1.1575 \psi_0 \\ G_{ep} - 25 & \text{for } 1.1575 \psi_0 < \Delta\psi \leq 2.5017 \psi_0 \\ G_{ep} - 25 + 20 \log(2.5017 \psi_0 / \Delta\psi) & \text{for } 2.5017 \psi_0 < \Delta\psi \leq 18 \end{cases}$$

2.4.2 Second model

There will be many difficulties in providing a relatively simple pattern that could be applied to a range of different satellite antennas without prejudice to any particular design or system. With this thought the template presented here by Model 2 does not intend to describe a single unique envelope, but a general shape. The template may be considered not only for a single antenna application, but as an overall representation of a family of templates describing antennas suitable for many different applications.

In the development of the model, an attempt has been made to take full account of the beam broadening that results from component beams scanned away from boresight of a shaped-beam antenna. A careful attempt has been made to encompass the effects of interference and mutual

coupling between adjacent beamlets surrounding the component beamlet under consideration. To avoid complexity in the formulation, two additional adjacent beamlets along the direction of scan of the component beamlets have been considered. The variation in beam broadening with F/D ratio has also been taken into account, the results have been tested over the range $0.70 \leq F/D \leq 1.3$ and modelled for an average scan plane between the elevation plane and azimuth plane. If the modelling had been done for the azimuth plane only, sharper characteristics than predicted might be expected. Other assumptions made in the model are as follows:

- the boundary of the component beams corresponding to the individual array elements has been assumed to correspond to the ideal -3 dB contour of the shaped coverage beam;
- the component beamlet radius, ψ_b , is given by equation (6) and corresponds to an aperture edge taper of -4 dB;
- the value of B which controls the main beam region, is directly modelled as a function of the scan angle of the component beam, the antenna diameter D and the F/D ratio of the antenna reflector.

The value of F/D used in this model is the ratio of focal length to the physical diameter of the reflector. The model is valid for reflector diameters up to 120λ , beam scanning of up to 13 beam widths and has shown good correlation to some 34 pattern cuts taken from four different antennas.

Recognizing that at some future date it may be desirable to impose a tighter control on antenna performance, this model provides two simple improvement factors, K_1 and K_2 , to modify the overall pattern generated at present.

General co-polar Model 2

The equations to the various regions and the corresponding off-axis gain values are described below. Those gain values are measured normal to the coverage area at each point and this technique is allied to the definition of coverage area described in Annex 2.

At present, the values of K_1 and K_2 should be taken as unity, $K_1 = K_2 = 1$.

The equations used in this model are normalized to a first side lobe (L_s) of -20 dB. Ultimately, the particular value of the first side-lobe level chosen for the given application would be substituted.

a) The main lobe skirt region: ($0^\circ \leq \Delta\psi < C\psi_b$)

In this region the gain function is given by:

$$G(\Delta\psi) = G_e - K_1 B \left[\left(1 + \frac{\Delta\psi}{\psi_b} \right)^2 - 1 \right] \quad \text{dBi} \quad (10)$$

where:

$G(\Delta\psi)$: reference pattern gain (dBi)

G_e : gain at the edge of coverage (dBi)

$\Delta\psi$: angle (degrees) from the (convex) coverage contour in a direction normal to the sides of the contour

$\psi_b = 32 \lambda/D$ is the beamlet radius (degrees) (corresponding to $L_s = -20$ dB in equation (6))

$B = B_0 - (S - 1.25) \Delta B$ for $S \geq 1.25$ and

$$B = B_0 \quad \text{for } S < 1.25$$

$$B_0 = 2.05 + 0.5 (F/D - 1) + 0.0025 D/\lambda$$

$$\Delta B = 1.65 (D/\lambda)^{-0.55}.$$

Equations for both the elevation and azimuth planes are given here in order to maintain generality.

$$\text{azimuth plane: } B_0 = 2.15 + T$$

$$\text{elevation plane: } B_0 = 1.95 + T$$

$$\text{where } T = 0.5 (F/D - 1) + 0.0025 D/\lambda$$

$$\text{azimuth plane: } \Delta B = 1.3 (D/\lambda)^{-0.55}$$

$$\text{elevation plane: } \Delta B = 2.0 (D/\lambda)^{-0.55}$$

D : physical antenna diameter (m)

λ : wavelength (m)

S : angular displacement A between the antenna boresight and the point of the edge-of-coverage, in half-power beamwidths of the component beam, as shown in Fig. 4, i.e.

$$S_1 = A_1 / 2\psi_b \text{ and } S_2 = A_2 / 2\psi_b$$

$$C = \sqrt{1 + \frac{(20 K_2 - 3)}{K_1 B}} - 1$$

and corresponds to the limit where $G(\Delta\psi)$ corresponds to a $-20 K_2$ (dB) level with respect to equivalent peak gain G_{ep} , i.e. $G(\Delta\psi) = G_e + 3 - 20 K_2$.

b) Near side-lobe region: $C\psi_b \leq \Delta\psi < (C + 0.5)\psi_b$

This region has been kept deliberately very narrow for the following reasons. High first lobes of the order of -20 dB occur only in some planes and are followed by monotonically decreasing side lobes. In regions where beam broadening occurs, the first side lobe merges with the main lobe which has already been modelled by B for the beam skirt. Hence it is necessary to keep this region very narrow in order not to over-estimate the level of radiation. (For class B antennas this region has been slightly broadened and the gain function modified.) The gain function in this region is constant and is given by:

$$G(\Delta\psi) = G_e + 3 - 20 K_2 \quad (11)$$

c) Intermediate side-lobe region: $(C + 0.5)\psi_b \leq \Delta\psi < (C + 4.5)\psi_b$

This region is characterized by monotonically decreasing side lobes. Typically, the envelope decreases by about 10 dB over a width of $4\psi_b$. Hence this region is given by:

$$G(\Delta\psi) = G_e + 3 - 20 K_2 + 2.5 \left[(C + 0.5) - \frac{\Delta\psi}{\psi_b} \right] \quad \text{dBi} \quad (12)$$

The above expression decreases from $G_e + 3 - 20 K_2$ at $(C + 0.5)\psi_b$ to $G_e + 3 - 10 - 20 K_2$ at $(C + 4.5)\psi_b$.

d) Wide-angle side-lobe region: $(C + 4.5)\psi_b \leq \Delta\psi < (C + 4.5)\psi_b D$,

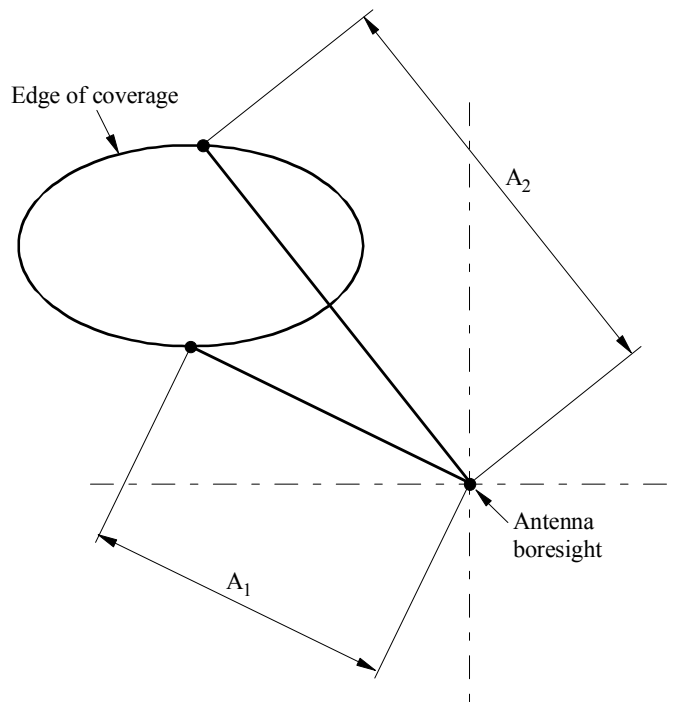
$$\text{where } D = 10^{[(G_e - 27) / 20]}$$

This corresponds to the region which is dominated by the edge diffraction from the reflector and it decreases by about 6 dB per octave. This region is then described by:

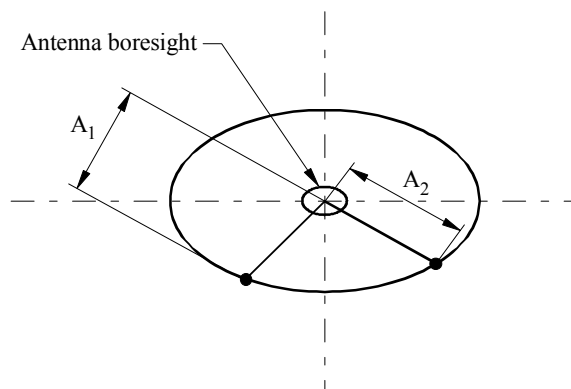
$$G(\Delta\psi) = G_e + 3 - 10 - 20 K_2 + 20 \log \left[\frac{(C + 4.5) \psi_b}{\Delta\psi} \right] \quad \text{dBi} \quad (13)$$

In this region $G(\Delta\psi)$ decreases from $G_e + 3 - 10 - 20 K_2$ at $(C + 4.5) \psi_b$ to $G_e + 3 - 16 - 20 K_2$ at $2(C + 4.5) \psi_b$. The upper limit corresponds to where $G(\Delta\psi) = 3$ dBi.

FIGURE 4
A schematic of a coverage zone



a) Boresight outside the coverage zone



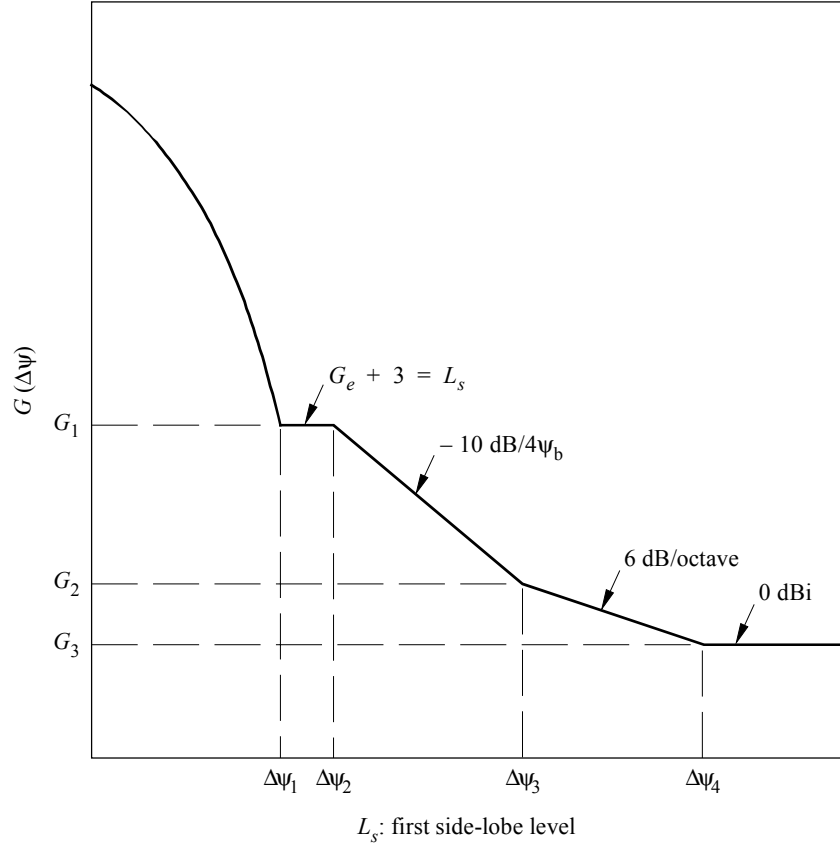
b) Boresight inside the coverage zone

A_1, A_2 : angular deviation (degrees) of the two points on the edge of coverage from the antenna boresight

- e) **Far-out side-lobe region:** $(C + 4.5) \psi_b D \leq \Delta\psi \leq 90$,
 where $D = 10^{[(G_e - 27)/20]}$
 $G(\Delta\psi) = 3$ dBi (14)

These regions are depicted in Fig. 5.

FIGURE 5
Different regions in the proposed model 2



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The model can also be extended to the case of simple circular beams, elliptical beams and to shaped-reflector antennas. These cases are covered by adjustment to the value of B in the above general model:

- for simple circular and elliptical beams B is modified to a value, $B = 3.25$
- for shaped-reflectors the following parameters are modified to:

$$B = \begin{cases} 1.3 & \text{for } 0.5 \leq S \leq 0.75 \\ 1.56 - 0.34 S & \text{for } 0.75 < S \leq 2.75 \\ 0.62 & \text{for } S > 2.75 \end{cases}$$

where:

$$S: (\text{angular displacement from the centre of coverage}) / 2\psi_b$$

$$\psi_b = 40 \lambda/D$$

$$K_2 = 1.25$$

It should be noted that the values proposed for shaped-reflector antennas correspond to available information on simple antenna configurations. This new technology is rapidly developing and therefore these values should be considered tentative. Furthermore, additional study may be needed to verify the achievable side-lobe plateau levels.

Use of improvement factors K_1 and K_2

The improvement factors K_1 and K_2 are not intended to express any physical process in the model, but are simple constants to make adjustments to the overall shape of the antenna pattern without changing its substance.

Increasing the value of K_1 from its present value of 1, will lead to an increase in the sharpness of the main beam roll-off.

Parameter K_2 can be used to adjust the levels of the side-lobe plateau region by increasing K_2 from its value of unity.

2.5 Shaped beam pattern roll-off characteristics

The main beam roll-off characteristics of shaped beam antennas depend primarily on the antenna size. The angular distance $\Delta\psi_L$ from the edge of coverage area to the point where the gain has decreased by 22 dB (relative to edge gain) is a useful parameter for orbit planning purposes: it is related to the antenna size as:

$$\Delta\psi_L = C (\lambda/D)$$

For central beams with little or no shaping, the value of C is 64 for –25 dB peak side-lobe level. However, for scanned beams C is typically in the range 64 to 80 depending on the extent of main beam broadening.

2.6 Reference pattern for intermediate scan ratios

recommends 2.1 and 2.2 have two reference patterns for the satellite antennas in the FSS, one for small coverage areas with scan ratios less than 3.5 and the other for wide coverage areas with scan ratios greater than 5.0. However, the radiation patterns for intermediate scan ratios ($3.5 < \delta < 5.0$) of satellite antennas have not been defined.

In order to fully utilize the Recommendation the radiation pattern for antennas with intermediate scan ratios between 3.5 and 5.0 should be defined. One approach would be to redefine either of the two models to cover the other region. However, as an interim solution it is proposed to connect the two models with a reference pattern defined by parameters similar to those used in *recommends* 2.1 and 2.2.

Based on this approach a new reference pattern, which is applicable only to Class A antennas, has been developed which satisfies the existing patterns for the small coverage and the wide coverage areas at $\delta = 3.5$ and $\delta = 5.0$ respectively. It is defined as a function of the beam-broadening factor Q_i

which is the ratio of upper limits of the main beam fall-off regions of the shaped beam ($\delta > 1/2$) and the pencil beam ($\delta = 1/2$). For intermediate scan ratios in the range $3.5 < \delta < 5.0$, the value of Q_i is interpolated as:

$$Q_i = Q + \left(\frac{C}{1.7808} - Q \right) \left(\frac{\delta - 3.5}{1.5} \right)$$

where:

$$Q = 10^{\left(\frac{0.000075 (\delta - 1/2)^2}{[(F/D_p)^2 + 0.02]^2} \right)}$$

$$C = \sqrt{1 + \frac{22}{B}} - 1$$

$$B = 2.05 + 0.5 (F/D - 1) + 0.0025 D/\lambda - (\delta - 1.25) 1.65 (D/\lambda)^{-0.55}$$

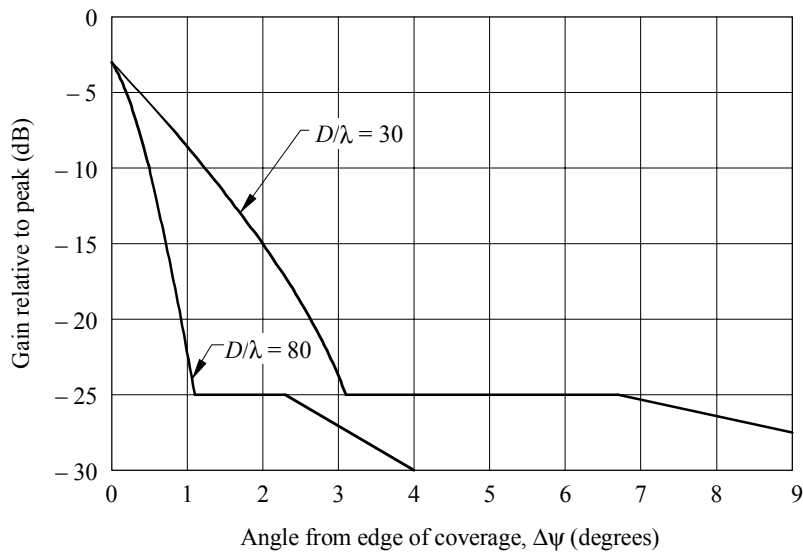
The reference pattern for intermediate scan ratios ($3.5 < \delta < 5.0$) is defined as:

$$G_{\text{dBi}}(\Delta\psi) = \begin{cases} G_{ep} + 0.256 - 13.065 \left(\frac{\Delta\psi}{Q_i \psi_0} + 0.5 \right)^2 & \text{for } 0 \leq \frac{\Delta\psi}{\psi_0} \leq 0.8904 Q_i \\ G_{ep} - 25 & \text{for } 0.8904 Q_i < \frac{\Delta\psi}{\psi_0} \leq 1.9244 Q_i \\ G_{ep} - 25 + 20 \log \left(\frac{1.9244 Q_i}{\Delta\psi} \right) & \text{for } 1.9244 Q_i < \frac{\Delta\psi}{\psi_0} \leq \frac{18}{\psi_0} \end{cases}$$

The variables in the above equations have been defined in *recommends* 2.1 and 2.2.

Figure 6 shows an example of the new reference pattern for $\delta = 4.25$ and for two different values of D/λ .

FIGURE 6
Proposed reference patterns for intermediate scan ratios
($3.5 < \delta < 5.0$)



D/λ : parameter of the curves

$\delta = 1.25$

$F/D = 1, F/D_p = 0.35$

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Further study is needed to validate this model for the intermediate scan ratio region.

ANNEX 2

1 Defining coverage area contours and gain contours about the coverage area

1.1 Defining coverage area contours

A coverage area can be defined by a series of geographic points as seen from the satellite. The number of points needed to reasonably define the coverage area is a function of the complexity of the area. These points can be displaced to account for antenna pointing tolerances and variations due to service arc considerations. A polygon is formed by connecting the adjacent points. A coverage area contour is constructed about this polygon by observing two criteria:

- the radius of the curvature of the coverage area contour should be $\geq \psi_b$;
- the separation between straight segments of the coverage area contour should be $> 2\psi_b$ (see Fig. 7).

If the coverage polygon can be included in a circle of radius ψ_b , this circle is the coverage area contour. The centre of this circle is the centre of a minimum radius circle which will just encompass the coverage area contour. If the coverage polygon cannot be included in a circle of radius ψ_b , then proceed as follows:

Step 1: For all interior coverage polygon angles $< 180^\circ$, construct a circle of radius ψ_b with its centre at a distance (ψ_b) on the internal bisector of the angle. If all angles are less than 180° (no concavities) Steps 2 and 4 which follow are eliminated.

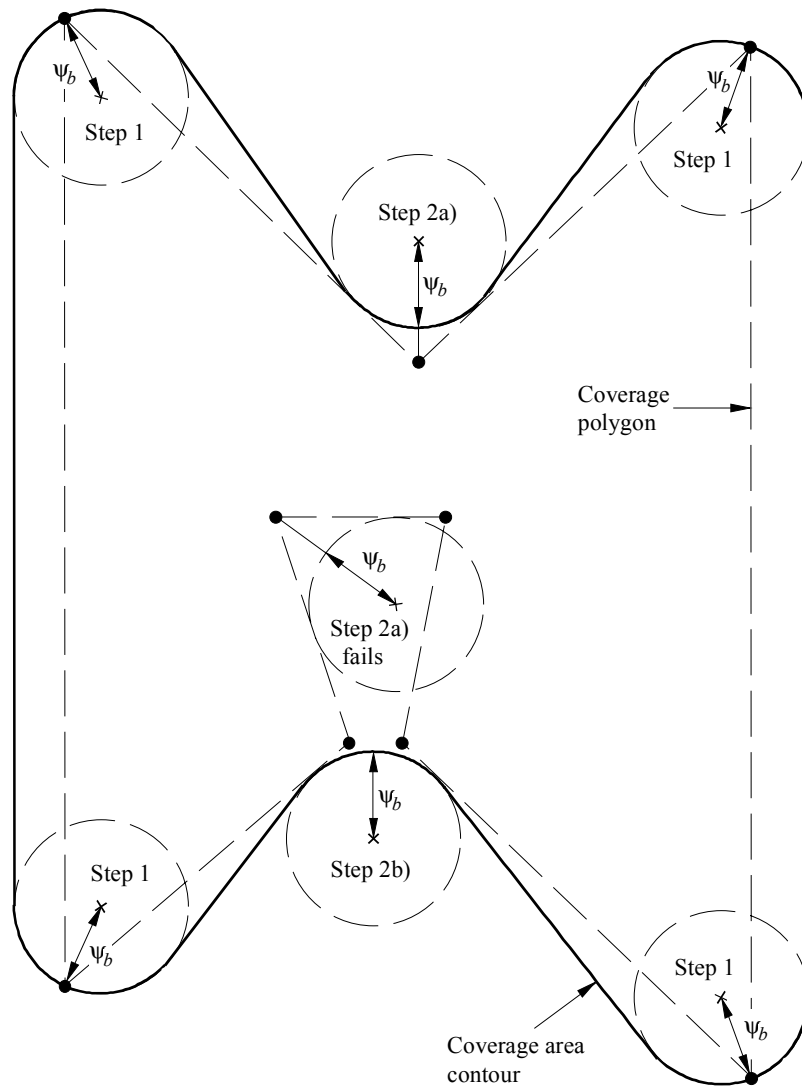
- Step 2:* a) For all interior angles $> 180^\circ$, construct a circle of radius ψ_b which is tangent to the lines connected to the coverage point whose centre is on the exterior bisector of the angle.
- b) If this circle is not wholly outside the coverage polygon, then construct a circle of radius ψ_b which is tangent to the coverage polygon at its two nearest points and wholly outside the coverage polygon.

Step 3: Construct straight line segments which are tangent to the portions of the circles of Steps 1 and 2 which are closest to, but outside the coverage polygon.

Step 4: If the interior distance between any two straight line segments from Step 3 is less than $2\psi_b$, the controlling points on the coverage polygon should be adjusted such that reapplying Steps 1 through 3 results in an interior distance between the two straight line segments equal to $2\psi_b$.

An example of this construction technique is shown in Fig. 7.

FIGURE 7
Construction of a coverage area contour



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1.2 Gain contours about the coverage area contours

As also noted in Annex 1, difficulties arise where the coverage area contour exhibits concavities. Using a $\Delta\psi$ measured normal to the coverage area contour will result in intersections of the normals and could result in intersections with the coverage area contour.

In order to circumvent this problem, as well as others, a two step process is proposed. If there are no concavities in the coverage contours, the following Step 2 is eliminated.

Step 1: For each $\Delta\psi$, construct a contour such that the angular distance between this contour and the coverage area contour is never less than $\Delta\psi$.

This can be done by constructing arcs of $\Delta\psi$ dimension from points on the coverage area contour. The outer envelope of these arcs is the resultant gain contour.

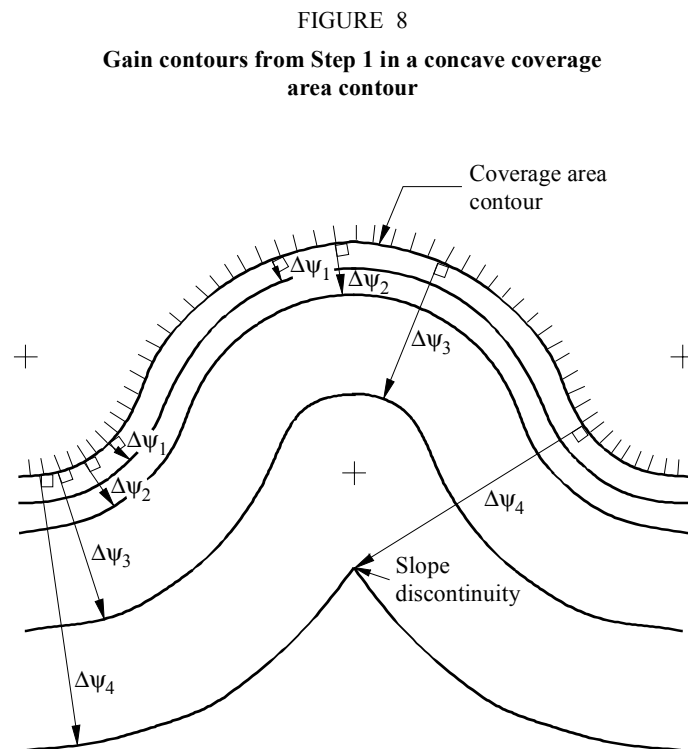
Where the coverage area contour is straight or convex, this condition is satisfied by measuring normal to the coverage area contour. No intersections of normals will occur for this case.

Using the process described in Step 1 circumvents these construction problems in areas of concavity. However, from a realistic standpoint some problem areas remain. As noted in Annex 1, side-lobe control in regions of concavity can become more difficult as the degree of concavity increases, the pattern cross-section tends to broaden and using the Step 1 process, discontinuities in the slope of the gain contour can exist.

It would appear reasonable to postulate that gain contours should have radii of curvature which are never less than $(\psi_b + \Delta\psi)$ as viewed from inside and outside the gain contour. This condition is satisfied by the Step 1 process where the coverage area contour is straight or convex, but not in areas of concavity in the coverage area contour. The focal points for radii of curvature where the coverage area contour is straight or convex are within the gain contour. In areas of concavity, the use of Step 1 can result in radii of curvature as viewed from outside the gain contour which are less than $(\psi_b + \Delta\psi)$.

Figure 8 shows an example of the Step 1 process in an area of concavity. Semi-circular segments are used for the coverage area contour for construction convenience. Note the slope discontinuity.

To account for the problems enumerated above and to eliminate any slope discontinuity, a Step 2 is proposed where the concavities exist.



Step 2: In areas of the gain contour determined by Step 1 where the radius of curvature as viewed from outside this contour is less than $(\psi_b + \Delta\psi)$ this portion of the gain contour should be replaced by a contour having a radius equal to $(\psi_b + \Delta\psi)$.

Figure 9 shows an example of the Step 2 process applied to concavity of Fig. 8. For purposes of illustration, values of the relative gain contours are shown, assuming ψ_b as shown and a value of $B = 3$ dB.

This method of construction has no ambiguities and results in contours in areas of concavities which might reasonably be expected. However, difficulties occur in generating software to implement the method, and furthermore it is not entirely appropriate for small coverage areas. Further work will continue to refine the method.

To find the gain values at specific points without developing contours the following process is used.

Gain values at points which are not near an area of concavity can be found by determining the angle $\Delta\psi$ measured normal to the coverage area contour and computing the gain from the appropriate equation: (10), (11), (12), (13) or (14). The gain at a point in concavity can be determined as follows.

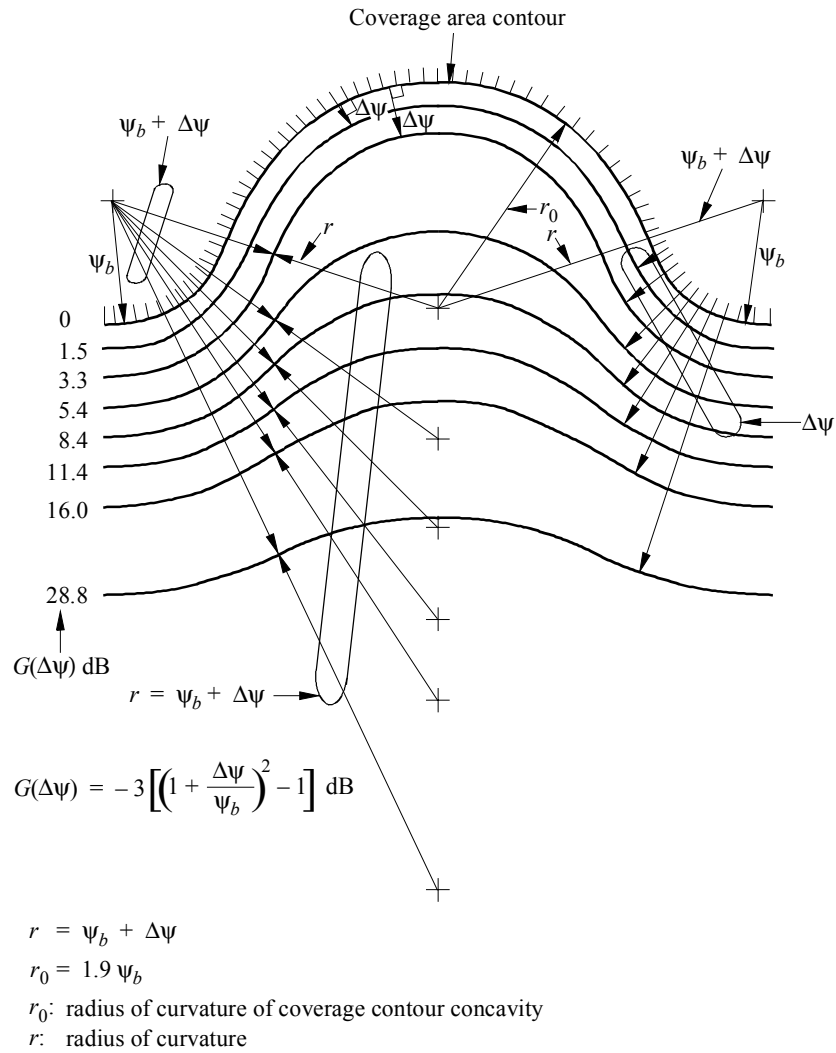
First a simple test is applied. Draw a straight line across the coverage concavity so that it touches the coverage edge at two points without crossing it anywhere. Draw normals to the coverage contour at the tangential points. If the point under consideration lies outside the coverage area between the two normals, the antenna discrimination at that point may be affected by the coverage concavity. It is then necessary to proceed as follows:

Determine the smallest angle $\Delta\psi$ between the point under consideration and the coverage area contour. Construct a circle with radius $(\psi_b + \Delta\psi)$, whose circumference contains the point, in such a way that its angular distance from any point on the coverage area contour is maximized when the circle lies entirely outside the coverage area; call this maximum angular distance $\Delta\psi'$. The value of $\Delta\psi'$ may be any angle between 0 and $\Delta\psi$; it cannot be greater than but may be equal to $\Delta\psi$. The antenna discrimination for the point under consideration is then obtained from equations (10), (11), (12), (13) or (14) as appropriate using $\Delta\psi'$ instead of $\Delta\psi$.

Two computer programs for generating the coverage area contours based on the above method have been developed and are available at the Radiocommunication Bureau.

FIGURE 9

Construction of gain contours in a concave coverage area contour – Step 1 plus Step 2



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