Multiple-beam groundstation reflector antenna system : a prelimary study

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Research Report

Eindhoven
University of Technology
Netherlands

Department of Electrical Engineering

Multiple-Beam Groundstation Reflector Antenna System: A Preliminary Study

by

P. Monnee
and
M.H.A.J. Herben

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ABSTRACT

As a wide-scanning multiple-beam reflector antenna, two systems are investigated. Firstly, a bifocal antenna, designed with the use of an existing method, appears to be unsuitable for wide-angle scanning. Secondly, a dual-reflector offset torus-antenna showed promising results. As an illustration of its benefit, a possible application is examined: the simultaneous reception of signals from a number (n) of geostationary Direct Broadcast Satellites with mutual distance of 6 degrees. Using this antenna yields advantage when compared, in respect of the total required reflector area, with n separate antennas.

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CONTENTS

1. INTRODUCTION

As communication satellite technology matured, increasing attention has been given to multiple-beam reflector antennas, especially to those carried by satellites. The great advantage of such an antenna system is obvious: one common reflector serves all beams necessary to cover several separated areas on earth simultaneously. Since, for geostationary satellites, the angle between the individual beam directions will be small, antenna systems with a relatively small scan range can be used. One of the design methods to obtain this kind of antennas is the modification of conventional antenna-systems, resulting in defocused single [1]-[3] and dual-reflector antennas [4]-[6]. All these antennas show a degradation of performance with increasing scan range. Literature surveys about scanning and multiple-beam antennas can be found in [7] and [8].

Due to technical developments in satellite station-keeping accuracy, a smaller mutual distance between the satellites has become possible, leading to an increasing occupation of the geostationary orbit. Therefore, multiple-beam antennas are also worth considering for use in earth terminals. Especially, future Direct Broadcast Satellites (DBS's) in Europe [9] offer advantageous challenges. These DBS's with a mutual separation of a multiple of 6 degrees will supply several countries with TV and radio signals in the band 11.7 - 12.5 GHz, using both right- and left-hand circularly polarised waves. The principle difference between satellite and earth application is the requirement of a far wider field of view for the earth station antenna: a view of approximately 40 degrees will be required, in The Netherlands, to receive the signals from DBS's to be placed at the orbital positions 5^{o}E, 19^{o}W and 31^{o}W [9]. This implies the rejection of the defocused reflector configurations, because of their limited scan capabilities.

This report presents the results of a preliminary theoretical study on a possible multiple-beam groundstation reflector antenna, operating at 12 GHz, with the property to view part of the geostationary orbit containing n DBS's with mutual distance of 6 degrees. Two different cases will be examined, namely individual and community reception. At first, a bifocal antenna-system will be considered, which appears to have unacceptable restrictions as far as scan capability is concerned. A second design, a dual-reflector offset torus-antenna, is investigated, showing promising results thus far. For moderate antenna-gain and a sufficient number of beams, a great advantage can be achieved with respect to the total reflector area required to provide simultaneous connectivity.

2. BIFOCAL DUAL-REFLECTOR ANTENNA

Rao [10], Kumazawa and Karikomi [11] and Claydon [12] presented a numerical method to design a bifocal dual-reflector antenna at a given maximum scan angle α. This symmetrical antenna system has its reflectors shaped such that if a cross-section is considered, plane waves incident with angle α (and $-\alpha$) from the symmetry axis give the best focusing in the (two) focal points. It has been demonstrated that there is no noticable loss of performance in the intermediate directions. However, the focal properties of the bifocal antenna still remain not ideal, because only rays lying in the cross-section plane will converge exactly, as contrasted with the remaining rays of the incident plane wave. This makes the scan properties of the antenna frequency dependent. Rao [10] showed that for a maximum scan angle up to $\alpha = 4$ degrees (at 4-6 GHz), usable systems can be designed with this method, but it seems unclear whether the same method can be used for the design of a multiple-beam antenna with a far wider field of view. And if so, what performance can be expected.

To examine the design method for larger values of α, a computer program has been written, based on a similar method described by Claydon [12]. Figure 1 shows the result of the program for a set of initial values given in the figure.

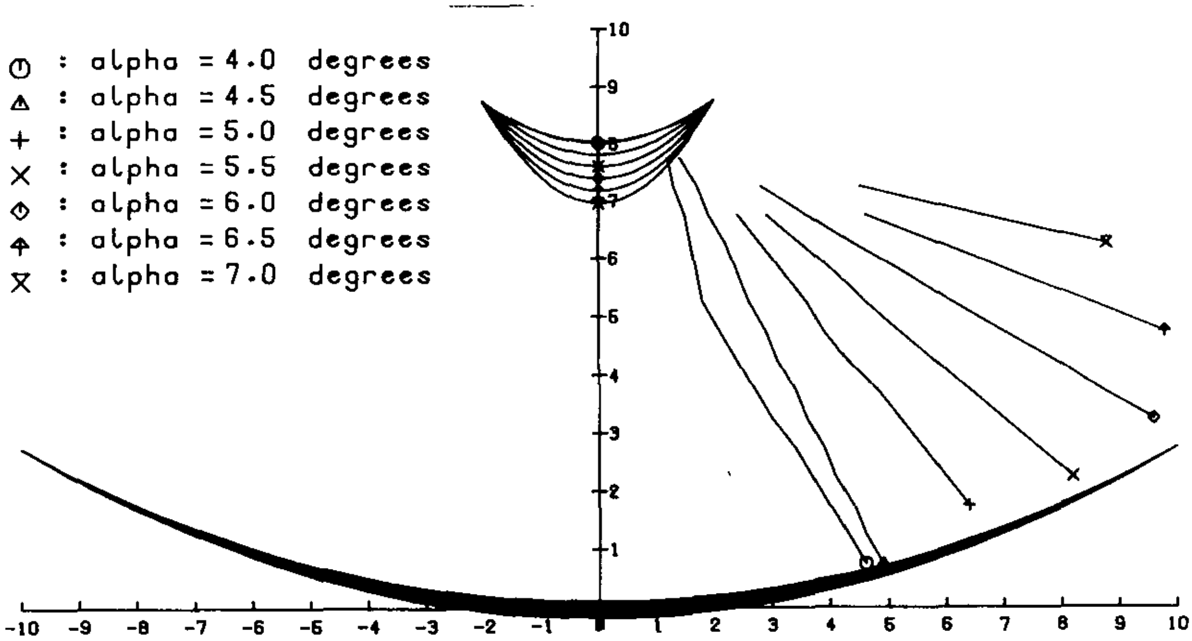


Fig. 1: Bifocal reflector-antenna systems for different values of the maximum scan angle α.

Several bifocal systems have been generated and plotted for different values of the maximum scan angle α. The marked lines indicate feed positions as close as possible to the symmetry axis. Each line corresponds to a certain scan angle α. It should be noticed that each feed position in principle generates a different sub- and main-reflector. The drawn reflectors belong to the feed position closest to the main-reflector. The figure shows that, already for a maximum scan angle of 7 degrees (scan range of 14 degrees), the feed will be situated critically near the edge of the system, giving rise to a very asymmetric aperture-illumination and, as a consequence of this, a low aperture efficiency can be expected. Improvements can only be obtained by largening the subreflector dimensions, but it is obvious that an unacceptable great blockage will be the price paid.

Offset configurations of the bifocal antenna [13] [14] give, in this respect, no improvements. Although blockage losses can be eliminated, the subreflector still has to be chosen relatively large and the aperture-illumination will remain very asymmetric. The same holds for the modified bifocal-antenna designs described recently by Rappaport [15] and Mizugutch and Watanabe [16]. So, it is concluded that the bifocal antenna is not suitable as a multiple-beam groundstation antenna with the desired wide instantaneous field of view (up to 40 degrees).

3. DUAL-REFLECTOR OFFSET TORUS-ANTENNA

3.1. Introduction

The spherical reflector antenna is known to be suited for scanning and multiple-beam purposes [17],[18]. Inherent to its spherical shape, wide scanning within a cone is possible, but unfortunately at the cost of rather poor collimating properties. If only scanning in a plane is desired (as in the present case), the torus reflector antenna is an alternative. Because of its partially parabolic shape, a better focusing can be obtained. The torus antenna in a single-reflector configuration has already received some attention in the literature. Both Hyde et al. [19] and Boswell [20] demonstrated good scan performance without much deterioration of the antenna characteristics.

Considering a dual-reflector antenna system as opposed to a front-fed system, illustrates the ability to locate the feed closer to the primary reflector, thus minimising the length of the lossy waveguide between the feed and the receiver. Moreover, possible feed spillover will, in the application considered, be directed to the cold sky instead of to the warm earth. This all will result in a lower antenna-noise temperature for the dual-reflector configuration. An offset configuration gives the additional advantage of no blockage of the plane wave(s) incident to the primary reflector.

In the present section the geometry of the dual-reflector offset torus-antenna will be described. An analysis of its scan capability is presented, particularly in relation to loss of antenna efficiency. Also the cross-polarisation properties with circularly polarised excitation will be evaluated in view of the possible DBS-application. To illustrate its benefit, a theoretical application of the torus antenna is proposed. It is demonstrated that both individual and community reception of n DBS's with mutual spacing of 6 degrees using a multiple-beam torus-antenna contains an advantage in comparison with n separate antennas.

3.2. Antenna geometry

The dual-reflector offset torus is defined as the surface obtained by revolving an offset Cassegrainian cross-section on a generating axis lying in the plane of the cross section (see figure 2). The generating axis, lying in the xz-plane, is chosen perpendicular to the parabola axis. The subreflector is situated so as to avoid blockage of the plane-wave incident on the primary reflector. The offset angle, which depends on D_s/D and f/D, must be kept as small as possible because, as indicated by Boswell [20], a large offset angle will result in loss of antenna gain. A vertical cross-section of this dual-reflector system will be parabolic-hyperbolic (figure 2a), giving the two focal points F_1 and F_0 in the usual way. In a horizontal cross-section the antenna has a circular contour, producing an image at approximately half the radius of curvature [17],[18]. The curvatures of the surface in the two mentioned planes are determined by the parameters f/D and R.

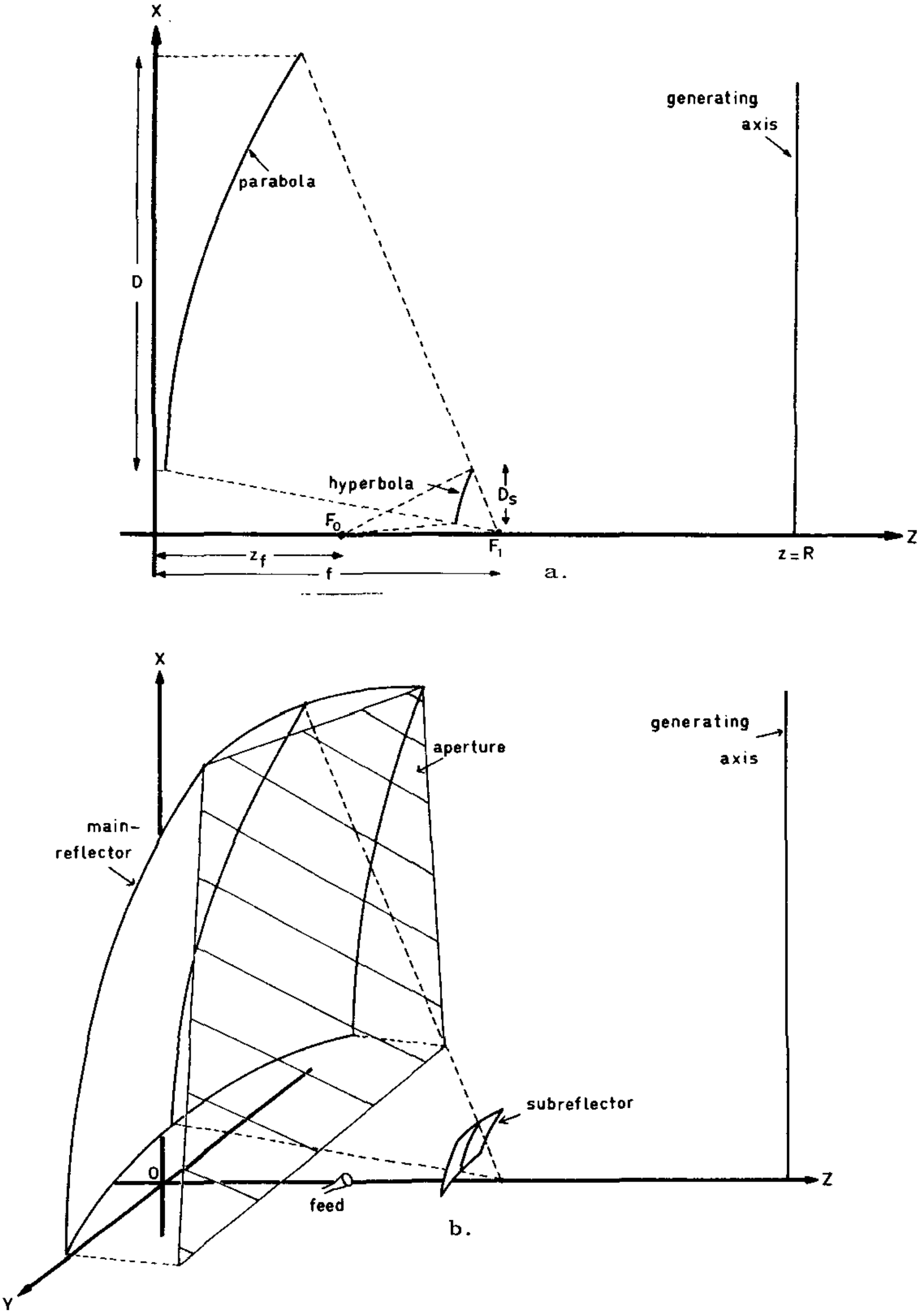


Fig. 2: Geometry of the dual-reflector offset torus-antenna.

a. Offset Cassegrainian cross-section.

b. Offset Cassegrainian cross-section revolved on the generating axis.

The two reflector surfaces are given by

$$(z-R)^2 + y^2 = (R - \frac{x^2}{4f})^2 \qquad \text{(main-reflector)} \qquad (1)$$

$$(z-R)^2 + y^2 = (R - a\sqrt{1 + \frac{x^2}{b^2}} - \frac{1}{2}(f + z_f))^2 \qquad \text{(subreflector)} \qquad (2)$$

with

$$a = \frac{f-z_f}{2e} \qquad (3)$$

$$b = a\sqrt{e^2-1} \qquad (4)$$

e: eccentricity of hyperbola,

z_f: distance between feed and origin O.

By extending this basic design in both directions (by rotation on the generating axis) and placing more feeds on the focal arc, several beams are obtained all lying in the same plane (yz-plane). The total reflector-width of the extended antenna becomes equal to the width of the basic design (2γ) plus the desired scan range. In this way a scan range of almost $180-2\gamma$ degrees should be possible. It is assumed that, after extension, all beams show the same performance as the beam of the basic design, because each feed is designed to illuminate mainly that part of the main-reflector with the dimensions of the basic design. Since one reflector now serves more beams, it seems reasonable to expect that, given a sufficient number of beams and/or a moderate mutual feed-separation, overlapping of illumination will appear and so a cost advantage can result.

The ultimate size of the extended torus is not only dependent on the total scan range and desired beam gain (gain for the basic design), but also on the basic antenna parameters such as γ, f/D, f/R and D_s/D. These parameters, for instance, strongly affect the antenna efficiency, and therefore a few considerations about them have to be made.

The parameter f/D is subject to a trade-off. A very short focal length leads to a main-reflector which is curved excessively and produces unacceptable losses due to large phase aberrations occuring in the antenna aperture. On the other hand, if the focal length is very long the horizontal dimensions of the reflector, required to cover a given scan range, becomes excessively large and the overlap of illumination will decrease. It has been found that a value for f/D equal to 0.96 is adequate [21]. The subreflector has been designed to be approximately square because it will be illuminated by a feed with a circular symmetric radiation pattern. The parameters z_f/D and D_s/D are given a value of 0.77 and 0.20, respectively, leading to an approximately square main-reflector and a suited reflector width of around 29 degrees ($=2\gamma$). The vertical dimension D of the almost trapesoidal antenna aperture can be used to fix the overall dimensions of the system, thus to control the antenna gain.

3.3. Analysis of the basic design

As a consequence of the non-ideal focusing, the antenna suffers from phase errors in its aperture, leading to a loss of efficiency and a degradation of its radiation pattern. Figure 3 shows contour plots of the aperture phase-distribution for a reflector diameter of 1 meter and a frequency of 12 GHz ($D/\lambda = 40$), obtained by a ray-tracing technique. The phase errors are proportional to the system dimension D/λ. Consequently, the antenna efficiency decreases with growing D/λ. So, the torus antenna is best suited as multiple-beam groundstation antenna with relatively small dimensions for its basic design.

It is known that the phase errors can be minimised by choosing a proper value for f/R. Hyde et al. [19] determined a value of 0.487 to be optimal, while Boswell [20] states a value of 0.485–0.488, both for the single-reflector configuration of the torus antenna. Computer calculations have shown that in the present case values between 0.474 (for small diameters; $D/\lambda = 40$) and 0.480 (for larger diameters; $D/\lambda = 90$) are appropriate.

Figure 3 shows that only at the central part of the aperture the phase errors are sufficiently small. The large phase errors at the edge will result in a large aperture illumination taper than for the classical Cassegrainian antenna, if the radiation pattern of the feed is optimised to realise maximum overall antenna-efficiency.

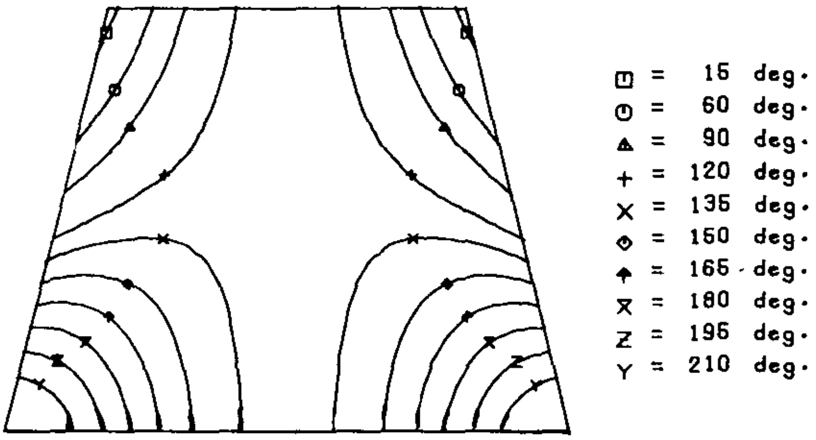


Fig. 3. Aperture phase distribution for torus antenna with $D/\lambda = 40$. Antenna parameters: $f/D = 0.96$, $D_s/D = 0.2$, $D = 1$ m, $z_f/D = 0.77$, $f/R = 0.474$, $\gamma = 14.41^{\circ}$.

Illumination of the subreflector by a feed with a circle-symmetric radiation-pattern modelled by

$$G_f(\psi) = \begin{cases} 2(N+1)\cos^N\psi & 0 \le \psi \le \frac{\pi}{2} \\ 0 & \frac{\pi}{2} \le \psi \le \pi \end{cases} \tag{5}$$

introduces a new parameter *N* by which both the aperture illumination taper and the subreflector spillover can be controlled. As expected, numerical analysis indicates that an optimum value can be assigned to *N* with respect to maximum overall antenna-efficiency. Figure 4 demonstrates this for the two cases discussed, i.e. individual and community reception of DBS-signals.

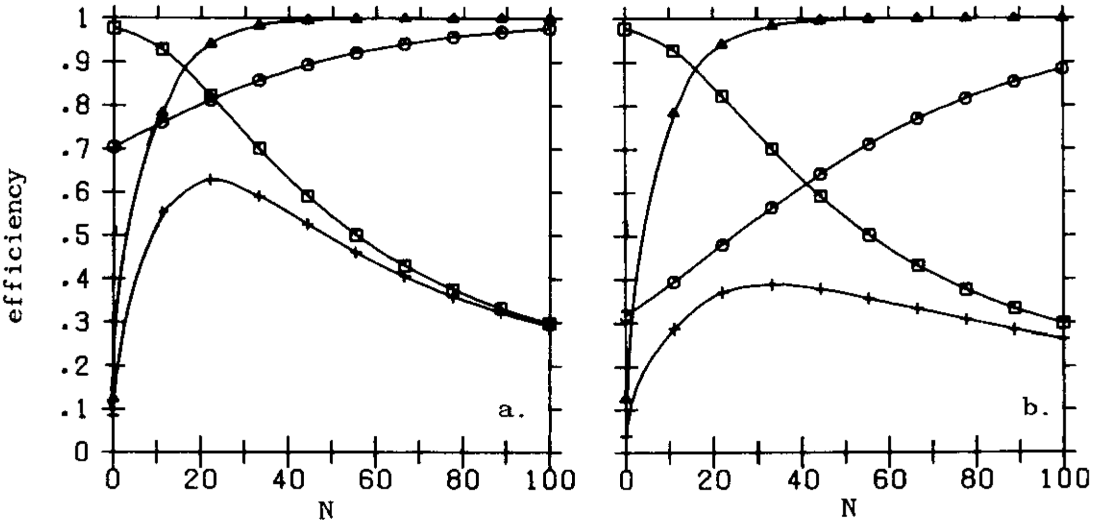


Fig. 4: The partial and overall efficiencies for the torus antenna.

a. The individual-reception torus antenna with $D/\lambda = 40$ and an antenna gain of 40 dB.

Antenna parameters: $f/D = 0.96$, $D_s/D = 0.2$, $D = 1$ m,

$z_f/D = 0.77$, $f/R = 0.474$, $\gamma = 14.41^o$.

b. The community-reception torus antenna with $D/\lambda = 90$ and an antenna gain of 46 dB.

Antenna parameters: $f/D = 0.96$, $D_s/D = 0.2$, $D = 2.25$ m,

$z_f/D = 0.77$, $f/R = 0.480$, $\gamma = 14.68^o$.

⊡ illumination efficiency

⊘ phase efficiency

▲ spillover efficiency

\+ overall antenna-efficiency.

The three contributing partial efficiencies are defined by

- illumination efficiency

$$\eta_{ill} \overset{\Delta}{=} \frac{1}{A} \frac{\{\iint_A |F(x,y)|dxdy\}^2}{\iint_A |F(x,y)|^2 dxdy} \qquad (6)$$

- phase efficiency

$$\eta_{ph} \overset{\Delta}{=} \frac{|\iint_A F(x,y)dxdy|^2}{\{\iint_A |F(x,y)|dxdy\}^2} \qquad (7)$$

- spillover efficiency

$$\eta_{sp} \overset{\Delta}{=} \frac{\iint_{sub.refl.} G_f(\psi)d\Omega}{\iint_{4\pi} G_f(\psi)d\Omega} \qquad (8)$$

with

$F(x,y)$: complex aperture-illumination,

A : antenna aperture area.

So, the overall antenna efficiency η_{tot} is given by

$$\eta_{tot} \overset{\Delta}{=} \eta_{ill}\ \eta_{ph}\ \eta_{sp}. \qquad (9)$$

Figure 4 shows that for individual DBS-reception ($D/\lambda = 40$) an overall efficiency of 60% is achieved, while in the case of community DBS-reception ($D/\lambda = 90$) the efficiency decreases to 40%.

Chu and Turrin [22] demonstrated offset parabolic reflectors to be free of cross-polarisation when circularly polarised illuminated by a feed with the polarisation properties of a Huygens-source. They also indicated that in the case of non-parabolic offset-configurations, this cross-polarisation is reduced to a second-order effect, if the surface just slightly deviates from the parabolic shape. For this reason, and because of the contemplated DBS-application, it is interesting to consider the cross-polarisation behaviour of the torus antenna under the condition of circular polarisation. To attain this object, the primary feed will be given the circular polarisation obtained from the superposition of two orthogonal Huygens sources with a phase-excitation difference of 90 degrees. The resulting elliptically polarised field in the antenna aperture can be resolved into a left-handed and a right-handed circularly polarised field, representing the co- and cross-polar fields. The contours in figure 5a and 5b are lines of constant power of both fields and, as expected, the crosspolar aperture-field component appears to be very small for both individual and community DBS-reception. It should be noticed, that the copolar-tapering has been selected in conformity with the optimum value of *N* determined for these systems (see figure 4).

The radiation patterns of the co- and crosspolar aperture fields are obtained using aperture integration [23]. So, the far field is given by

$$E_{CP,XP}(R,\theta,\varphi) = \frac{j}{\lambda R} e^{-j\beta R} \iint_A F_{CP,XP}(x,y) \, e^{j\beta(\sin\theta(x\cos\varphi + y\sin\varphi))} dxdy \tag{10}$$

with

$F_{CP}(x,y)$: complex copolar aperture illumination,

$F_{XP}(x,y)$: complex crosspolar aperture illumination,

$\beta = 2\pi/\lambda$,

λ : wavelength.

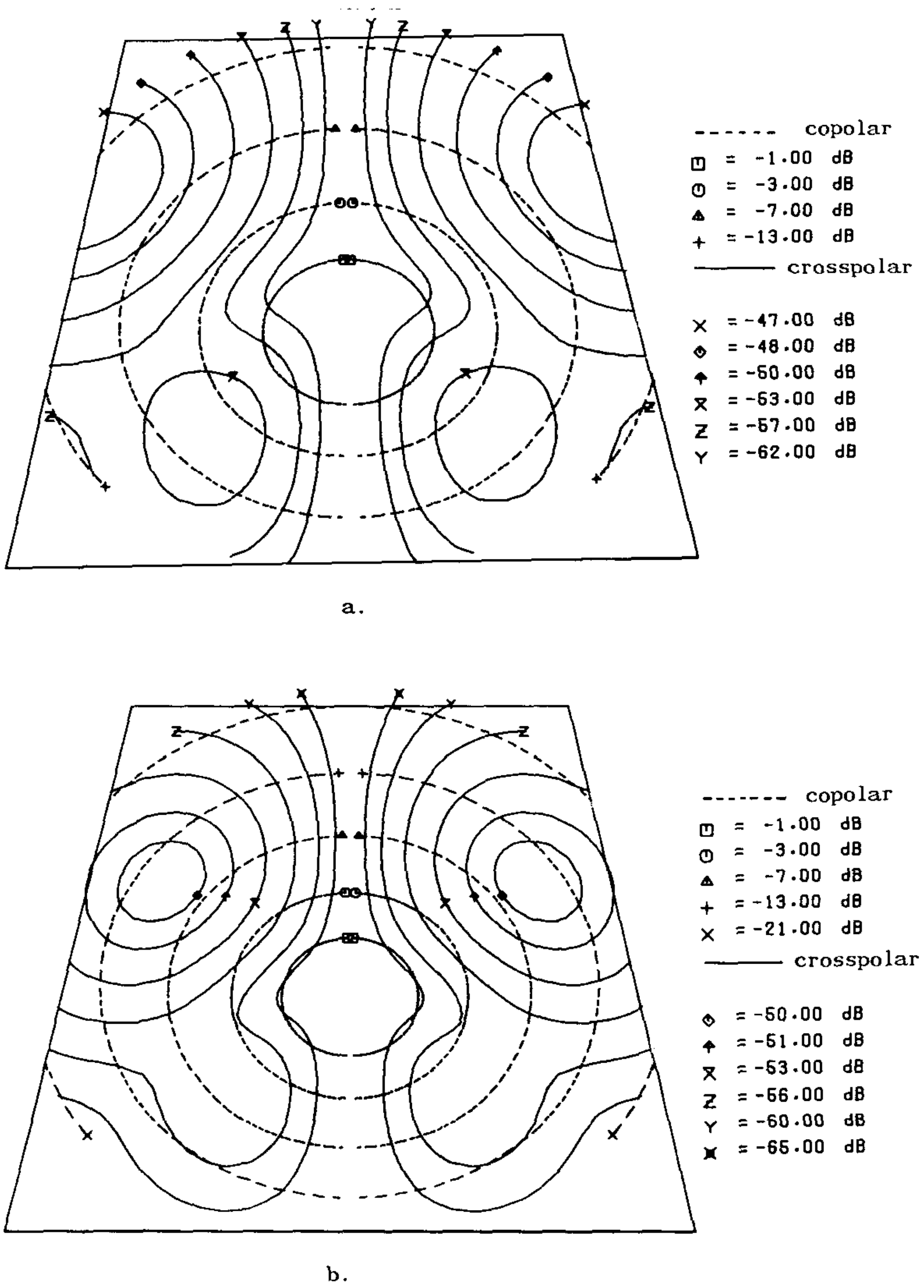


Fig. 5: Co- and crosspolar aperture illumination for the individual (a) and community-reception (b) torus antenna.

The validity of this method in relation to the angle θ, strongly depends on the aperture dimensions in terms of wavelengths. Rusch and Potter [23] and Lee et al. [24] derived formulas for the upper bound of θ for which aperture integration is allowed. According to these formulas a value of $\theta = 6$ degrees should be the ultimate for the largest antenna system considered ($D/\lambda = 90$).

Figures 6a and 6b show the copolar far-field pattern for the horizontal ($\varphi = 90^o$) and vertical ($\varphi = 0^o$) plane, respectively, for the individual-reception antenna. The radiation patterns for community-reception are shown in the figures 7a and 7b. Distortion of the patterns is observable when they are compared with the patterns of reflector antennas without aperture phase errors.

Due to the offset configuration, the symmetry of the pattern in the vertical plane is affected and a beam-squint of 0.3 and 0.2 degrees is present for the individual- and community-reception antenna, respectively. This beam-squint can be explained from the aperture phase distribution shown in figure 3 [21]. As a consequence, the computed overall-efficiencies shown in figure 4 are somewhat too low, the true efficiencies are slightly higher. Squinting of the beam also occurs in the horizontal plane as a result of the use of circular polarisation. The amount of beam shift in this plane appears to be very small and agrees closely with that predicted by the formula of Adatia and Rudge [25],

$$\text{beam-squint} = \arcsin\left(\frac{\sin\Psi_0}{4\pi f}\lambda\right) \tag{11}$$

for an offset parabolic reflector antenna with offset angle Ψ_0. Using equation 11 gives a beam squint of 0.08 and 0.03 degrees for the individual- and community-reception antenna, respectively. Computed results for the present design (figures 6 and 7) show a squint of 0.07 and 0.03 degrees, respectively.

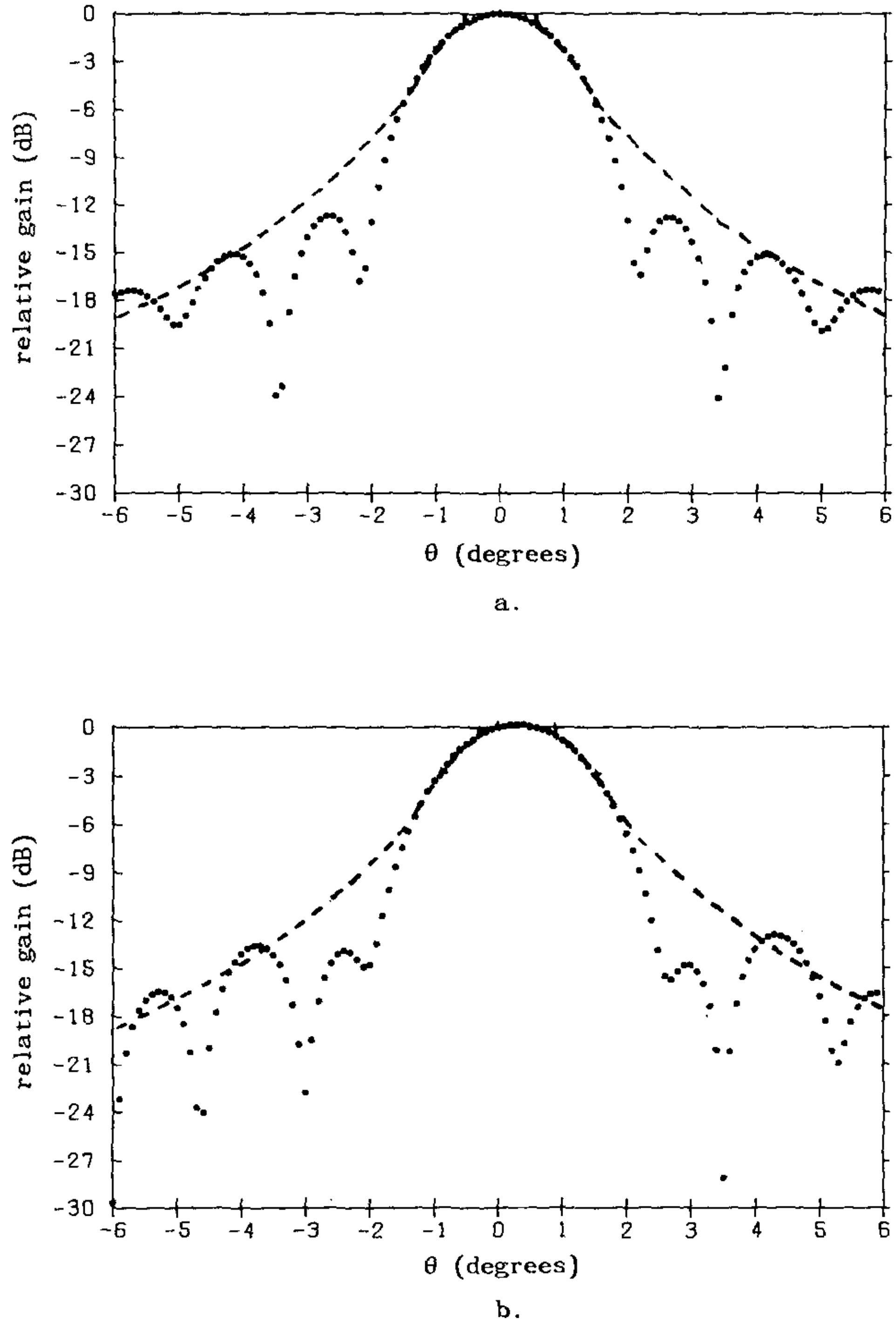
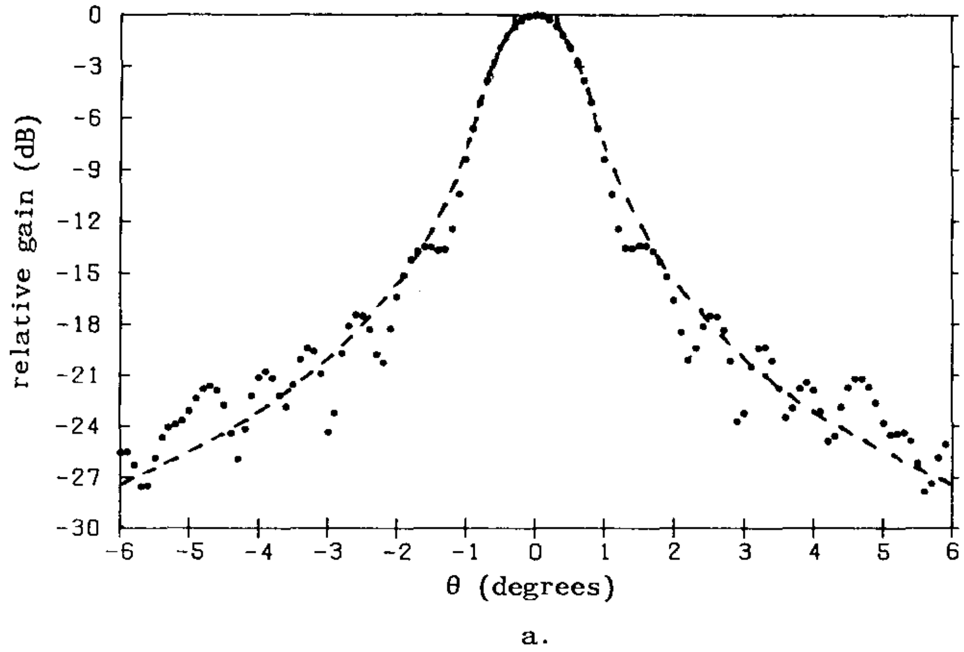


Fig. 6: Copolar radiation pattern of the individual-reception torus antenna for $\varphi = 90$ degrees (a) and $\varphi = 0$ degree (b).

----- CCIR Reference curve [26].



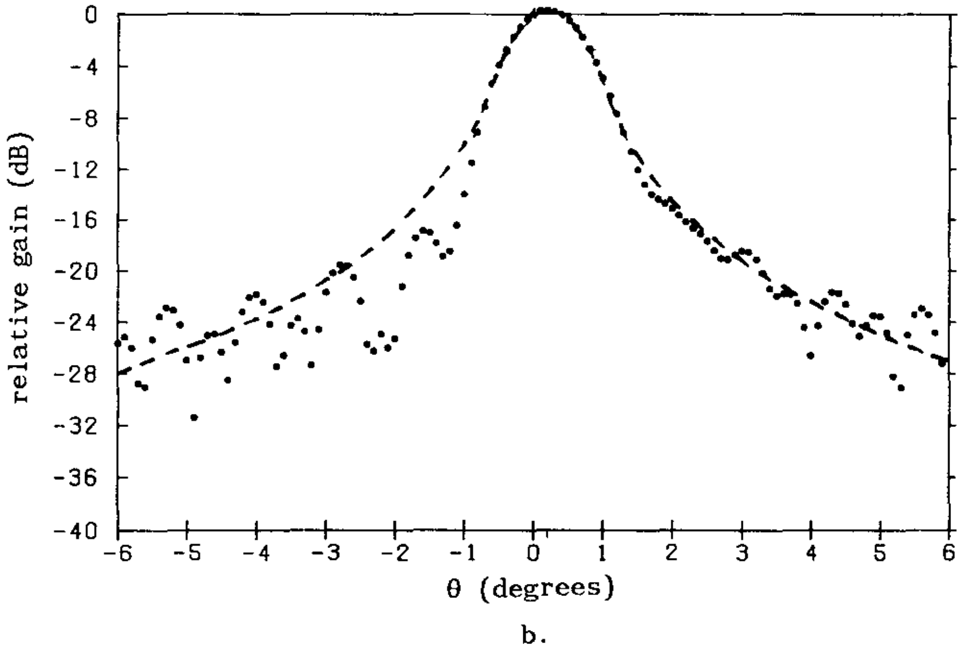


Fig. 7: Copolar radiation pattern of the community-reception torus antenna for φ = 90 degrees (a) and φ = 0 degree (b).

----- CCIR reference curve [26].

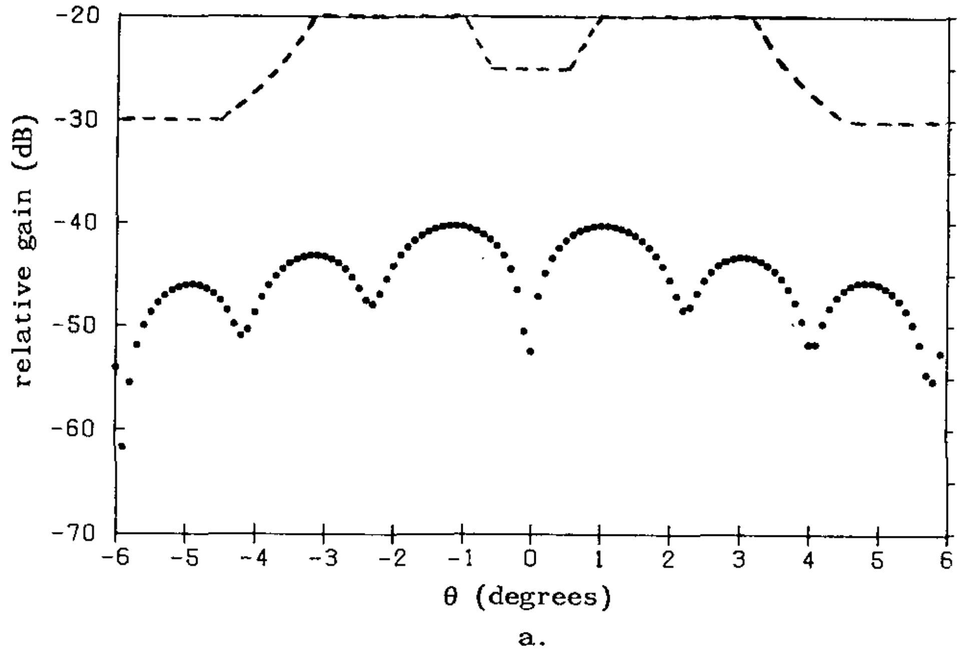
The crosspolar radiation patterns of both antennas are shown in figure 8. As expected from the crosspolar aperture distribution shown in figure 5 the far-field cross-polarisation is very low.

Also shown in the figures 6, 7 and 8 are the CCIR reference curves for DBS earth-station receiving antennas [26]. It is seen, that in the case of the copolar patterns, the CCIR norms are not completely realised. The crosspolar patterns however, remain far below the CCIR reference curves.

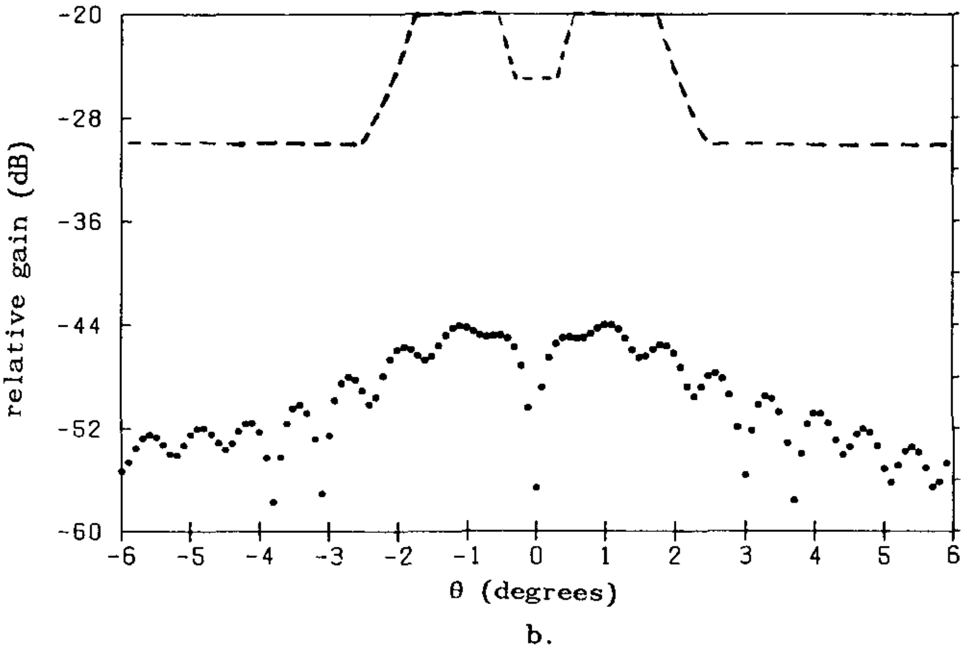
3.4. Theoretical application

As mentioned before, and also indicated by the CCIR [27], a possible application of the torus antenna may be as a (small) multiple-beam earth-station antenna, for instance for the simultaneous reception of the signals from several DBS's. If a gain of 40 dB for individual reception, and 46 dB for community reception must be realised using an (offset) parabolic reflector antenna with 80 percent efficiency, the diameters would become 0.9 m and 1.8 m and the corresponding beamwidths 2 degrees and 1 degree, respectively. These values are in agreement with those given by CCIR [26]. When a torus reflector antenna is to be used, the vertical dimension of the main-reflector has to be chosen 1.0 m (D/λ = 40) and 2.25 m (D/λ = 90), respectively, in order to achieve these beamgains.

Consider the torus antenna to be able to receive the signals of n DBS's with mutual orbital distance of 6 degrees. The required scan range for the antenna is approximately $(n-1)$ 6 degrees, (note that in general the scan range will differ from this value because the actual scan range depends on the location of the receiving antenna and the satellites), so the basic design has to be extended to a width of 29 ($= 2\gamma$) + $(n-1)$ 6 degrees. The most important advantage of the torus antenna over n separate conventional parabolic reflector antennas stems from the more effective use of (main) reflector surface as illustated in figure 9.



a.



b.

Fig. 8: Crosspolar radiation pattern of the individual- (a) and community-reception (b) torus antenna for $\varphi = 90$ degrees. ----- CCIR reference curve [26].

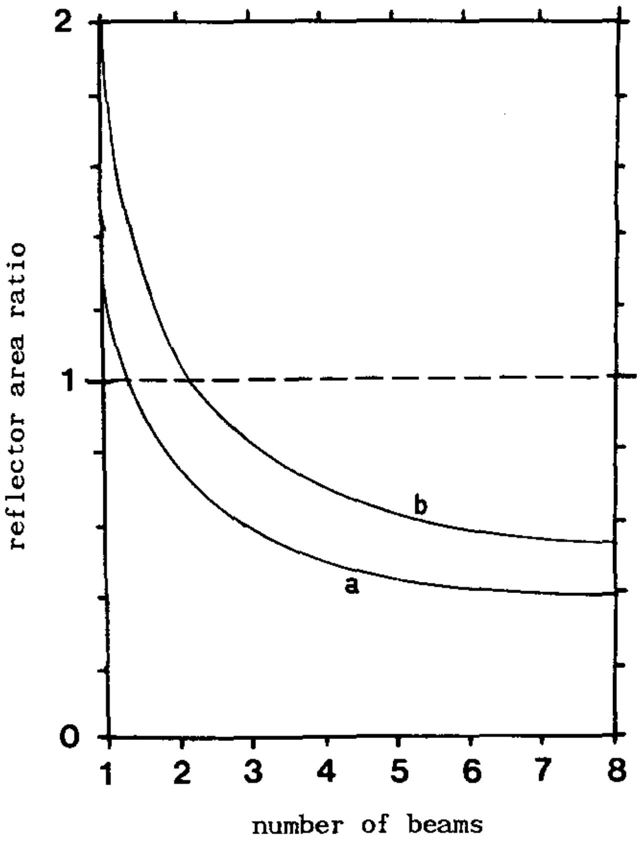


Fig. 9: The total main-reflector area of the multiple-beam torus antenna normalised to the total reflector area of *n* separate parabolic reflector antennas as a function of the number of beams (*n*).

Curve a: individual reception.

Curve b: community reception.

In this figure the total main-reflector area of the multiple-beam torus antenna normalised to the total reflector area of *n* separate parabolic reflector antennas is plotted as a function of the number of feeds (beams), for the two cases considered. Both torus and parabolic reflector antenna have a beam gain of 40 dB for individual and 46 dB for community reception. It appears that already for two beams in the case of individual reception and for three beams in the case of community reception approximately 80 percent of the reflector area of *n* separate parabolic reflector antennas is required. This situation improves further with increasing number of beams.

As an additional advantage of the torus antenna over *n* separate parabolic reflector antennas can be mentioned the limited distance between the feed horns, so a propitious choice can be made for the position of the receiver. A possible disadvantage could be the more firm mounting that is required because of the larger dish. However, the price of this mount may be comparable with the price of the *n* (cheaper) mounts necessary to bear the parabolic dishes.

It should be noticed that for the torus antenna described, the distance between the feed and the subreflector, and the vertical dimension of the subreflector appear to be quite small. In terms of wavelengths approximately 6 λ and 8 λ respectively for the individual-reception antenna, and approximately 12 λ and 18 λ respectively for the community-reception antenna. It seems therefore questionable whether the method of geometric optics, which is used within the antenna system, still holds and whether diffraction at the subreflector is negligible. The subreflector is obviously placed in the near-field of the feed horn. A possible idea to get round this doubt could be the integration of the feed and its part of the subreflector to a horn reflector antenna configuration, or the use of a dielectric cone feed as described by Olver et al. [28]. These configurations permit small subreflector dimensions and a small distance between feed and subreflector. Furthermore, the primary feed horn can be kept very small. The only condition for application in the present design is that there is no overlap of illumination on the subreflector (note that under this condition a sufficient overlap of illumination on the main-reflector remains possible!). By choosing the subreflector sufficiently small, this condition can be fulfilled.

When this condition is satisfied, another advantageous modification of the antenna becomes possible. By shaping the subreflector in the horizontal plane (i.e. leaving the circular contour), the phase errors in the antenna aperture can be set to zero (theoretically) and consequently the phase efficiency η_{ph} becomes 100 percent (equation 7). This would result in a torus antenna with a radiation pattern whose shape is independent of D/λ. However by shaping the subreflector in such a way the control of the amplitude of the aperture field distribution is lost, what in its turn may lead to a decrease of the illumination efficiency η_{ill} (equation 6). Whether this increase of η_{ph} and decrease of η_{ill} will result in an increase of the overall antenna efficiency η_{tot} (equation 9) and an improvement of the copolar radiation patterns, shown in the figures 6 and 7, should be the subject of further investigations.

Another point, not yet mentioned, is the fact that the presented torus antenna only allows scanning in one plane while (more than two) geostationary satellites and the groundstation antenna are generally not lying in one plane. However, the out-of-plane angles are quite small, so this problem can easily be solved by small appropriate lateral feed-displacements [20].

4. CONCLUSIONS

Reflector antenna systems were investigated which are able to provide simultaneous connectivity with DBS's placed at different orbital positions. Future European DBS's at 5^o E, 19^o W and 31^o W require groundstation antennas, in The Netherlands, with a field of view of approximately 40 degrees.

Defocused reflector antennas and the bifocal reflector-antenna appear unsuitable for this purpose, because of their limited scan capabilities. On the contrary, the dual-reflector torus antenna, with moderate D/λ, is capable to provide the required field of view. Due to phase errors in its antenna aperture. the torus antenna has a somewhat low antenna efficiency (60 percent for individual reception and 40 percent for community reception), and its copolar radiation pattern does not completely meet the CCIR norms. Improvements may possibly be derived by shaping the subreflector, which should be the subject of further investigations. The crosspolar pattern however, remains far below the CCIR reference curve.

Comparison of the multiple-beam torus antenna with *n* separate parabolic dishes shows that the torus antenna may yield great benefit with respect to the total main reflector area required, to realise simultaneous reception of the signals coming from *n* DBS's with mutual orbital distance of 6 degrees.

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