Compact Multimode Horn with Low Sidelobes for Global Earth Coverage

Christophe Granet, Trevor S. Bird, *Fellow, IEEE*, and Graeme L. James, *Fellow, IEEE*

***Abstract*—A new multimode corrugated horn is described for full-earth coverage from a geostationary satellite. The horn has low sidelobes, low cross polarization, and is compact. We outline the design of this horn and compare its performance with other circular horn types, including conventional single and multimode-corrugated horns and dielectric loaded horns. A design was fabricated and measured results are described for return loss, radiation patterns, and axial ratio. These measurements demonstrate excellent agreement with computer predictions using mode-matching software.**

***Index Terms*—Horn antennas, satellite antennas.**

I. Introduction

GLOBAL earth coverage from a geostationary satellite is often required for telemetry and command signals as well as conventional communications traffic. From the geostationary orbit at about 36 000 km above the earth, the earth subtends an angle of 17.4°. With an increased number of satellites orbiting the earth, reducing the possibility of interference with other satellites is becoming more important than in the past. To minimize this interference, the amount of sidelobe energy should be as low as possible, both for the principal and cross-polarized signals. Taking these considerations into account, it is apparent that an ideal full-earth coverage antenna should be circularly symmetric and, therefore, most global coverage antennas are either reflectors or horns. While the beam of a reflector antenna can be shaped to provide the desired earth coverage, a disadvantage of reflectors is that the feed spillover can be high and this can lead to significant sidelobe energy and interference.

Horn antennas, on the other hand, are often used for global coverage because they are simpler than reflectors and have low, well-controlled sidelobes. Some horns used successfully for global-coverage include the smooth-wall conical, multimode conical, and corrugated-wall types. The multimode and corrugated varieties have been used to cover most communications satellite bands such as described by Kitsuregawa for transmit and receive band horns for C-band [1]. None of the above mentioned horns have been designed especially for low-sidelobes, although Ludwig showed that the pattern of a circular horn could be controlled by selecting the modes [2] and some of these ideas have found application in feeds for reflectors. Examples include a prime-focus two-hybrid mode feed in [3] and a two-mode corrugated horn designed to maximize the efficiency of a Cassegrain reflector as in [4] or be used as a feed for earth coverage for the global positioning system (GPS) in [5]. While these last two horns give excellent radiation patterns with relatively low sidelobes, they are very long and, therefore, may be unsuitable for satellite applications. Another possibility is the corrugated horn recently described by Gonzalo *et al.* [6]–[8]. This horn has low sidelobes and is quite compact (where "compact" refers to its physical dimensions).

In the present application the aim was to develop a horn with the lowest possible sidelobes and, at the same time, produce a circularly polarized beam with a 3-dB beamwidth given by the angle subtended by the earth. The application called for narrow-band operation and low cross polarization and, because the intended use was on a satellite, the horn had to be as compact as possible. As the sidelobe requirement was crucial, we concentrated particularly on the radiation characteristics of the various horn designs and, given the circular polarization requirement, considered circularly symmetric horn designs only. These can be of various types: 1) corrugated horn designed for single (HE_{11}-mode) hybrid-mode operation; 2) corrugated horns designed for dual or multihybrid-mode operation; and 3) hybrid-mode horns using dielectric loading to support the desired modes.

In the next section, we survey possible horn types that could meet our requirements. As a result of our investigations a new compact multimode horn has been developed and this is described in Section III. An experimental model has been built and tested and these results are compared in Section IV with the theoretical design.

II. Survey of Horns with Low Sidelobes

A. Design Objectives

The design objectives of a typical antenna required for global earth coverage are listed in Table I. As the sidelobe requirement was crucial, we concentrated mainly on the radiation characteristics of the various horn designs. Given the very narrow bandwidth specification of <1%, the input match can be readily improved, if necessary, with selective tuning in the final design.

We considered the three types of hybrid-mode horn designs discussed below in Sections II-B–D. All the calculations were made with accurate software based on the mode-matching method. In this technique, we deduce a scattering matrix for the modal fields at each junction along the length of the horn. Such junctions arise from a change in waveguide diameter forming the corrugated surface or a change in diameter between two partly filled waveguide sections in the case of a dielectrically loaded horn. From these individual scattering matrices an overall scattering matrix is obtained for the entire

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TABLE I
DESIGN OBJECTIVES

Centre frequency	f_c GHz
Bandwidth	$0.995 f_c \leq f \leq 1.005 f_c$
3dB beamwidth	17.4°
Azimuth pattern	Symmetrical
Gain	> 20 dBi
Sidelobes	low as possible (- 35 dB or better)
Cross-polarization	< -40dB at f_c
Polarization	linear or circular
Weight	as low as possible

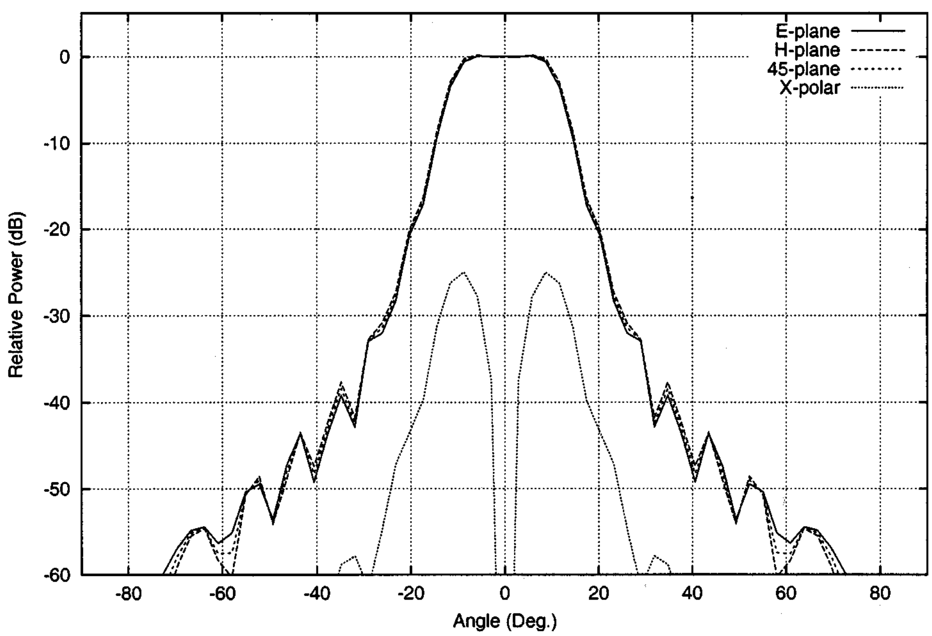


Fig. 1. Radiation pattern of a JPL-type corrugated horn at f_c.

horn [9], [10]. Then, assuming a TE_{11}-mode only is excited in the input waveguide and that the aperture, is located in a ground plane, the complete performance of the horn can be deduced.

All the software used in the theoretical study had been extensively tested previously in a variety of examples and applications. None of these applications, however, had the extremely low sidelobe requirement specified in this project. As a result, care was taken to ensure that the solution had converged and results from alternative programs were in agreement. An important parameter for numerical accuracy is the number of modes used to represent the field throughout the horn. The number of modes, therefore, was increased until the solutions converged. In the analysis, we assumed negligible reflection and mode coupling at the radiating aperture and this was verified by several examples using computer software that took this effect into account [11]. Furthermore, in all calculations, diffraction from the aperture flange was included by means of the geometrical theory of diffraction [12] or the physical theory of diffraction [13]. As expected, the effect of the flange was generally insignificant, consistent with low-wall currents caused by radiating hybrid-modes from a large aperture.

TABLE II
RADIATION PATTERN DETAILS OF THE JPL-TYPE CORRUGATED HORN

Horn	H-plane taper @ 8.7°	E-plane taper @ 8.7°	45-plane taper @ 8.7°	Aperture Diameter	Length	1^{st} sidelobe
JPL-type	-0.22 dB	-0.59 dB	-0.42 dB	9.5 λ_c	30 λ_c	-32 dB

B. HE_{11}-Mode Corrugated Horns

The characteristic behavior of the radiated field from HE_{11}-mode horns operating sufficiently near the balanced hybrid condition [14] is a high degree of radiation pattern symmetry, low cross-polarization and low sidelobe levels. It is this last characteristic that was of particular interest for this application.

The various types of single-mode HE_{11}-mode horn design can be further classified into two main categories: 1) narrow-band horns and 2) wide-band horns [15].

In the narrow-band horn, the phase variation of the field across the aperture is small (ideally zero), producing a radiated field with a well-defined main beam, distinct sidelobes, and nulls, and a phase center at or close to the aperture of the horn. As the name implies, this type of design is restricted in bandwidth performance (not an issue in this application) as both pattern beamwidth and phase center change significantly with frequency. Several examples giving the required beamwidth were investigated but the designs were generally too long (around $17\lambda_c$ for the better designs, where λ_c is the free-space wavelength at the center frequency, f_c, of the band) with a first sidelobe level of around -26 dB. This was considered unsatisfactory and this type of horn was not investigated any further.

In the wide-band horn design the phase center variation of the field in the aperture plane is deliberately made large to the extent that the horn becomes "gain saturated." This means that the radiated beamwidth is largely independent of increasing frequency, as is the phase center which is now at a position near the throat region within the horn. Given the beamwidth specifications, several wide-band horn designs were produced, with the best example being a compact design ($4\lambda_c$ long) with a $3\lambda_c$ aperture diameter. The radiation pattern, however, was unsuitable. It differed considerably from the narrow-band design with the large phase-variation in the aperture field producing a radiation pattern with no distinct sidelobes. Whereas the first sidelobe of the narrow-band horn was -26 dB at an angle θ, the radiation level of the wide-band design at the same angle is only -20 dB and with a slower "rolloff" rate than that of the narrow-band design.

As both narrow-band and wide-band designs were unsuitable for the current application, an alternative design was considered, the so-called wide-band compact corrugated horn [16]. While horns of this design were considerably shorter than the narrow-band designs with the same aperture diameter, the penalty paid was an increase of about 6 dB in the peaks of the pattern sidelobes.

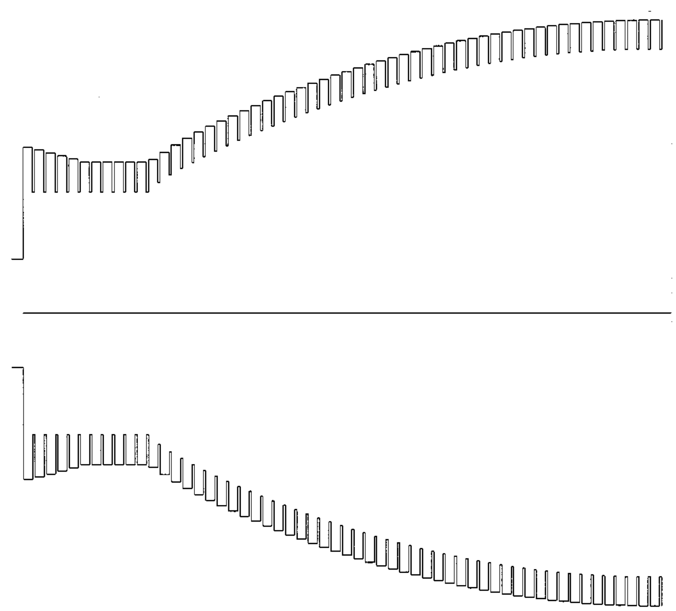


Fig. 2. Basic geometry of the bowl-shaped multihybrid mode corrugated horn

Another horn type considered is due to Gonzalo *et al.* [7], [8]. This horn has two smoothly joined sections comprising a conventional sin-squared taper from the input waveguide followed by a Gaussian taper to the aperture. Horns designed by this approach have quite low sidelobes. We found that the lowest peak sidelobe obtainable for a horn with a 17.4° half-power beamwidth was about -33 dB. Although this horn gave excellent pattern symmetry and low cross polarization (peak ~ -40 dB), it was $8.92\lambda_c$ long (aperture diameter $4.23\lambda_c$), which was considered too long, as well as too heavy, for the present application.

As none of the single HE_{11}-mode horns appeared to be attractive for our application, we turned our attention to multihybrid-mode horns.

C. Multihybrid-Mode Corrugated Horns

One of the first successful applications of horns where higher-order modes were deliberately included to improve horn radiation performance was due to Potter [17] and also Ludwig [2].

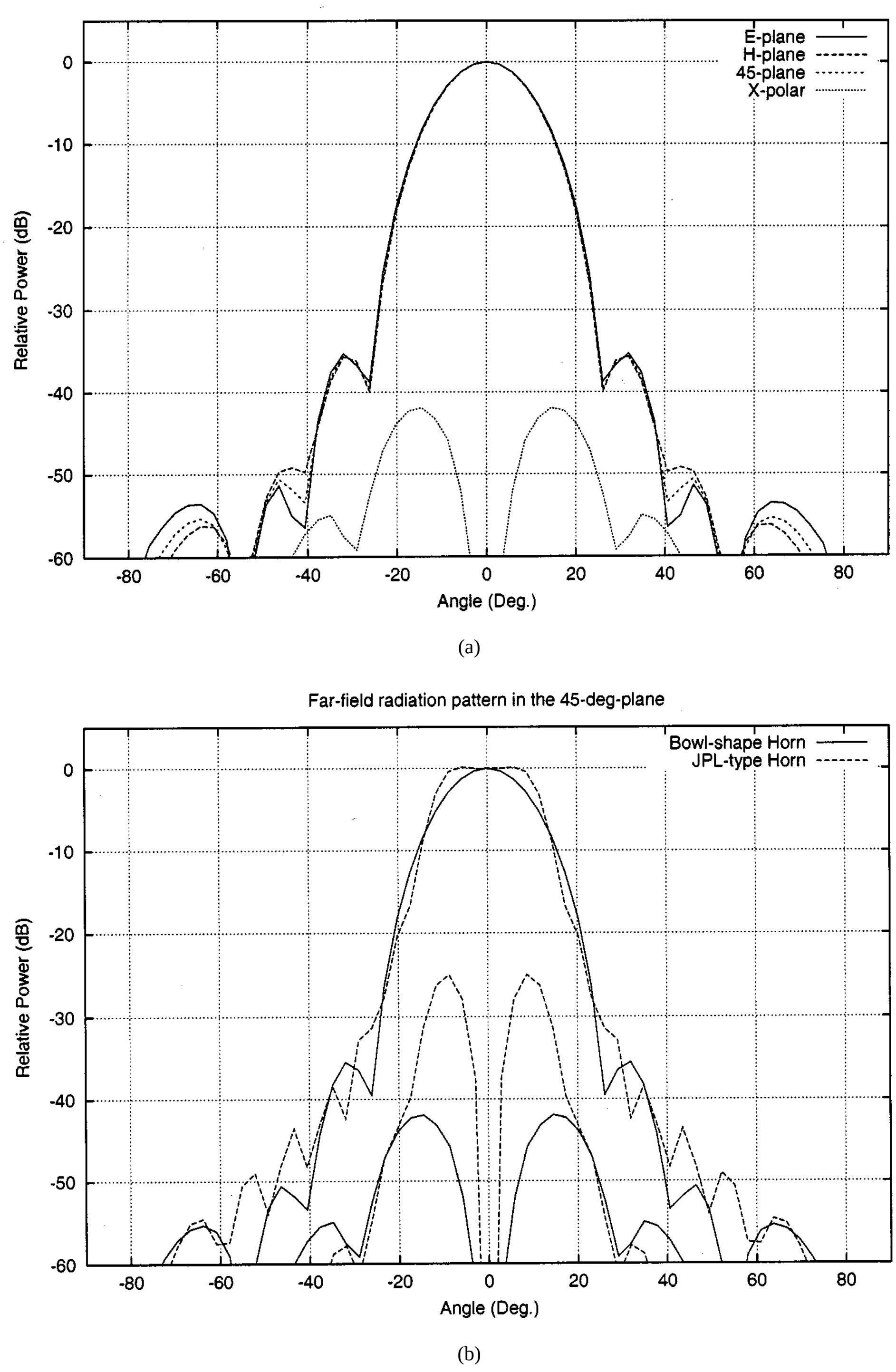


Fig. 3. (a) Radiation pattern at f_c of the bowl-shaped multihybrid mode corrugated horn and (b) comparison in the 45°-plane with the JPL-type horn.

Later, Thomas [3] extended the concept to a dual-hybrid-mode horn. In all cases, the basic principle is to design the horn such that two or more modes are in the correct amplitude and phase relationship in order to give a desired radiation pattern. Others have also investigated the dual-hybrid-mode horn (i.e., [3]–[5]). One of the more successful designs is that from researchers at Jet Propulsion Laboratories (JPL) [4] who achieved a radiation pattern almost ideal for our requirements. Based on that work, we designed a JPL-type horn for our application. The results are reproduced in Fig. 1 and the horn details given for f_c in Table II. While this horn is very long ($30\lambda_c$) and impractical for application as an on-board satellite antenna, it does provide a benchmark radiation pattern with which to compare results for more practical horn configurations.

We undertook an extensive range of computer simulations of multihybrid-mode horn geometries, where the basic geometry shown in Fig. 2 proved to give close to optimum performance. The horn consists of a uniform circular waveguide input, which supports the TE_{11}-mode, an abrupt step from smooth-walled to corrugated waveguide, followed by a profiled corrugated "bowl-

TABLE III
RADIATION PATTERN DETAILS OF THE BOWL-SHAPED MULTIHYBRID-MODE CORRUGATED HORN

H-plane taper @ 8.7°	E-plane taper @ 8.7°	45-plane taper @ 8.7°	Aperture diameter	Length	1st sidelobe	Gain
-2.97 dB	-2.85 dB	-2.91 dB	4.6 λ_c	5.6 λ_c	-36 dB	20.9 dBi

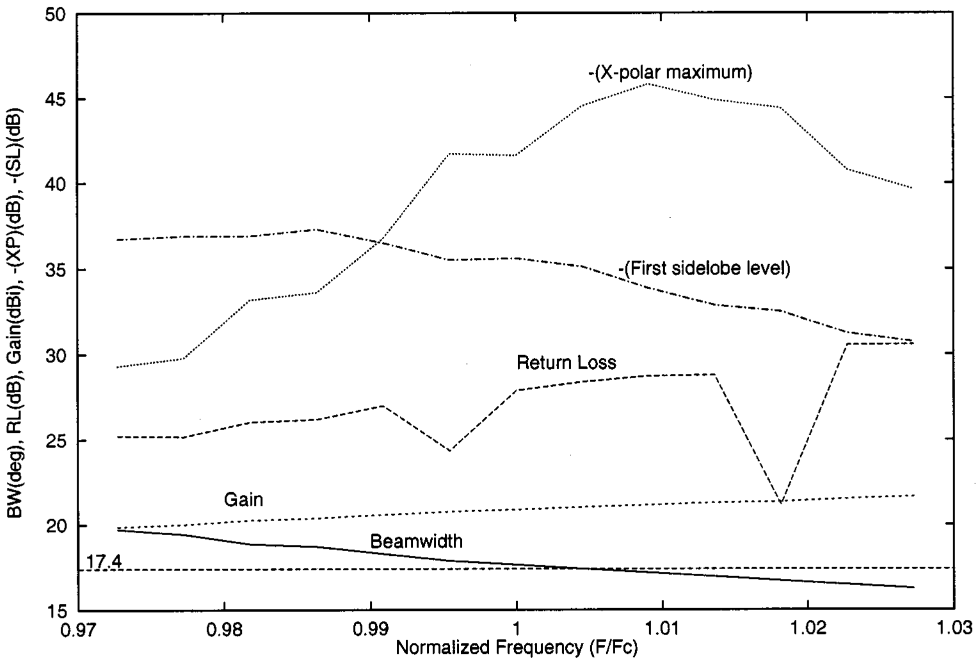


Fig. 4. Performance of the bowl-shaped horn over a ±2.5% bandwidth (note that the cross-polarization and sidelobe peaks are plotted as absolute values).

shaped" section to the aperture. This is our preferred design and details are given in Section III.

D. Dielectrically Loaded Hybrid-Mode Horns

While corrugated horns have for many years been the norm for hybrid-mode radiators, there has been increasing interest over the past decade in dielectrically loaded hybrid-mode horns [18], [19]. This type of hybrid-mode horn may not be suited to the current application because of the difficulty in obtaining suitable, and space qualified, dielectric materials. Nevertheless, it was worthwhile comparing its performance with that of corrugated horns to see if it offered any advantages in electromagnetic performance. As part of this study, several designs were investigated but none of them gave better performance than the bowl-shaped multihybrid-mode corrugated horn just described.

III. DESIGN OF THE NEW COMPACT MULTIMODE HORN

We now give a more detailed description of the bowl-shaped multihybrid-mode corrugated horn (Fig. 2). This horn consists of an input feed waveguide, a HE_{1n} mode generator section which excites multihybrid modes (mode-converter) and a flared section which preserves the basic characteristics of these modes while bringing them into the appropriate phase relationship at

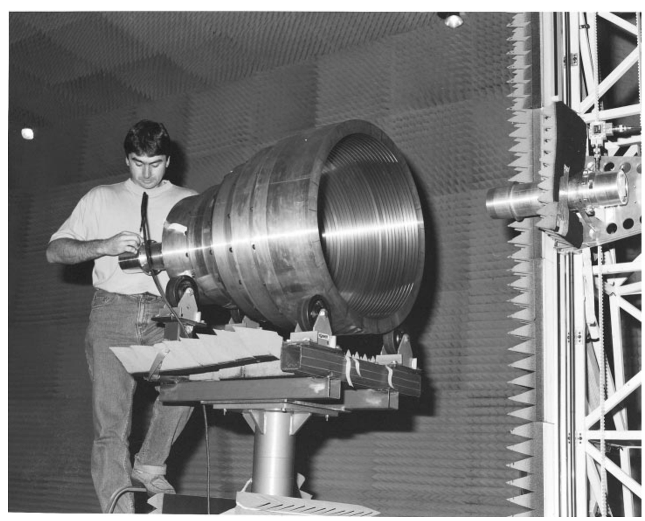
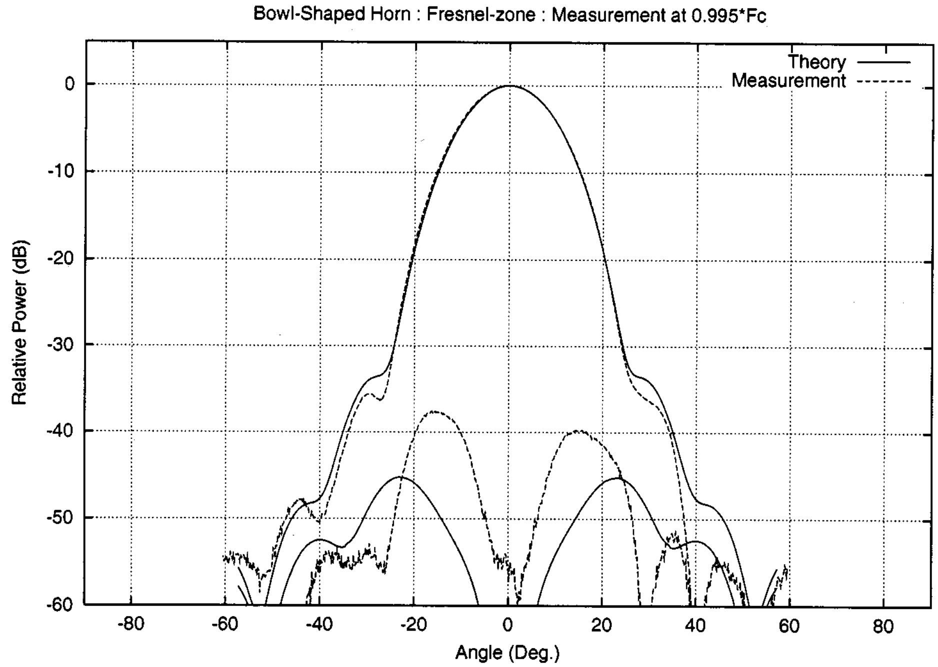
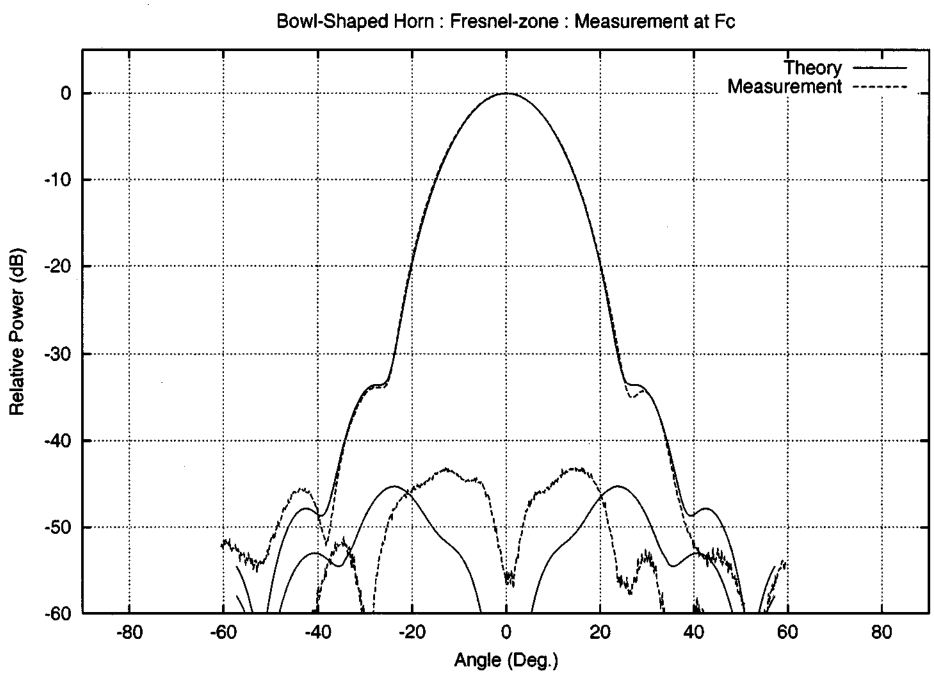


Fig. 5. Photo of the bowl-shaped multihybrid-mode corrugated horn with its linear-polarization input section in the planar near-field anechoic chamber.



(a)



(b)

Fig. 6. The 45°-plane measured and theoretical Fresnel zone radiation patterns of the bowl-shaped horn at a distance $51\lambda_c$ from the horn aperture: (a) at 0.995 f_c, (b)f_c.

the horn aperture. The profile of the flared section is defined by its radius

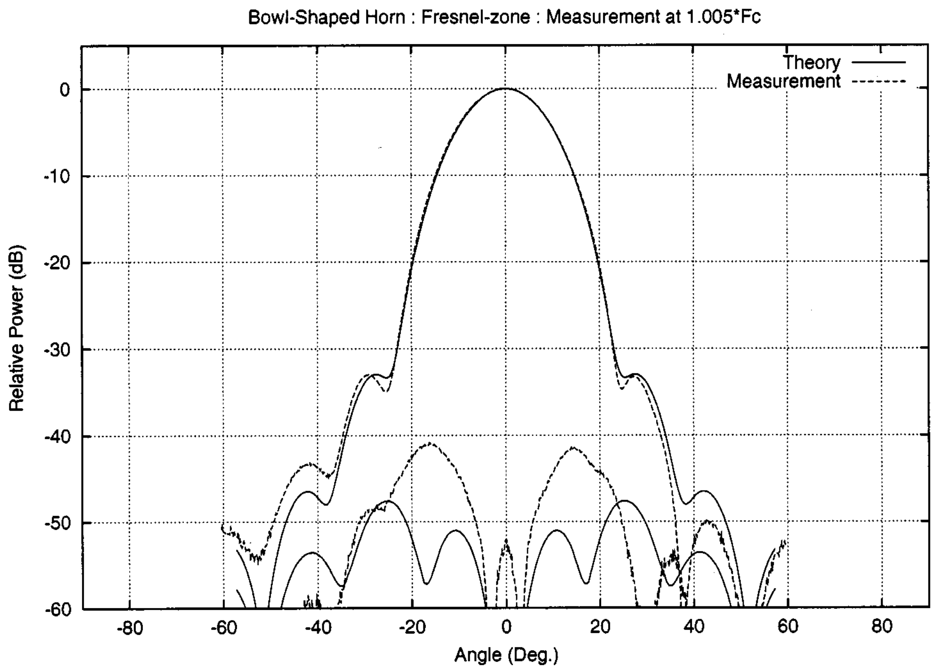
$$a(z) = a_i + (a_o - a_i)\sin^p\left(\frac{\pi z}{2L}\right)$$

where

- a_i radius of the mode generator;
- a_o output radius;
- L length of the flared section;
- p power of the profile.

For low sidelobes we have found that p should be $\leq$1 and the optimum value for the present application is $p = 0.8$. The mode generator section is designed with radius of about $a_i = 2.2a_w$, where a_w is the radius of the input waveguide.

The radiation pattern of a bowl-shaped horn that is designed to meet the objectives given in Table I is shown in Fig. 3(a) and a comparison in the 45°-plane with the JPL-type horn is shown in Fig. 3(b). The characteristics of the calculated radiation pattern at f_c are summarized in Table III. This shows that as well as meeting the gain and



(c)

Fig. 6. (*Continued.*) The 45°-plane measured and theoretical Fresnel zone radiation patterns of the bowl-shaped horn at a distance $51\lambda_c$ from the horn aperture: (c) 1.005 f_c.

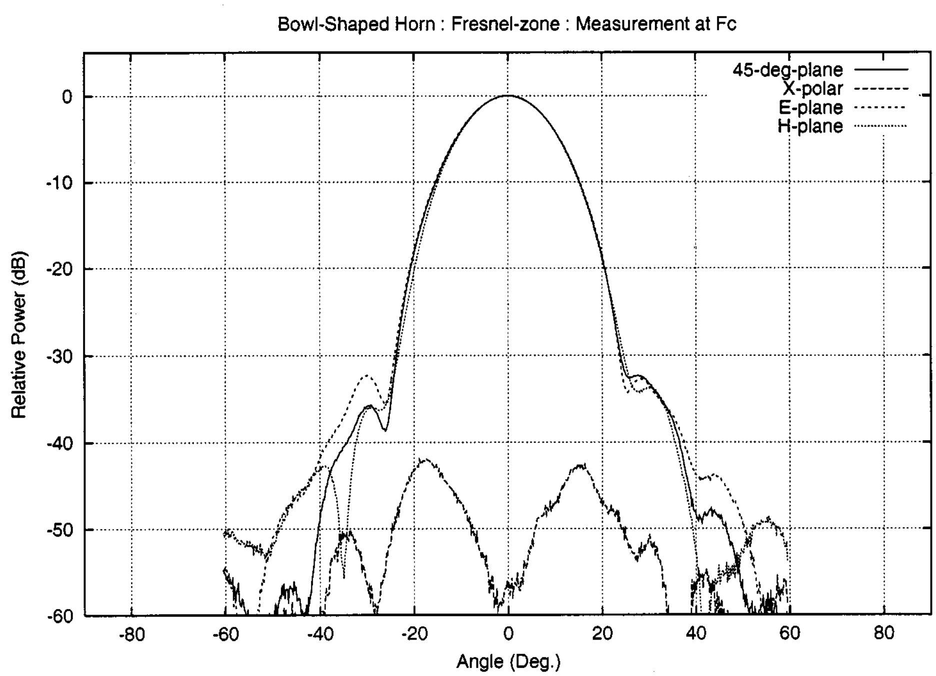


Fig. 7. The measured Fresnel zone radiation pattern at f_c in the E, H and 45°-planes at $66\lambda_c$ from the aperture.

sidelobe requirements, the horn is very compact, being only $5.6\lambda_c$ in length.

Some properties of a typical horn with $p = 0.8$ are shown in Fig. 4 for the case of a horn designed for full-earth coverage at the center frequency f_c. The figure shows the variation of the beamwidth, input return loss, gain, peak cross polarization and peak sidelobe level as a function of frequency. We see that although the horn was designed for narrow-band operation the performance is acceptable for many applications over at least a ±2.5% bandwidth.

IV. A Prototype Compact Multimode Corrugated Horn

To verify the design and evaluate its sensitivity to manufacturing tolerances, a full-size prototype bowl-shaped multihybrid-mode corrugated horn was manufactured and tested. The

TABLE IV
GAIN OF THE BOWL-SHAPED MULTIHYBRID-MODE CORRUGATED HORN

	Gain (dBi)		
Frequency	0.995 f_c	f_c	1.005 f_c
Theory (at 59 λ_c) (Fresnel zone)	21.4	21.5	21.7
Measured (at 59 λ_c) (Fresnel zone)	21.1 ± 0.3	21.2 ± 0.3	21.3 ± 0.3
Theory (far-field)	20.71	20.85	21.00
Predicted far-field from near-field data	20.74 ± 0.2	20.85 ± 0.2	21.01 ± 0.2

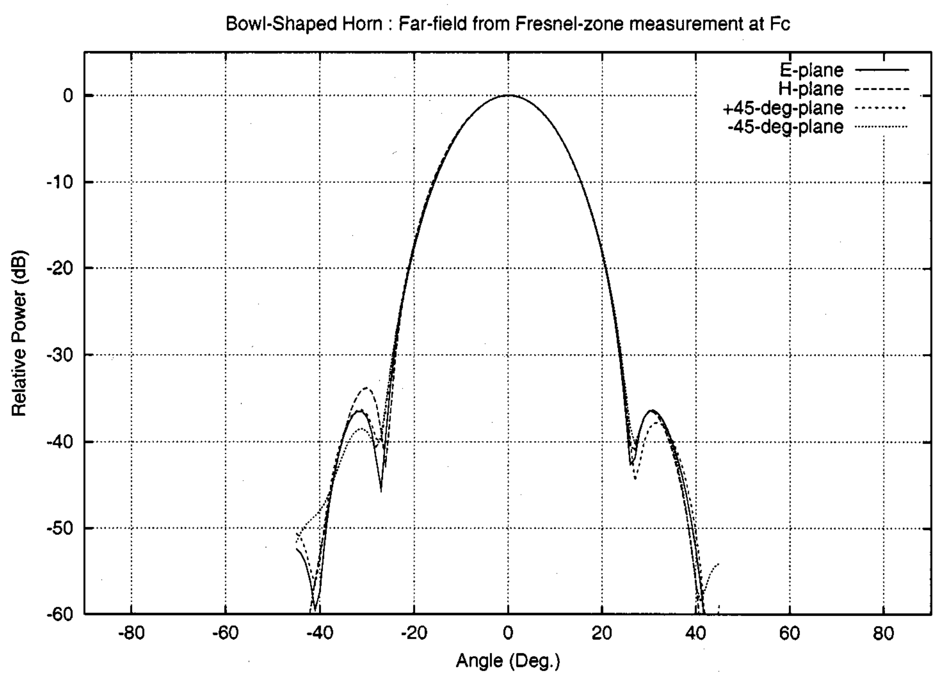


Fig. 8. Far-field radiation patterns at f_c as calculated from the near-field data

mode generator of this horn has 11 corrugations at the input followed by the bowl-shaped section of 45 corrugations terminating in an aperture diameter of $4.6\lambda_c$. Two input sections were produced—one for linear polarization to enable accurate testing of the horn and the other for generating circular polarization. Fig. 5 shows the prototype horn being prepared for measurement. The return loss of the horn, which was measured by de-embedding these input sections using a vector network analyzer, gave a value of ~28 dB over the frequency band.

Of particular importance here is the low sidelobe levels and care was taken during the measurements to ensure accurate results. Radiation patterns in the Fresnel zone (51-66λ_c from the horn aperture) were taken in the principal planes and, overall, there was very good agreement between theory and experiment. The 45°-plane radiation patterns across the band, comparing the Fresnel zone theoretical calculation with the measured data, are shown in Fig. 6, and the complete set of E, H and 45°-plane measured patterns taken at a distance of $66\lambda_c$ at f_c are shown in Fig. 7. For circular polarization operation, an axial-ratio ≤0.1 dB was measured across the band.

The gain was measured at a distance of between $51\lambda_c$ and $59\lambda_c$ from the horn aperture using the gain-comparison method. The results obtained are presented in Table IV.

Additional measurements were made in a near-field range to verify the sidelobe performance in the far-field region. The measured radiation patterns at f_c are shown in Fig. 8. In addition, our near-field data processing software predicts the gain of the horn from the near-field data and these predictions are summarized in Table IV. We see the predicted far-field gain is in very close agreement with the measured data.

V. Conclusion

A new corrugated horn has been developed for full-earth coverage from a geostationary satellite. This multihybrid-mode horn has very low sidelobes, a well defined gain and is exceptionally compact. The theoretical design has been verified with an experimental antenna and excellent agreement was achieved between theoretical and measured data. With the design now proven, the next stage is to produce a lightweight version of the horn suitable for installation on a satellite.

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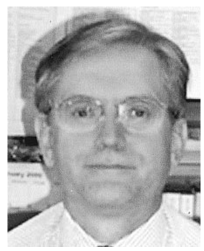

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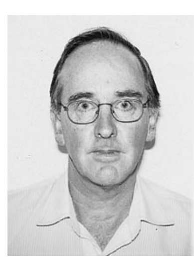

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