A Shaped-Beam Microstrip Patch Reflectarray

D. M. Pozar, *Fellow, IEEE*, S. D. Targonski, and R. Pokuls

***Abstract*— This paper describes a microstrip reflectarray antenna designed to produce a shaped-beam coverage pattern using phase synthesis. The concept is demonstrated with a Ku-band linearly polarized reflectarray designed to provide coverage of the European continent and measured results are compared to those obtained for a previously designed shaped-reflector antenna designed for the same coverage specifications. Results validate the shaped-beam reflectarray concept, although there are disadvantages to the reflectarray such as narrow bandwidth and reduced aperture efficiency that may offset the mechanical and cost advantages of the flat surface of the reflectarray.**

***Index Terms*— Printed antennas, reflectarrays, shaped-beam antennas.**

I. Introduction

A reflectarray is an array of reflecting elements that are space fed with a feed antenna. The reflection phase from the reflectarray elements are designed so that the reflected energy from the array is collimated to form a main beam in a given direction. Reflectarrays were first described in the early 1960's [1], but the development of microstrip technology in the 1970's has given the subject additional impetus due to the ease of manufacture of large arrays of printed reflecting elements [2]–[8]. The reflectarray has inherent mechanical advantages over parabolic reflector antennas and, hence, there is interest in using these antennas as replacements for standard reflectors.

Parabolic and shaped-reflector antennas have long been used for fixed satellite service applications. These antennas are mounted on spacecraft in geostationary orbit and are designed to produce a shaped beam in order to most efficiently illuminate a selected geographical area with a minimum gain. In addition, stringent isolation and crosspol requirements are often placed on these antennas. Shaped-beam reflector antenna structures, however, suffer from mechanical drawbacks such as bulkiness, the need for an expensive custom mold for each coverage specification, thermal problems, and others. A flat reflectarray configuration is attractive because it allows a single mechanical design to be used repeatedly for a wide variety of different coverage specifications without the need for expensive fabrication of a new mold, and associated thermal and mechanical modeling, for each new design. The only changes required are that the printed reflecting element dimensions be changed for each design in order to generate the new shaped beam. Details such as the substrate and backing structure design (both mechanical and electrical) remain the same. Thus, many of the high recurring costs associated with shaped-reflector antennas can be eliminated with flat printed reflectarrays. The flat geometry of a reflectarray also lends itself to easier placement and deployment on the spacecraft bus and also in terms of manufacture.

As is well known, however, reflectarrays suffer from several disaddvantages when compared with parabolic reflectors—such as limited bandwidth and slightly reduced aperture efficiency [3]–[8]. For wide-bandwidth applications, the standard parabola will always be the preferred design choice due to its true time-delay characteristics. But for narrow-band applications or for applications where electrical performance may be traded off for cost or mechanical advantages, a reflectarry antenna may be preferred. In fact, a significant number of communications satellite applications require only about 5% bandwidth (e.g., direct broadcast satellites).

Reflectarray work to date has concentrated on the generation of pencil beam patterns. This paper describes the design, manufacture, and test of a planar reflectarray that generates a shaped beam for European continental coverage. A standard shaped-reflector antenna had previously been designed and tested for this application, so we are able to provide a direct comparison of the performance of a shaped-beam reflectarray with that of a traditional shaped reflector. The coverage area for this application requires that the beam be fairly severely shaped, and thus the design provides a good test of the feasibility of shaped-beam reflectarrays. The paper will show the variation of the beam shape and coverage parameters with frequency and compare with results obtained for the the shaped-reflector baseline design. Results show that shaped-beam reflectarrays are capable of providing performance close to that of traditional shaped-reflector antennas.

II. Characteristics of Microstrip Patch Reflectarrays

Principle of Operation: The usual microstrip reflectarray consists of an array of microstrip patches or dipoles printed on a thin grounded dielectric substrate. A feed antenna illuminates the array and the individual elements are designed to scatter the incident field with the proper phase to form a planar phase surface in front of the aperture. Space feeding the reflectarray eliminates the complexity and losses of a microstrip feed network. There is a great deal of flexibility in choosing the feeding geometry for a reflectarray, as it is possible to use prime focus feeding, offset feeding, and novel types of cassegrain feeds. The concept of the reflectarray is not new, but the rapid development of microstrip antenna technology, coupled with the need for low-cost, high-gain, and aesthetically pleasing antennas for commercial applications, has led to the use of microstrip elements in a variety of reflectarray configurations [3]–[8]. It is also possible to scan the main beam, obtain

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monopulse patterns, and perform phase-synthesized pattern shaping with a microstrip reflectarray. This last possibility is the subject of the present paper.

Element Types: One of the key features of microstrip reflectarray implementation is how the individual elements are made to scatter with the desired phases. One method is to use microstrip patches of the same size with stubs of variable length to control the reflection phase [2], [3], and [7], but a better approach is to use patches of variable size to control the phase [4], [5], and [8]. Both methods can be viewed as techniques for introducing a small shift in the resonant frequency of an element, which has the effect of changing the phase of the reflected field, as discussed in further detail in [8]. Using elements of variable size allows much more freedom in laying out an array for dual or circular polarization (with the additional advantages of improved bandwidth and simpler analysis) when compared with stub-tuned elements. Contrary to a statement in [7], variable sized patches are no more sensitive to etching tolerances than are stub-tuned patches since the resonant frequency in both cases is inversely proportional to patch length. The variable size-patch technique, coupled with a full-wave moment method analysis, has been demonstrated with variety of microstrip reflectarrays at frequencies ranging from 5 to 77 GHz [5], [8].

The concept of using variable size rectangular patch elements to vary the reflection phase can be extended to other types of elements, such as circular patches, annular ring elements, and crossed dipole elements. These elements will respond to both vertical and horizontal polarizations, which is an advantage for dual linear or circularly polarized antennas. For linearly polarized antennas, however, it is preferable to use linearly polarized elements such as thin dipoles or rectangular patch elements because these polarization-selective elements will reduce cross-polarization levels. Since loss decreases with an increase in patch width, wider rectangular elements are preferred over thin dipoles. Wide patch elements also have better bandwidth characteristics compared to thin dipoles. Thus, for the linearly polarized reflectarray antenna considered here, rectangular patch elements were used.

III. Reflectarray Design and Implementation

As stated above, the purpose of this work was to design a flat microstrip reflectarray to produce a specified shaped-beam pattern, and to compare the performance of this reflectarray with that of a conventional shaped-reflector antenna designed to produce the same shaped beam. The shaped-reflector antenna had been previously designed and modeled using highly accurate and proven methods at Spar Aerospace and coordinates defining the contour of the shaped reflector were available for use in the design of the microstrip reflectarray.

Description of the Shaped-Reflector Antenna: The Ku-band reflectarray was designed with the same aperture size and coverage specification as a traditional shaped reflector that had been previously designed and evaluated at Spar Aerospace Ltd. This shaped reflector was designed to illuminate continental Europe with a shaped coverage pattern at two 5% frequency bands at 14 and 18 GHz. The original design employed two superimposed gridded and shaped reflectors, with each gridded shell handling a separate polarization. The gridding ensures that a high degree of polarization purity is maintained. The reflectors had elliptical projected apertures with major and minor axes of 110 and 90 cm, respectively, with focal lengths of 76 cm.

TABLE I
Shaped-Reflector Antenna Design Specification and Performance

Parameter	Specification	Performance Achieved (shaped reflector)
Directivity at edge coverage	23.0 dB	23.4 dB
Cross-pol isolation	-30 dB	-35 dB
Gain slope	10 dB/°	5.6 dB/°

The coverage requirements for the shaped-reflector antenna and the performance actually achieved by the baseline design using the gridded shaped reflector are given in Table I for the frequency band of 13.8–14.5 GHz and for the specified coverage region [indicated by the polygon in the reflectarray patterns plotted in Fig. 6(a)–(c)].

Commercial reflector design software (Ticra's POS program) was used to design the shaped-reflector antenna. This program is based on physical optics and uses an optimization engine driving a reflector analysis program to arrive at a doubly curved reflector shape to yield a target directivity within a given geographical contour. The output of the program is in the form of coefficients of a Zernike polynomial which describes the reflector surface. Once the coefficients are known, it is a simple matter to find any point (x, y, z) on the surface by series summation. The required patch reflection phases are then derived from the shaped-reflector contour using the technique described below. Fig. 1 shows the surface contours of the Spar Aerospace shaped reflector with the parabolic component subtracted out.

Translating the Desired Aperture Phase to the Patch Reflection Phase: The relation of the flat microstrip reflectarray to the shaped-reflector antenna is illustrated in Figs. 2 and 3. The reflector and feed system are positioned in the (x, y, z) coordinate system with the (x', y', z') coordinate system used locally on the reflectarray. The phase center of the feed is located at $(x_f = 0, y_f = 0, z_f)$ in the (x, y, z) system. The microstrip reflectarray is assumed to lie on the surface formed along the top and bottom edges of the reflector, meaning that the reflectarray surface is tilted at an angle of $\theta_b = 22.8°$ with respect to the x axis. The projected area in the x-y plane of the elliptical shaped reflector was 90 cm $\times$ 110 cm. To duplicate the aperture size of the shaped reflector, the ellipse of the reflectarray should have a major axis (y') length of $a = 110$ cm and a minor axis (x') length of $b = 90$ cm/cos (22.8°) $= 97.62$ cm. Because of the availability of standard substrate sizes, however, the large dimension of the reflectarray was limited to $b = 90$ cm; this results in a drop of about 0.35 dB in directivity as compared to that of the shaped reflector.

Since we know the coordinates of the previously designed shaped reflector that produces the desired beam shape through phase synthesis, ray tracing can be used to determine the necessary reflection phases of the reflectarray elements to

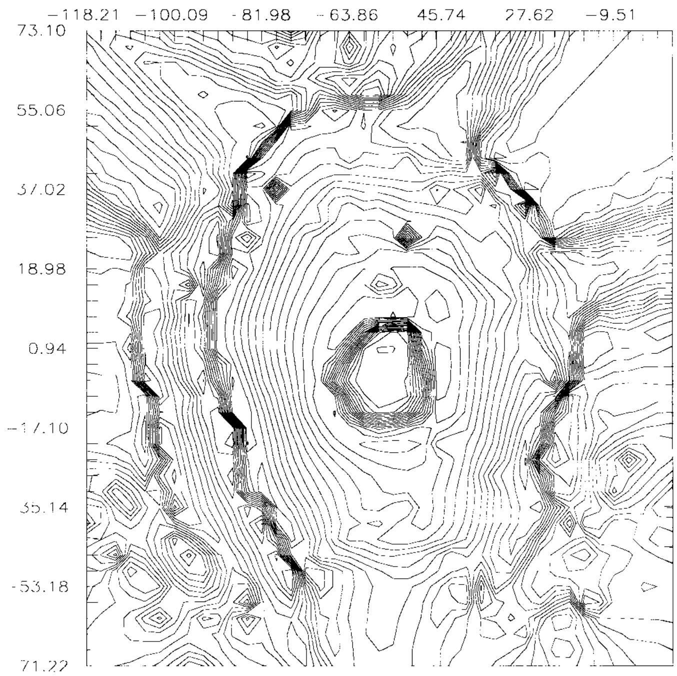


Fig. 1. Contours of constant phase derived for the shaped-reflector surface obtained from physical optics. The scales are in centimeters, with an arbitrary origin. Phase contours are in increments of 20°; the elliptically shaped outline of closely spaced contours represents the edge of the reflector.

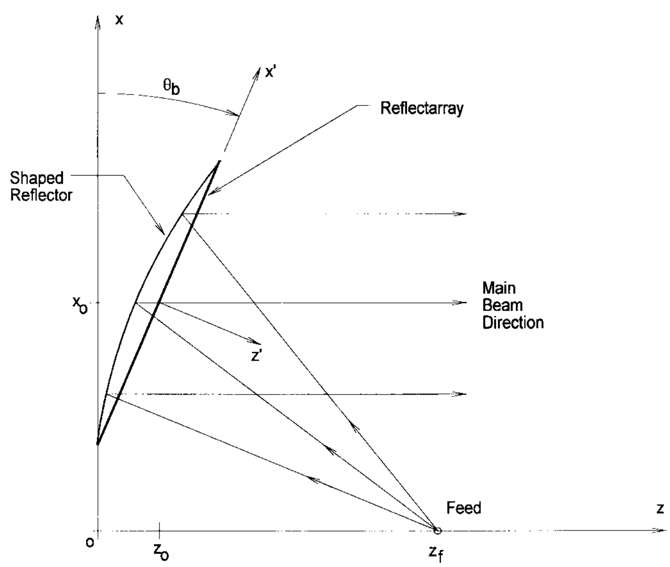


Fig. 2. Side view of the geometry and coordinate systems for the shaped-beam reflectarray antenna.

duplicate the same radiating aperture phase distribution as was synthesized for the shaped-reflector antenna. This procedure is illustrated with the aid of Fig. 2. The total path length from the feed to the reflectarry aperture is the sum of the distance from the feed to a point on the shaped reflector and the distance from that point to the corresponding point on the reflectarry with the rays satisfying Snell's law on the reflector surface. In this way, a progressive phase shift is generated in addition to the phase required to shape the main beam and no additional phase shift is needed to scan the beam in the desired direction.

Since the reflectarray is designed in the primed coordinate system, the following coordinate transformation is used to find the point (x, y, z) on the shaped-reflector surface that corresponds to the point $(x', y', z' = 0)$ at a given patch element on the reflectarray:

$$x = x_0 + x' \cos\theta_b \tag{1a}$$

$$y = y' \tag{1b}$$

$$z = z + 0 + x' \sin\theta_b \tag{1c}$$

where $(x_0, y_0 = 0, z_0)$ are the coordinates of the origin of the (x', y', z') system relative to the (x, y, z) system. If the coordinates of a point on the shaped reflector are given as (x_{sh}, y_{sh}, z_{sh}), then the required reflection phase of the reflectarray patch element located at $(x', y', z' = 0)$ is given by

$$\phi = k_0\left(\sqrt{x^2 + y^2 + (z_{sh} - z_f)^2} + z - z_{sh}\right) \tag{2}$$

where (x, y, z) are given by (1), and z_f is the z-coordinate of the phase center of the feed horn.

For the design considered in this paper, the following values were used:

size of reflectarray ellipse:

$a = 110.$ cm, $b = 90.$ cm

origin of reflectarray coordinate system:

$(x_0, y_0, z_0) = (63.0, 0., 8.5)$ cm

phase center of feed horn:

$(x_f, y_f, z_f) = (0., 0., 63.5)$ cm

main beam scan angle:

$(\theta_b, \theta_b) = (22.8°, 0°)$

tilt angle of feed horn to z' axis:

$\theta_t = 19.7°$.

The above placement of the feed horn results in an incidence angle of $\theta_f = 26°$, relative to the normal of the reflectarray. As discussed in [6], main-beam squint versus frequency is minimized when the incidence angle of the feed antenna is close to the main-beam scan angle.

Selection of Elements and Substrate: The bandwidth of the reflectarray is related to the bandwidth of the reflectarray elements, which, for patch elements, is determined primarily by the substrate dielectric constant and thickness. Rogers Duroid 5880, with a dielectric constant of 2.2, was selected for the substrate material due to its low loss tangent and good homogeneity characteristics, which is especially important for a large array. Paper designs were completed for two substrate thicknesses, of 0.031 in and 0.062 in. Each of these designs used a rectangular grid of patches with spacings of 0.56λ in the E-plane (x' direction) and 0.68λ in the H-plane (y' direction), which are small enough to avoid grating lobes. The thinner material is preferable for weight and cost considerations, but analysis showed that the bandwidth of the reflectarray on the thinner substrate was significantly less than that for the thicker substrate, primarily in terms of beam-shape distortion at the band edges. Thus, the thicker substrate was selected for the prototype reflectarray model.

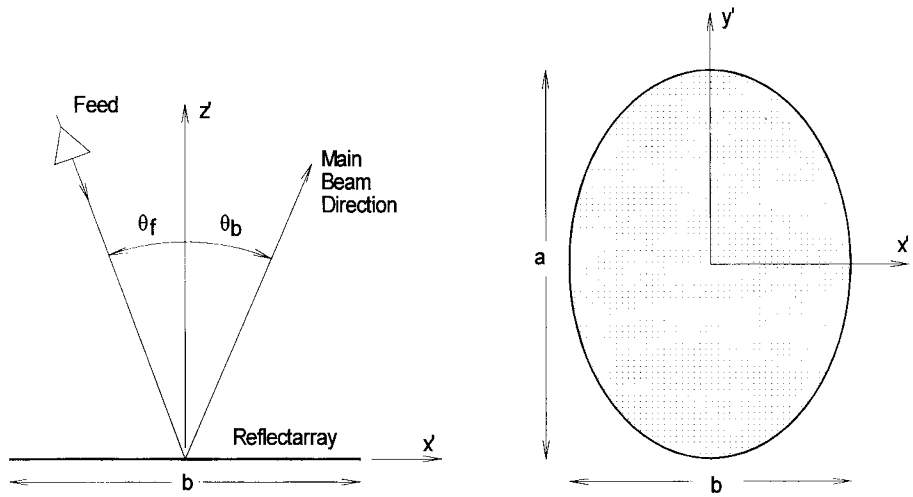


Fig. 3. Local (x', y', z') coordinate system and front view of the shaped-beam microstrip reflectarray. The reflectarray is polarized in the x' direction.

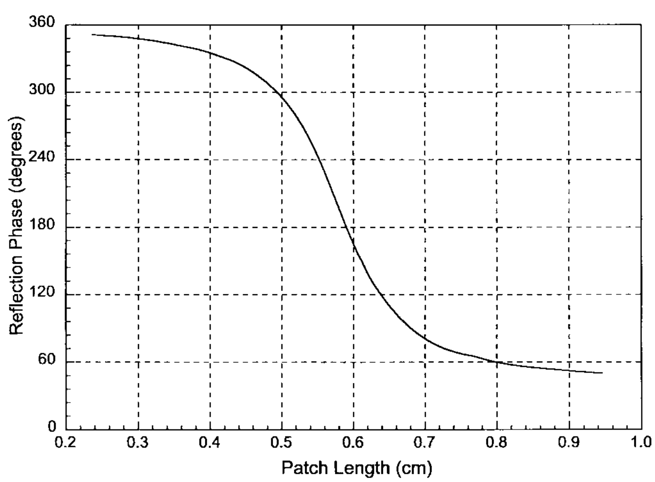


Fig. 4. Reflection phase versus element length for the shaped-beam microstrip reflectarray on 0.062 in Duroid. Frequency is 14.15 GHz, E-plane spacing is 1.187 cm, H-plane spacing is 1.442 cm, patch width is 0.84 cm, incidence angle is 0°.

Determination of Patch Dimensions: Once the element type and substrate parameters have been determined and the desired reflection phases are known, the patch dimensions can be calculated. For this step, all patch widths were set to be 0.84 cm as the array was linearly polarized. A full-wave moment-method analysis, as described in detail in [5], was used to generate a table of reflection phase versus patch-element length for various incidence angles. A graph of this data typically takes the form of an "S" curve, as shown in Fig. 4, for broadside incidence at 14.15 GHz for the patches used in this work. Resonance occurs when the reflection phase is 180° (phase reference at the ground plane of the substrate). For element lengths much shorter than this, the reflection phase approaches 360°, while for element lengths much greater than this the reflection phase approaches a minimum value of $2k_o d$, where d is the substrate thickness. Thus, it is possible to choose an element length to achieve almost the full 360° range of reflection phases. Elements requiring unattainable phase due to lengths either too long or negligibly short were not included in the array layout. A photograph of the final shaped-beam microstrip reflectarray prototype is shown in Fig. 5.

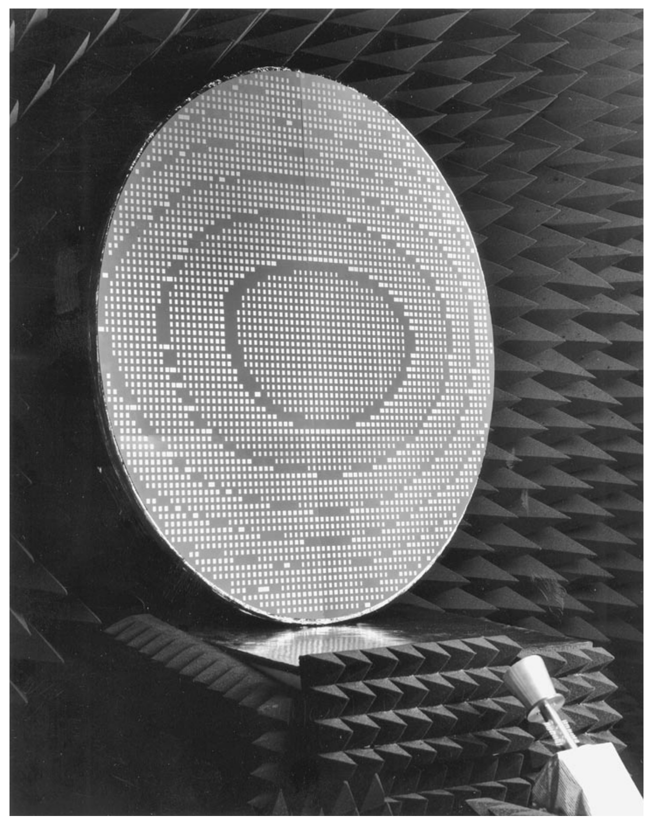


Fig. 5. Photograph of the prototype microstrip reflectarray.

Calculation of Reflectarray Performance: Once the patch dimensions have been determined, the same full-wave analysis technique that was used to determine the reflection phase versus patch length can be used to evaluate the actual reflection phases for each reflectarray element as a function of the actual incidence angle, the incident polarization, and the patch length. This is an intensive calculation, but due to an extremely efficient infinite periodic spectral domain technique and computer code, the total run time for the analysis of the reflectarray requires only a few minutes on a fast PC. The analysis provides radiation patterns, which were made over the full range of elevation and azimuth angles to form contour plots of the copolar radiation field. These are shown in Fig. 6(a)–(c) for frequencies at the lower band edge, the middle of the band, and the upper band edge, respectively.

The desired coverage area of continental Europe is shown as a dashed polygonal contour in Fig. 6(a)–(c). The specification was for a minimum directivity of 23 dB for all areas within the coverage area and it can be seen that this requirement is well satisfied for virtually all but a small coverage area for frequencies at the lower and upper band edges where the directivity is within 0.5 dB of the desired value. As expected, the directivity is highest at the mid-band frequency of 14.15 GHz.

IV. Measurement and Results

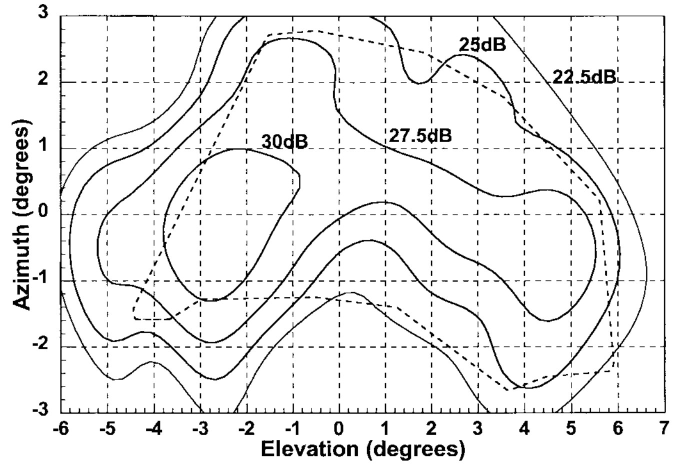
The layout of the reflectarray was performed using Autocad. The Autocad file was then used to generate a photo-etch film with which to perform the etching. Due to the large size of the reflectarray, it was necessary to etch the reflectarray in four separate sections. After etching, the four Duroid sheets were mounted on Styrofoam backing in order to provide support. Care was taken to ensure good alignment between the sections.

A corrugated horn mounted on a three-axis positioner was used to illuminate the array. This horn had the same edge taper and 3 and 10 dB beamwidth characteristics as the horn used in the Spar Aerospace shaped-reflector design. It was necessary to reposition the feed several times in order to find the optimal location. Testing was done in a near-field range using a Near-Field Systems Ltd. scanner and software. Near-field measurements were taken and transformed to the far-field in the usual manner using proprietary software.

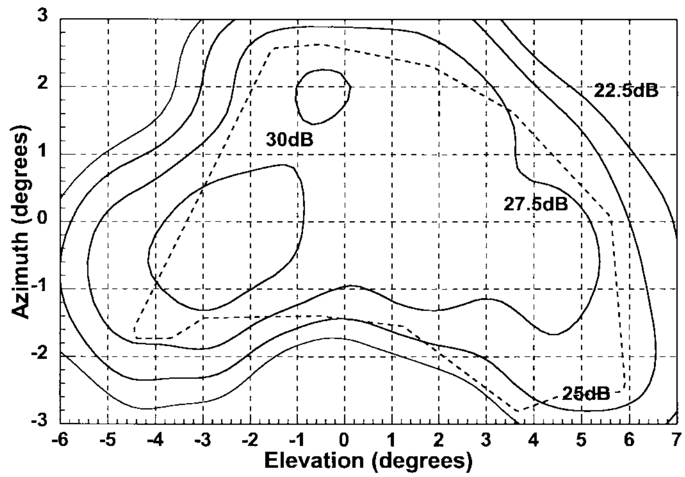
Shown in Fig. 7(a)–(c) are the copolar patterns obtained from measurement. Again, the desired coverage pattern is shown by a dashed polygonal line. The edge of the desired coverage gain specification of 23 dBi is met over this area for all frequencies except for small regions in the lower right of the contour plots. This performance is obtained in spite of the fact that the smaller aperture size of the reflectarray leads to a reduction of approximately 0.35 dB. Table II shows the minimum gain within the coverage contour as well as the percentage of the area within the desired coverage contour having a measured gain greater than 23 dBi over a range of frequencies extending beyond the desired operating band of the reflectarray.

Note that the best results are obtained at the lower band-edge frequency of 14.50 GHz, and not the center frequency (the design frequency) of 14.15 GHz. Most importantly, however, is the fact that a minimum gain of 23 dB is obtained over more than 99% of the coverage area over a frequency range from 13.8 to 14.85 GHz, which is a bandwidth of about 7%. The desired operating bandwidth of the reflectarray is 5%.

Crosspolar pattern measurements were also taken and it was found that the crosspolar isolation (copol minus crosspol) was better than −30 dB within the coverage region. The relatively low levels of crosspol are due to the fact that dimensions of the patches are constant in the crosspolar direction (i.e., the reflection phases are the approximately the same). Thus, the crosspol radiation from the feed is not focused, but is rather reflected specularly and, hence, crosspol levels are very low.



(a)



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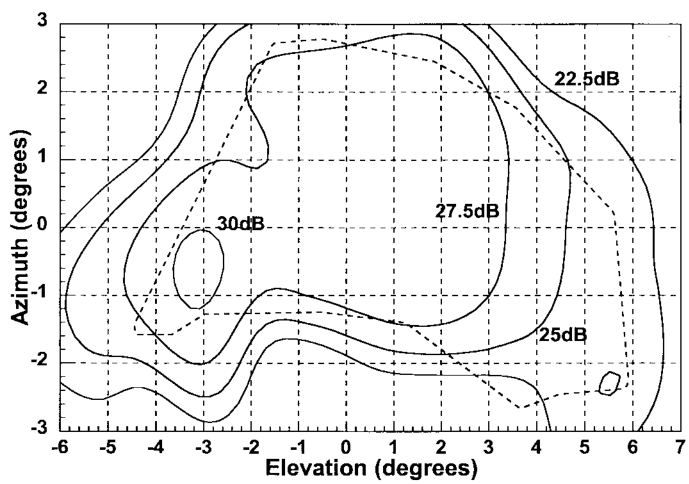
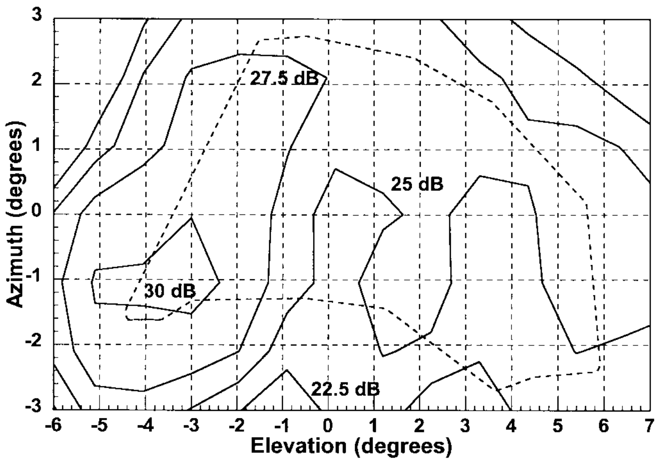
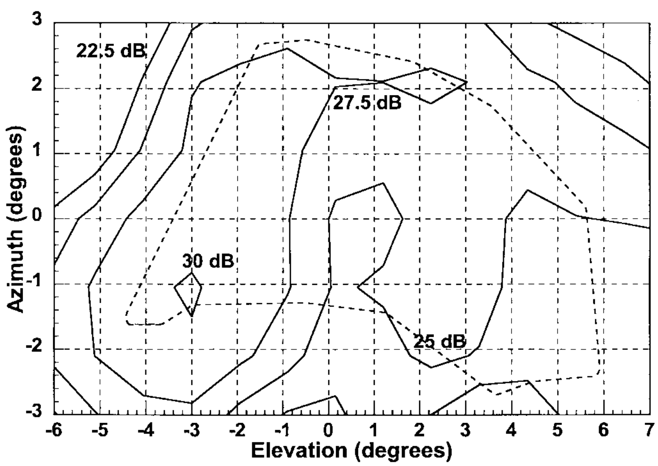


(c)

Fig. 6. (a) Calculated copolar pattern contours at 13.8 GHz. The desired coverage area is shown by the dashed polygonal contour. (b) Calculated copolar pattern contours at 14.15 GHz. The desired coverage area is shown by the dashed polygonal contour. (c) Calculated copolar pattern contours at 14.5 GHz. The desired coverage area is shown by the dashed polygonal contour.



(a)



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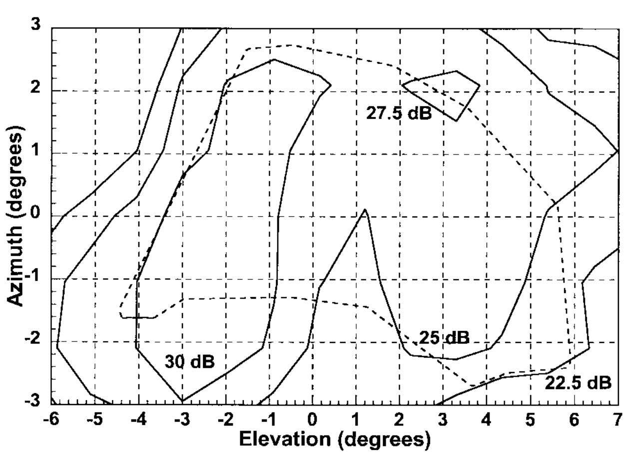

(c)

Fig. 7. (a) Measured copolar pattern contours at 13.80 GHz. The desired coverage area is shown by the dashed polygonal contour. (b) Measured copolar pattern contours at 14.15 GHz. The desired coverage area is shown by the dashed polygonal contour. (c) Measured copolar pattern contours at 14.50 GHz. The desired coverage area is shown by the dashed polygonal contour.

V. Conclusions and Recommendations

A shaped-beam reflectarray has been designed, built, and tested. The measured results indicate that beam shaping can be performed using a reflectarray, although the pattern bandwidth is not as wide as that of a traditional shaped reflector. Nevertheless, measurements over a frequency bandwidth of 7% indicate that 99% of the coverage area was illuminated with the minimum desired directivity of 23 dB and this is sufficient for the system requirements. It should be noted that this is for the lower band only, and does not include the upper band at 18 GHz, while the standard shaped reflector covered both bands.

TABLE II
Minimum Gain Within Coverage Area and the Fraction Area of Coverage Contour Meeting Minimum Gain Specification

Frequency (GHz)	Minimum Gain (dB)	Percent of Area with 23 dB Minimum Gain
13.10	18.8	93.3
13.45	21.7	98.2
13.80	21.5	99.0
14.15	21.5	99.0
14.50	22.5	99.6
14.85	22.0	99.4
15.20	21.9	98.8

The desired reflectarry aperture phase was obtained from a previously obtained shaped-reflector surface obtained by a physical optics design process, coupled with a full-wave analysis to determine the patch dimensions. Although this has yielded acceptable results, a better method would be to find the required reflectarray excitations using an array synthesis technique directly, without the intermediate step of shaped-reflector synthesis. In addition, in order to increase the bandwidth of the reflectarray, it would be beneficial to perform this optimization over frequency, taking into account the frequency dependance of the reflectarray elements. It is standard practice to perform optimizations of this type for shaped-reflector analysis and, thus, this procedure should also be done for the reflectarray, thereby accounting for the effect of the nonlinear frequency dependance of the reflectarray elements.

The possibility of using different types of reflectarray elements also exists. The reflectarray elements used here were rectangular patches, but other elements, such as concentric rings, may be used with the possibility of wider element bandwidth. In addition, since concentric rings are dual-frequency structures, it may be possible to design a reflectarray that yields two different reflection phases at two widely separated frequencies of operation. Then a dual-band reflectarray could perhaps be made to simultaneously cover both the receive (18 GHz) and transmit (14 GHz) bands.

The concept and demonstration of the shaped-beam microstrip reflectarray was originally reported in November 1994 [9], but publication was postponed in order to protect the proprietary nature of this work. A later conference paper suggested the possibility of generating a shaped beam from a reflectarray antenna [10].

References

[1] R. G. Malech, "The reflectarray antenna system," in *12th Annu. Antenna Symp.*, USAF Antenna Res. Develop. Program, Univ. Illinois, Urbana–Champaign, Sept. 1962.

[2] R. E. Munson, H. Haddad, and J. Hanlen, "Microstrip reflectarray antenna for satellite communication and RCS enhancement or reduction," U.S. patent 4 684 952, Aug. 1987.
[3] J. Huang, "Microstrip reflectarray," in *IEEE Int. Symp. Antennas Propagat.*, Ontario, Canada, June 1991 pp. 612–615.
[4] D. M. Pozar and T. A. Metzler, "Analysis of a reflectarray antenna using microstrip patches of variable size," *Electron. Lett.*, vol. 29, pp. 657–658, 1993.
[5] D. M. Pozar, S. D. Targonski, and H. D. Syrigos, "Design of millimeter wave microstrip reflectarrays," *IEEE Trans. Antennas Propagat.*, vol. 45, pp. 287–295, Feb. 1997.
[6] S. D. Targonski and D. M. Pozar, "Minimization of beam squint in microstrip reflectarrays using an offset feed," in *IEEE Int. Symp. Antennas Propagat.*, Baltimore, MD, July 1996, pp. 1326–1329.
[7] J. Huang and R. J. Pogorzelski, "A Ka-band microstrip reflectarray with elements having variable rotation angles," *IEEE Trans. Antennas Propagat.*, vol. 46, pp. 650–656, May 1998.
[8] D. M. Pozar and S. D. Targonski, "A microstrip reflectarray using crossed dipoles," *IEEE Int. Symp. Antennas Propagat.*, Atlanta, GA, July 1998, pp. 1008–1011.
[9] D. M. Pozar and S. D. Targonski, "Design of a shaped beam microstrip reflectarray," Tech. Rep., Antenna Design Associates, Inc., Amherst, MA, Nov. 1994.
[10] J. Huang, "Capabilities of printed reflectarray antennas," in *IEEE Int. Symp. Phased-Array Syst. Technol.*, Boston, MA, Oct. 1996, pp. 131–134.

D. M. Pozar (S'74–M'80–SM'88–F'90), for a photograph and biography, see p. 1625 of the November 1997 issue of this TRANSACTIONS.

S. D. Targonski, for a photograph and biography, see p. 296 of the February 1997 issue of this TRANSACTIONS.

R. Pokuls, for a photograph and biography, see p. 1296 of the September 1998 issue of this TRANSACTIONS.