N79-11269

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WAVEGUIDE-EXCITED SLOT ARRAYS FOR SYNTHETIC ARRAY RADAR APPLICATIONS

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SUMMARY

The planar array antenna configuration offers many advantages compared with reflector antennas when microwave efficiency, precise control of the beam shape, and stowed and deployed volumes are important considerations. Of planar arrays, those with waveguide-excited slots provide better performance than arrays of printed-circuit radiators or dipole radiators because the dissipative losses associated with the waveguide feed system can be made to be very small. In this paper, the basic design considerations for waveguide slotted arrays are reviewed, with emphasis on those design requirements that are most significant to both airborne and spaceborne synthetic array radar (SAR) systems. As an illustration of both design procedures and performance capability of slotted waveguide planar arrays, an L-band planar array was designed, fabricated, and tested. This array has an aperture approximately one meter wide by two meters high and was designed to be a typical submodule of a larger antenna. Measurements of radiation patterns, gain, and VSWR were recorded and are presented, together with the performance characteristics predicted on the basis of theoretical analysis.

1.0 INTRODUCTION

The use of planar array antennas for large spaceborne SAR systems has many advantages compared with reflector types of antennas. These advantages include high aperture efficiency, precise control of the aperture distribution function, excellent packaging and stowage characteristics, freedom from non-uniform solar illumination due to feed shadowing, and reduced surface tolerances. The latter are permissible because the aperture acts as a generator or source of the microwave energy rather than as a reflector. The use of slotted waveguide and waveguide feed structures has the further advantage of extremely low dissipative loss. In addition, there is a wealth of design data, computer programs, and experience available for slotted array design that generally assures achievement of predicted performance levels.

An example of an X-band array which was designed, fabricated, and space-qualified for a SAR application at the Hughes Aircraft Company some years ago is shown in Fig. 1. This antenna, which was roughly 7.27 meters (24 feet) long by 1.2 meters (4 feet) high, was found to have outstanding microwave performance characteristics most of which were directly attributable to the use of a waveguide feed and slotted waveguide radiating sections. The subject of the present paper is a feasibility demonstration model of a planar array with a similar design configuration but developed at L-band. It is shown that, at L-band as at X-band, the slotted waveguide type of planar array can provide superior performance.

2.0 GENERAL DESIGN CONSIDERATIONS

Typical SAR system requirements call for a radiation pattern with a fan beam shape, with the antenna oriented so that the broad section of the beam provides the desired swath coverage. The fan beam pattern requirement naturally leads to the use of a long narrow aperture of the type shown in Fig. 1. Typically in a planar array, the aperture is divided both electrically and mechanically into a number of modules or subarrays as shown in Fig. 2. The modules are electrically combined with a corporate feed structure as indicated. The subdivision of the aperture provides a useful frequency bandwidth, allows for thermal expansion joints to prevent aperture bowing, simplifies fabrication of the antenna, and facilitates folding if required for stowage during launch and retrieval.

In Fig. 3, it is possible to see most of the essential details of the construction of a single module of an array. In practice, the modules in a given array are usually identical, so that Fig. 3 actually characterizes a complete antenna system. As shown, the radiating elements of the module are formed from resonant slots cut in the broadwalls of a number of sections of waveguide. Each section of waveguide thus becomes an individual linear array. The module aperture is formed by joining these waveguide sections together in the manner illustrated. The individual linear array elements are slot coupled to a cross

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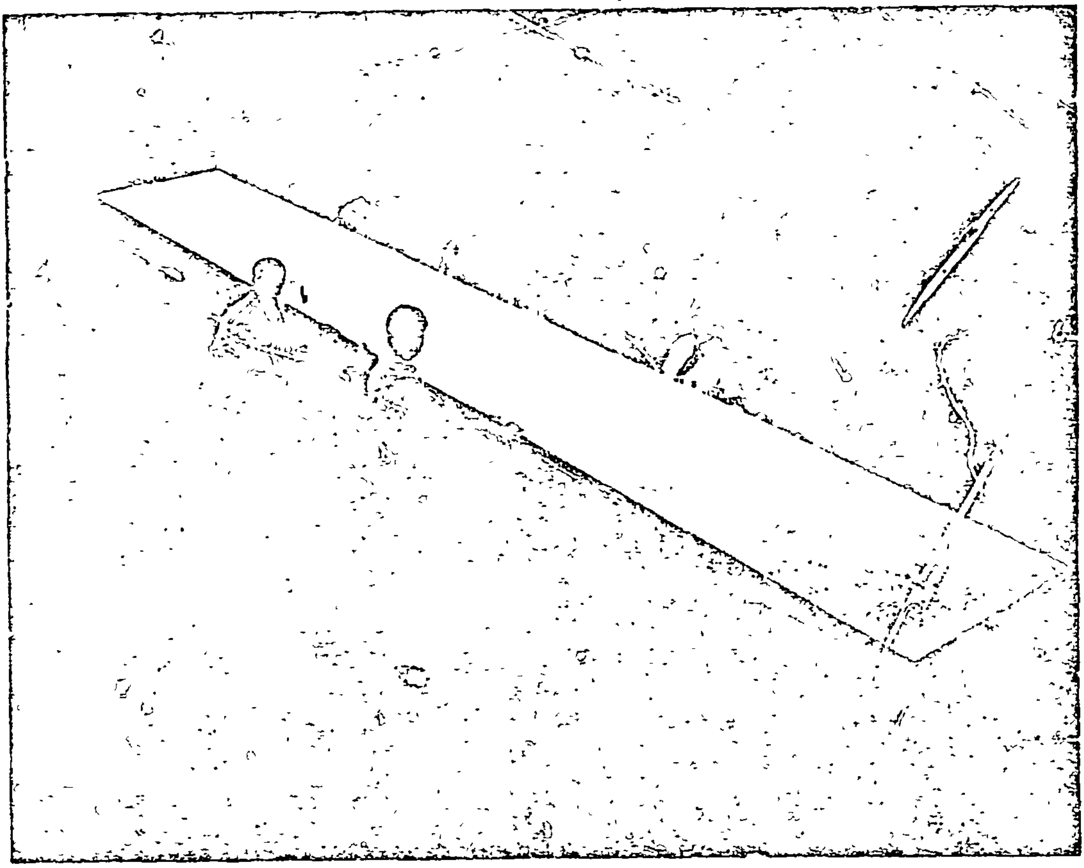

Figure 1. Space-qualified X-band array for SAR applications.

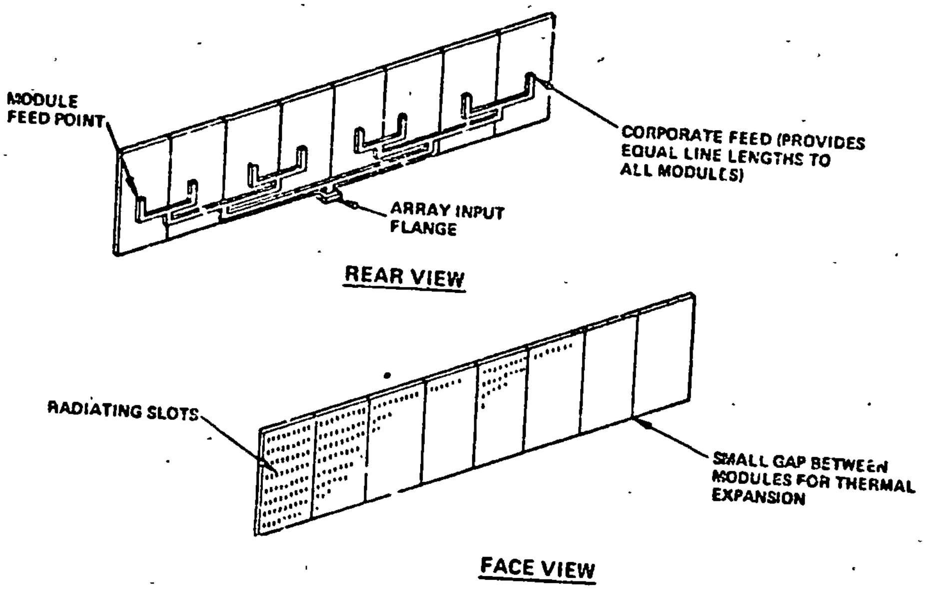

Figure 2. Subdivided aperture.

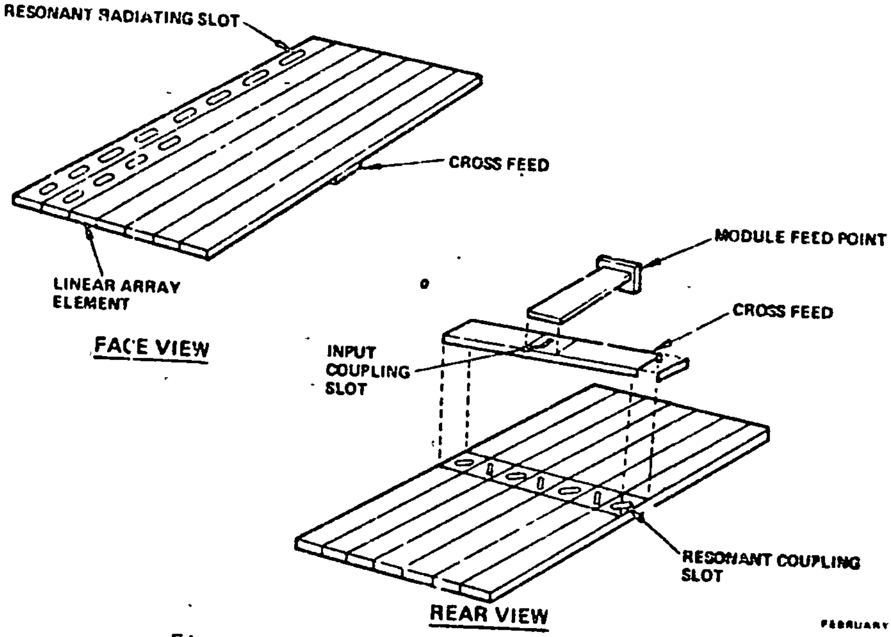

Figure 3. Typical module construction.

feed guide that runs across the back of the module. The cross feed is in turn slot coupled to a flanged module feed guide section. This feed guide is the common feed point for all the slots in a given module.

In the module configuration of Fig. 3, it is generally most convenient to employ a resonant, or standing-wave design, for both the cross feed and the linear array element guide sections. For good pattern characteristics to be obtained over a wide frequency range with this type of design, the number of elements that appear in series in any given element must be limited. Typically, for example, it has been found that square arrays of 16 slots can provide useful bandwidths of about 10 percent.

The aperture distribution in the slot array can be tailored to provide precise control of the antenna beam shape. The mechanisms for such control are simple: the amount of power radiated by any individual slot is controlled by the amount the slot is offset from the centerline of the waveguide in which it appears, the power coupled from the cross feed to any individual linear array element is controlled by the angle at which the coupling slot is cut with respect to the guide axis, and the resonant frequencies of the slots are determined by the slot lengths. In the interest of mechanical simplicity, it is common to use separable aperture distribution functions in the E- and H-planes; this approach leads to a design in which all waveguide array elements have identical radiating slot patterns.

An indication of the degree of flexibility possible in the design of the module is provided by the equivalent circuit representation of Fig. 4. Each of the slot susceptances is individually controllable, as is the impedance transformation ratio of each of the coupling slots. Thus, various design configurations involving both different aperture distributions and different internal impedance levels can be easily realized. Because both radiating and coupling slot characteristics are well documented on both theoretical and experimental levels, design of a module for any desired set of pattern, bandwidth, gain, and impedance characteristics is a straightforward process. In general, the effects of such factors as mutual coupling between slots are accounted for during the design process by the use of the appropriate slot data.

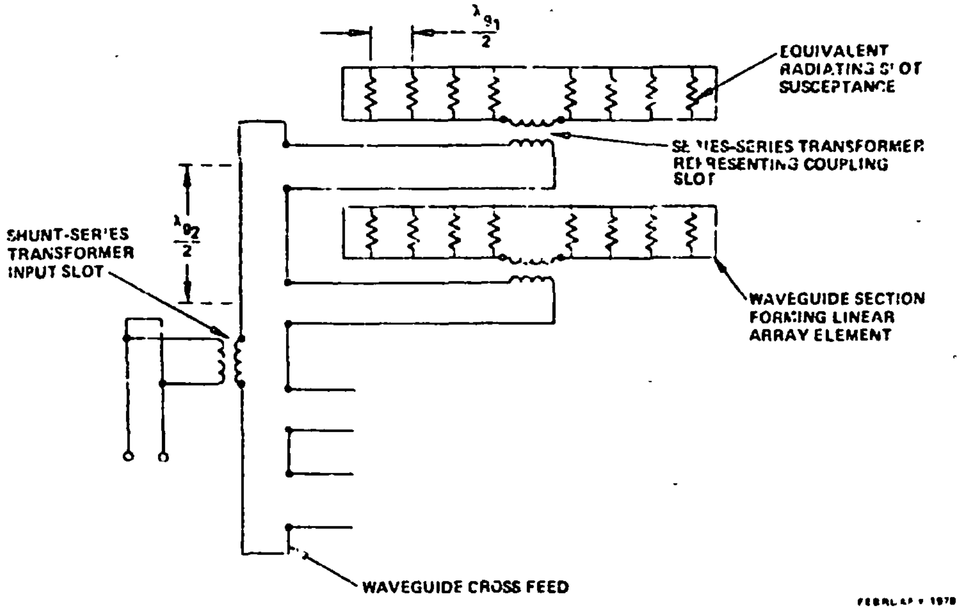

Figure 4. Equivalent circuit of module.

The design procedure for most cases can be summarized neatly:

- The antenna gain and pattern requirements determine the aperture size and shape.
- The radar signal bandwidth requirements then establish the maximum module size.
- The radiating and coupling slots are then selected to generate the aperture distribution corresponding to the beamshape requirements.
- The impedance levels and resonant frequencies of the slots are designed to provide a good input impedance match.

3.0 BRASSBOARD MODEL OF AN L-BAND ARRAY MODULE

Fig. 5 presents a photograph of an array module that was fabricated to demonstrate the performance capabilities of a slotted waveguide array at L-band frequencies. This module contains six waveguide linear array elements; each waveguide element has 13 radiating slots. The cross feed runs across the back of the aperture between the 6th and 7th rows of radiating slots. The input guide couples into the center of the cross feed. Half-height waveguide (4.6 cm or 1.6 inch high) was used throughout to minimize the thickness of the structure. The module was designed for use in an array of eight such modules. The various components of the module are easily identified by a comparison of Fig. 5 and Fig. 3.

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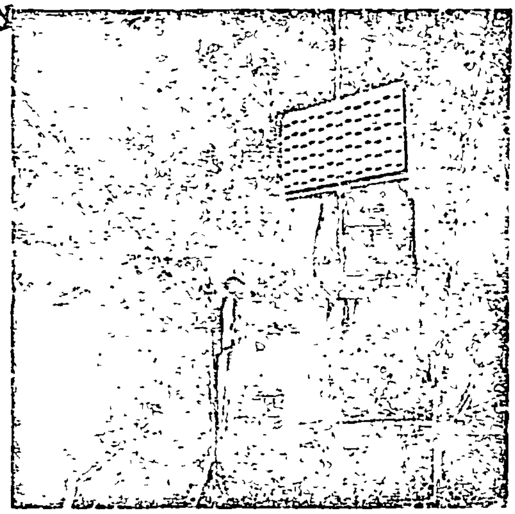
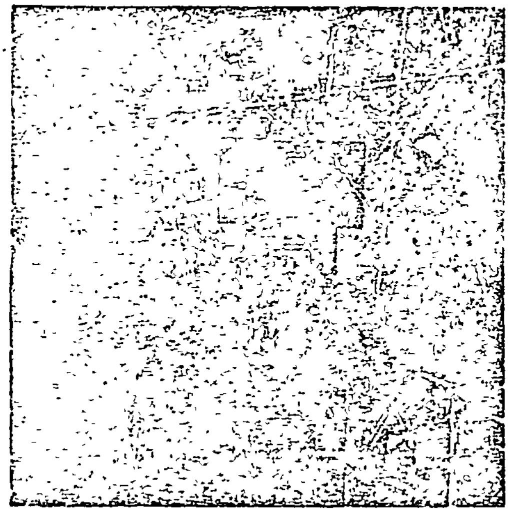


a. Front



b. Rear

Figure 5. Brassboard model of L-band module.

The radiation patterns in both E- and H-planes, gain, and VSWR of the brassboard module were measured. Results are illustrated and discussed below.

3.1 RADIATION PATTERNS

The measured principal plane radiation patterns of the brassboard model are shown in Fig. 6. The aperture distribution along the long dimension of the module was designed to give a first sidelobe level of 16.5 dB. The small crosses on the corresponding H-plane pattern (Fig. 6b) indicate the design or predicted levels and positions of the sidelobe peaks. As can be seen, the agreement between theory and measurement is excellent. Intercardinal plane patterns, which were also recorded, showed no indications of spurious lobes.

In the E-plane the array was designed for a uniformly weighted aperture along both the array and the module. This leads to an interesting dilemma peculiar to the design of the module as a demonstration piece of hardware: if the module is designed to generate a uniform distribution in the E-plane when it is part of a full array of eight modules, it will almost certainly have a nonuniform weighting when used separately. If, on the other hand, the module is designed to have a uniform E-plane distribution when used as a separate module, the array amplitude distribution will be nonuniform when a number of modules are joined together. The reason for this behavior is the strong E-plane mutual coupling that exists between the radiating slots. In a large antenna nearly all the slots see a common E-plane environment, and the mutual coupling is usually accounted for in the radiating slot data used in the design. In a small antenna, such as the module, if a uniform aperture excitation is required, the coupling slots in the cross feed are used to correct for the edge effects and compensate for the different behavior of the slots located close to the side of the array.

In the present design the module was designed and laid out as if it were part of a full array. As a result, the mutual coupling results in an effective amplitude taper in the module, and the sidelobe levels are considerably lower than the 13.3 dB normally to be expected. While it is quite feasible to calculate what the sidelobe levels should be, in the interest of economy this step is generally not done because the computation and the acquisition of the specific slot data required are relatively expensive. For these reasons, an

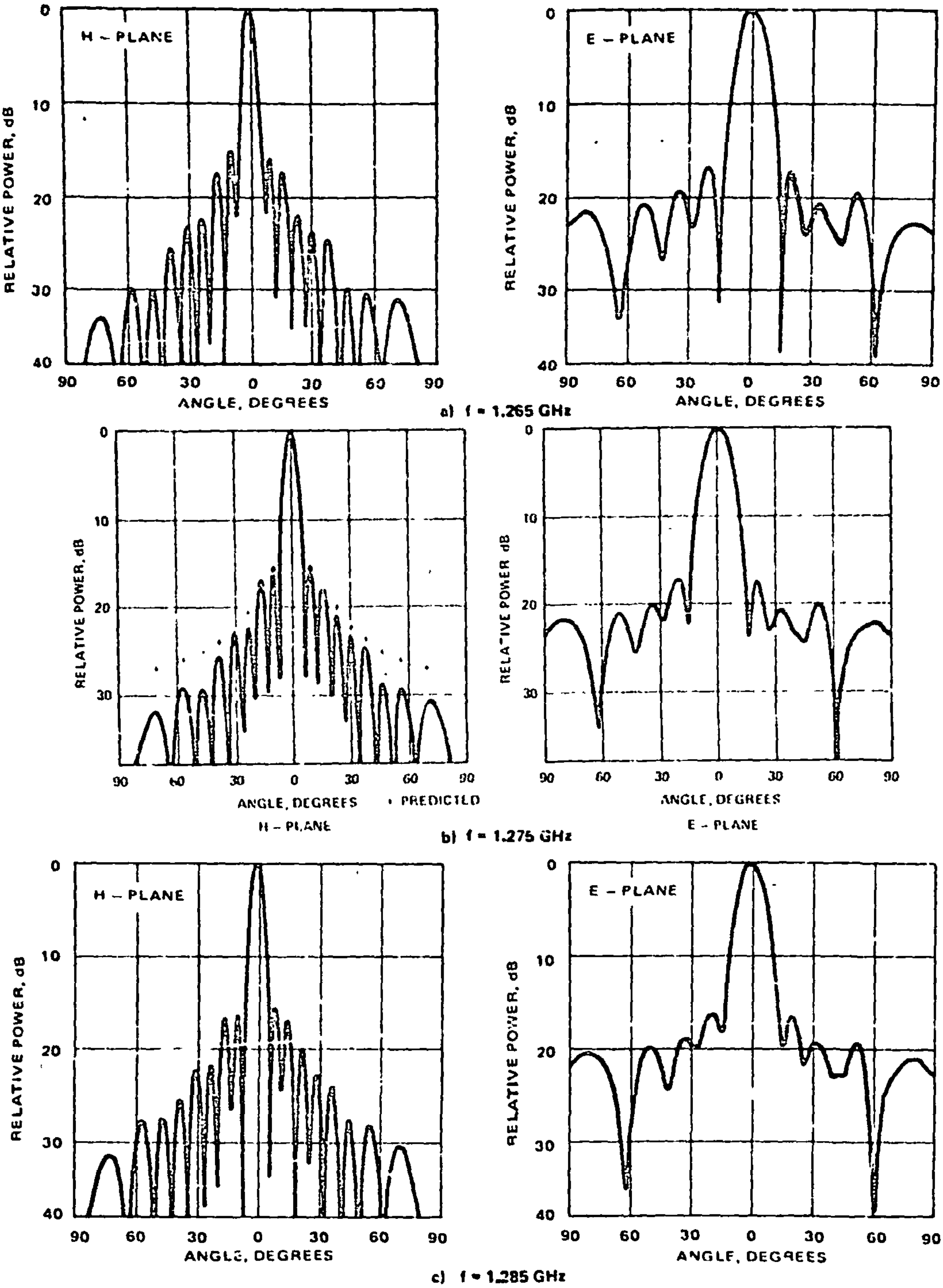


Figure 6. Measured E- and H-plane patterns of brassboard module.

estimate of the module E-plane sidelobe levels was not made. However, the E-plane sidelobes of the full, eight module array can confidently be predicted to be 13.3 dB.

Two particular aspects of both the E- and H-plane patterns that should be observed are the symmetry of the sidelobe levels and the deep clean nulls. These characteristics indicate good tolerance control of the module and small microwave and mechanical design and construction errors.

The measured performance of the module with respect to radiation pattern characteristics is summarized in Figs. 7 and 8 which show the first sidelobe level and 3-dB beamwidth as functions of frequency. The predicted curve for the 3-dB beamwidth of the H-plane pattern is also plotted in Fig. 8. The E-plane 3-dB beamwidth for the module was not predicted because the mutual coupling effects that lead to low sidelobes in this plane also produce a broader beamwidth than would otherwise be observed.

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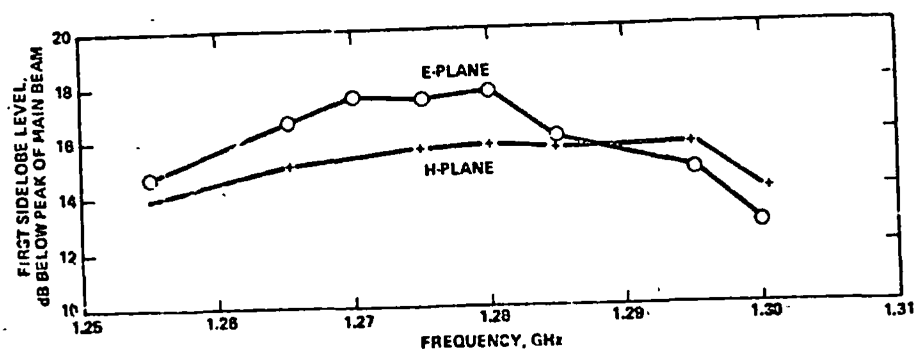

Figure 7. Measured sidelobe levels.

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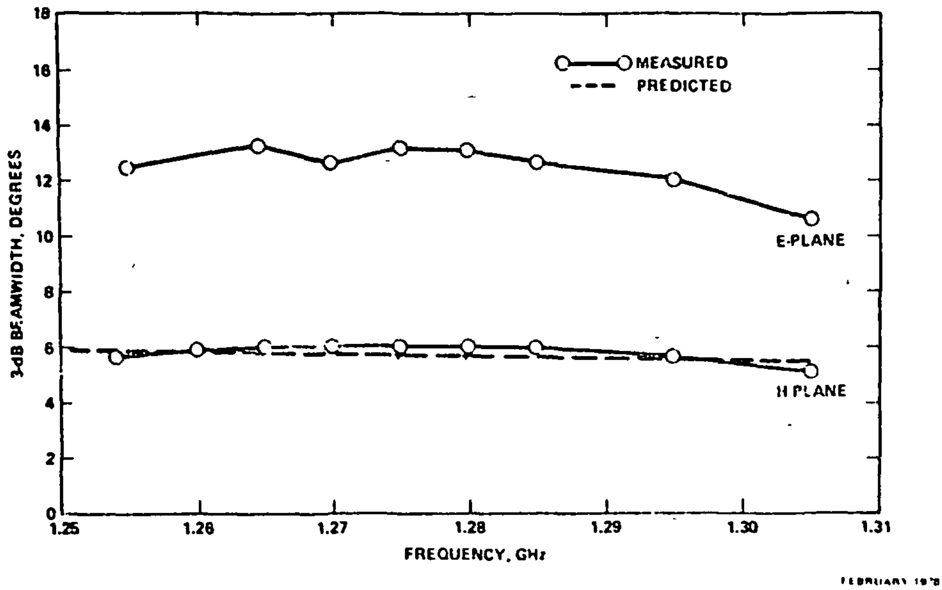

Figure 8. Variation of 3-dB beamwidth with frequency.

3.2 GAIN

The maximum theoretical gain of a planar slot array is relatively simple to calculate with a high degree of precision. The procedure is to compute the so-called area gain from the well-known expression

$$G_0 = \frac{4\pi A}{\lambda^2}$$

where

A = aperture area

λ = wavelength

and then subtract the losses associated with the aperture weighting function used for sidelobe level control and beam shaping.

A gain of 26.9 dB was calculated for the brassboard module for the design frequency of 1.270 GHz. A loss allowance of 0.10 dB, which included the calculated value for the H-plane weighting and an estimated value, based on experience, for the E-plane weighting, was made for the aperture weighting.

The measured gain of the module is plotted as a function of frequency in Fig. 9. For purposes of comparison, the maximum theoretical gain (G) achievable with an aperture of the module dimensions is also plotted on the same figure. The difference between the two curves at any frequency represents the losses due to random manufacturing errors, waveguide dissipative losses, design errors, and input mismatch.

The aperture efficiency is defined at Hughes as 100 times the ratio of the measured gain to the maximum theoretical gain of the aperture. When defined in this manner, the efficiency becomes a measure of the success of the antenna design in terms of achieving the theoretical pattern and gain characteristics. In the case of the L-band module, the aperture efficiency measured at 1.270 GHz is approximately 94 percent.

It should be noted that the gain data of Fig. 9 were measured through a stepped half-height to full-height transition and a coaxial-to-waveguide adapter. The gain was corrected for the gain reduction introduced by the waveguide transition and adapter dissipative losses. The input mismatch losses, however, were left in the data.

3.3 MODULE VSWR

The input voltage standing-wave ratio (VSWR) of the module, also measured through a stepped half-height to a full-height waveguide transition and a coaxial-to-waveguide adapter, is plotted in Fig. 10. As can be seen, the VSWR remained below 1.4:1 over most of the bandwidth. No matching or tuning devices were employed to obtain these results.

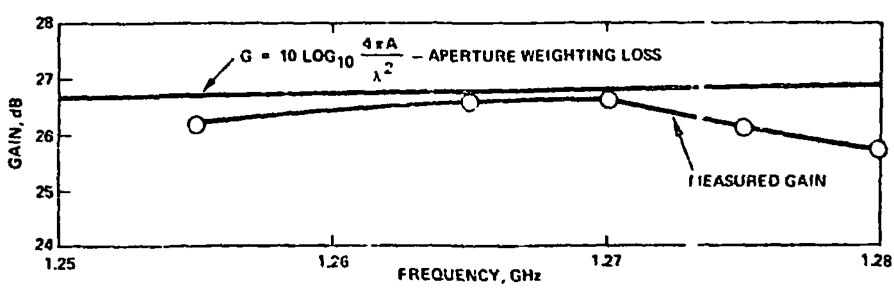

Figure 9. Measured gain of brassboard module over design bandwidth.

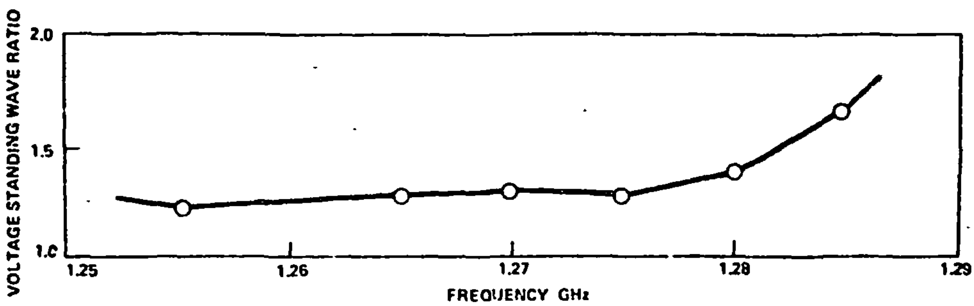

Figure 10. Measured voltage standing-wave ratio of module.

3.4 SUMMARY OF MODULE PERFORMANCE CHARACTERISTICS

The performance of the module, as characterized by the microwave measurements, is summarized in Table 1. The design objectives, which were based on theoretical values, are also tabulated for the purposes of comparison. Exact values of the cross polarization components of the radiation field are not given in the table because the measured values were so low that they implied that the module cross polarization was significantly better than that of the transmitting source used for the pattern measurements.

3.5 FULL SCALE ARRAY PERFORMANCE

As a final step, the measured module data were utilized as the basis for a prediction of the performance characteristics of a full-scale array of eight modules. These results are given in Table 2. It is believed that the numbers shown represent the full array performance with the same high degree of accuracy provided by the module data in Table 1.

The estimate of the array weight was based on the use of thin wall (51 mm or 0.020 inch) aluminum waveguide for the module panels and corporate feed and an aluminum honeycomb support structure. The physical design of array and support was predicted on the assumption of a structural resonant frequency requirement of 25 Hz. The mechanical design did not provide for aperture folding. Techniques for forming and maintaining the necessary waveguide cross sections with the thin wall aluminum waveguide have been developed and demonstrated at Hughes under both funded and company-sponsored research efforts.

TABLE 1. PERFORMANCE OF L-BAND BRASSBOARD MODULE

Parameter	Design Objective	Measured (at 1.270 GHz)
Gain, dB	26.87	26.60
Beamwidth, degrees H-plane E-plane	 5.9 NA	 6.0 13.2
First sidelobe, dB H-plane E-plane	 16.5 NA	 -15.8 -17.4
Input VSWR	<1.5:1	<1.3:1
Bandwidth (GHz)	1.265 to 1.285	1.255 to 1.285
Cross polarization, dB	<30	<30
Efficiency (relative to weighted aperture), percent	>90	94
Aperture dimensions	1.04 x 2.12 x 0.04 meters (41.1 x 83.28 x 1.6 inches)	1.04 x 2.12 x 0.04 meters (41.1 x 83.28 x 1.6 inches)

TABLE 2. PROJECTED PERFORMANCE FOR ARRAY OF EIGHT MODULES

Parameter	Performance
Aperture	2.12 x 8.33 meters (83.28 x 328 inches)
Gain (eight times module gain less corporate feed losses), dB	35.3
Bandwidth	1.255 GHz to 1.285 GHz
Beamwidth, degrees	
H-plane	6 0
E-plane	1.31
First sidelobe levels, dB	
H-plane	-15.8
E-plane	-13.3
Input VSWR	<1.5:1
Cross polarization, dB	<30
Weight (array panels, structural support, thermal control systems), pounds	220

4.0 CONCLUSIONS

The measured performance characteristics of the L-band module described in this paper demonstrate the feasibility of slotted waveguide planar arrays for L-band SAR systems. In every respect the module exhibits a superior level of microwave performance, and it was established that excellent agreement between predicted and measured performance can be obtained by the use of simple, straightforward design procedures.

The relatively low microwave frequencies for which this module was designed represent the lower end of the range for which waveguide slotted arrays are most attractive. Below L-band the dissipative loss characteristics of striplines and coaxial lines are sufficiently low as to warrant their considera-tion for use as the feed elements. As the frequency is increased, however, the loss advantages of the slotted waveguide configuration become increasingly great. At the same time, the waveguide dimensions decrease rapidly to the point at which the volume savings that can be obtained through the use of TEM line configurations have no particular significance.