20 GHz ACTIVE APERTURE
FOR COMMUNICATION SATELLITES

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ABSTRACT

The trend to higher frequencies for satellite to earth communications, together with requirements for increased reliability and graceful degradation, has resulted in the need for a 20 GHz active aperture transmitting array.

In this paper the preliminary design of such an array is discussed. The array is designed for 35 dB of gain and -30 dB sidelobes. Quantized amplitude tapering, gain distribution, phase shifter quantization, prime power requirements, array and element trade-offs are discussed. The impact of multiple beam operation for frequency reuse is addressed.

INTRODUCTION

In most spacecraft applications, traveling wave tube amplifiers (TWTA) have been used as the rf power source.

Although the use of the TWTA in space has proven to be a reasonably reliable device, it nevertheless is typically used in a configuration representing a single-point failure (requiring redundancy) and, frequently, with an antenna system necessitating mechanical motion which adversely impacts the stability of the satellite.

The advent of solid-state GaAs field-effect transistor (FET) devices operating at 20 GHz, with an order of magnitude better mean time between failures (MTBF) than that of the TWTA, has made possible active transmitting antenna systems with enhanced reliability. The low power output levels of these devices, however, necessitate the use of a large number of devices to achieve the required output power. One of the most efficient methods for accomplishing this is through spatial power combining. The phased array may be easily configured to employ spatial power combining as well as inertialess electronic steering.

Antenna Parameters

For this communication application, the active aperture must have the characteristics shown in Table 1.

Table I. Aperture Characteristics

Frequency	20.2-21.2
Gain	35 dBI
Sidelobe level (relative to peak)	-30 dB
RF power	20 watts (at 1 dB compression)
Operation	Linear transmitter
Steering	Electronic
Polariztion	LHCP
Scan volume	±10 degrees cone

The emphasis of the study was to define a configuration to meet the specifications of Table I while maintaining efficient utilization of prime power and graceful degradation.

THE ACTIVE PHASED ARRAY

The active phased array shown in block diagram form in Figure 1 satisfies the system requirements. Some of the major features of this design are:

1. Quantized amplitude distribution.
2. Phase randomization.
3. Distributed gain and redundancy.
4. Use of high gain elements and multiple beam capability.

Aperture Design

The aperture efficiency of the amplitude taper selected for this design (see below) is 72 percent. Since the rf power generation immediately precedes the antenna elements, there is little circuit loss. A total of 1.25 dB was estimated to be the reduction in efficiency due to loss, random errors, etc. The gain of the aperture is given by

$$G = \frac{4\pi A\eta}{\lambda^2 L} \tag{1}$$

where A is the aperture area, η is the aperture efficiency, L is the loss, and λ is the wavelength. An aperture area of $470\lambda^2$ is required for 35 dB gain.

A triangular grid and maximum element spacing was used to minimize the number of radiating elements. To avoid operating near the grating lobe condition at 10 degrees scan, spacing between elements of $0.925\lambda^2$ was used resulting in 640 elements with an effective area/element of $0.74\lambda^2$. To recover this aperture area, end-fire elements with a gain of ≈9.7 dB are used. The most promising elements in this frequency range for the required circular polarization are the cigar and poly-rod elements.

Amplitude Quantization

The amplitude distribution envelope (i.e., the function which is sampled to produce the phased array element amplitudes) should maximize aperture efficiency while meeting the sidelobe requirements. Functions which have this property are well-known, i.e., Taylor, Dolph-Chebychev, Blackman, etc.(1) Unfortunately, when an array with gain immediately preceding each element is examined, it becomes apparent that a new amplifier design is required for each output power level if efficient dc to rf power conversion is to be obtained. This becomes unwieldy and costly.

Good performance may be obtained with a distribution which consists of constant power level steps.

Using the 35 dB Taylor as a basis, a quantized amplitude distribution may be obtained as shown in Figure 2. The amplitude has been quantized to four steps which will thus require only four output level designs.

The antenna pattern for the quantized distribution is shown in Figure 3. The sidelobe levels are approximately 35 dB, and the aperture efficiency is 72 percent. Since the 35 dB Taylor has an aperture efficiency of 77 percent, the penalty for using the quantized distribution is approximately a 3.4 percent increase in aperture diameter.

Gain Distribution

The gain distribution is constrained by the requirement to produce the 20 watts total output power (at 1 dB gain compression) with the relative amplitudes shown in Figure 2. The gain structure must provide good dc to rf conversion efficiency and high reliability and graceful degradation.

For the 640 elements required in this design, the highest output level required at any element is +20 dBm, and the minimum level is +8 dBm. Note that rather than the usual problem of obtaining high output power, the difficulty is one of maintaining efficiency at low output powers, especially in the early stages of the final amplifiers. Due to this phenomena, it becomes desirable to distribute the gain throughout the rf manifold.

Two gain configurations were investigated. Configuration A had only gain at the input to the rf manifold (dual redundant) and at the elements. Configuration B had gain distributed throughout the manifold as well as initial and final gain sections. A preliminary estimate of dc power requirements indicates that Configuration A requires 473 watts while Configuration B requires 287 watts. The effect of the distributed gain on graceful degradation and the phase and amplitude tolerances of the distributed amplifiers require further investigation.

Redundancy in this design is provided efficiently by the approach of Figure 4. Normally, only one of the amplifiers is active. Since they are isolated from each other by the hybrid, all output power (except for circuit losses) is input to the rf manifold. The hybrid thus is the first power divider of the manifold. The 90 degree relative phase shift of the two outputs is compensated for by the phase shifter settings. In the case of failure of an amplifier, the other amplifier is powered up, and the failed amplifier is powered down. The resulting 90 degree phase shift introduced by this action is compensated for by the array controller.

Phase Quantization

The effect of phase quantization (due to digital phase shifters) is to produce quantization lobes and/or random sidelobes. If the errors due to quantization are periodic, quantization lobes appear. Digital phase shifters on paths with otherwise identical phase will produce these lobes, which can be quite strong.(2) They steer much more rapidly than the main beam but in the opposite direction. An example of this phenomenon is shown in Figure 5. The level of the quantization lobe is approximately 6 dB per phase shifter bit requiring a minimum of 5-bit phase shifters for a -30 dB sidelobe level. Since fewer bits are desired to reduce the technical risk, design costs, and power consumption, an alternate method is employed.

To break up the periodic structure of the errors, each path may have a randomly distributed phase. This may be due to phase shifts through the corporate feed or phase shifts in the amplifiers. Further, they may be inserted intentionally or due to manufacturing tolerances. They must, however, have a standard deviation larger than the least significant bit, be uncorrelated, and have known phase calculations. The phase errors are thus randomized, producing random sidelobe levels. The rms sidelobe level due to quantization is given approximately for this array by

$$\text{rms sidelobe level} = \pi^2 / (3N\eta 2^{2B} \tag{2}$$

where B is the number of bits in the phase shifter, N is the number of elements in the array, and η is the aperture efficiency. For N = 640 and B = 4, the rms sidelobe level will be

-45.5 dB for. the quantized taper in Figure 2. It is unlikely that the peak sidelobe will exceed the rms value by more than 8 to 10 dB.(3) With careful design and good control of the phase and amplitude error of the amplifiers, rf manifold, and phase shifters the peak sidelobes should be significantly less than 30 dB. These random error components must be included in the error budget.

Reliability

It has been shown by Skolnik(4) that the expected rms sidelobe level increase due to failed elements is given approximately by

$$S_{rms} = (P_e - P_e^2)(\Sigma i^2)/(\Sigma i)^2 \tag{3}$$

where S_{rms} is the rms sidelobe level, P_e is the probability of an element being active (assumed the same for a elements), and the i’s are the element excitations. The ratio of the sums in Equation 3 is the reciprocal of the gain of the array if it were composed of isotropic elements. For elements with gain,

$$[\ \Sigma i^2] / [\ \Sigma i]^2 = \text{element gain/array gain} \tag{4}$$

For the present array, this factor is -25.3 dB. Thus for P_e = 5 percent, the expected rms sidelobe level is 38.5 dB indicating a graceful degradation.

If more than one element is driven by an amplifier, the effect is more pronounced. If, for example, each group of four elements of the array is driven by an amplifier, the probability of that amplifier being active would have to be ≈99 percent to obtain the same sidelobe performance. This clearly means that amplifiers within any rf manifold must be redundant.

Multiple Beam Capability

For some applications, including frequency reuse, multiple beams are quite attractive. Figure 6 illustrates the modification of the basic active phased array for dual beam operation. In this discussion it is assumed that the signals for the two beams occupy the same spectrum but are not coherent. The rf manifold and phase shifters are duplicated--one for each beam. These signals are then summed and input to the final amplifier. Since this amplifier is linear, superposition holds, and the resultant radiating pattern will be the sum of the individual patterns, i.e., two beams.

In the event of third-order intermodulation products in the final amplifier, unwanted signals will be produced. The signals within each beam will be those which would be present if the other rf manifold were not present. However, the intermodulation products between the two beams will produce beams to either side of the main beam. They will, of course, be at a level relative to the main beam implied by the size of the third-order intermodulation products of the final amplifier.

CONCLUSIONS

In this paper, some of the advantages of a solid-state active phased array have been discussed. Among these are spatial power combining, graceful degradation, and inertialess steering.

To realize these advantages in a cost effective manner, amplitude quantization and phase randomization are employed. DC to rf conversion efficiency is enhanced by distributing the gain throughout the rf manifold, but the effects on graceful degradation and design tolerances of the amplifiers require further investigation.

ACKNOWLEDGEMENTS

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REFERENCES

1. Harris, Fredric J., 1978, “On the Use of Windows for Harmonic Analysis with the Discrete Fournier Transform,” Proceedings of the IEEE, Volume 66, p. 51.

2. Skolnik, Merrill I., 1980, “The Electronically Steered Phased Array Antenna in Radar,” Introduction to Radar Systems, Ed.2. McGraw-Hill Book Company, New York, New York, pp. 321-322.

3. Steinberg, Bernard D., 1976, “Theory of the Random Array,” Principles of Aperture and Array System Design, John Wiley & Sons, New York, New York, pp. 134-167.

4. Skolnik, Merrill I., 1969, “Nonuniform Arrays,” Chap. 6 of Antenna Theory, Pt. I., R.E. Collin and F.J. Zucker (eds.), McGraw-Hill Book Company, New York, New York, p. 231.

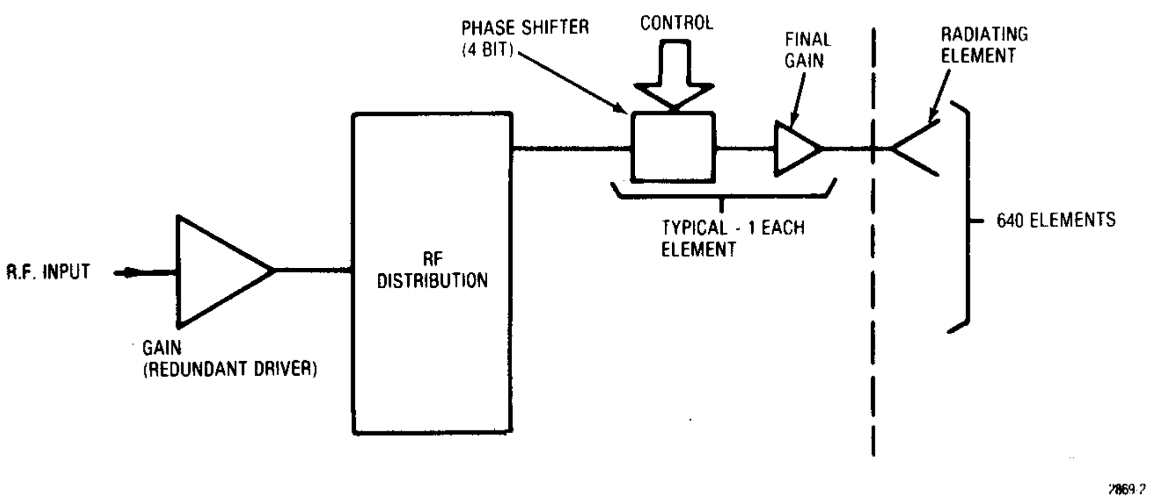


Figure 1. Active Phased Array

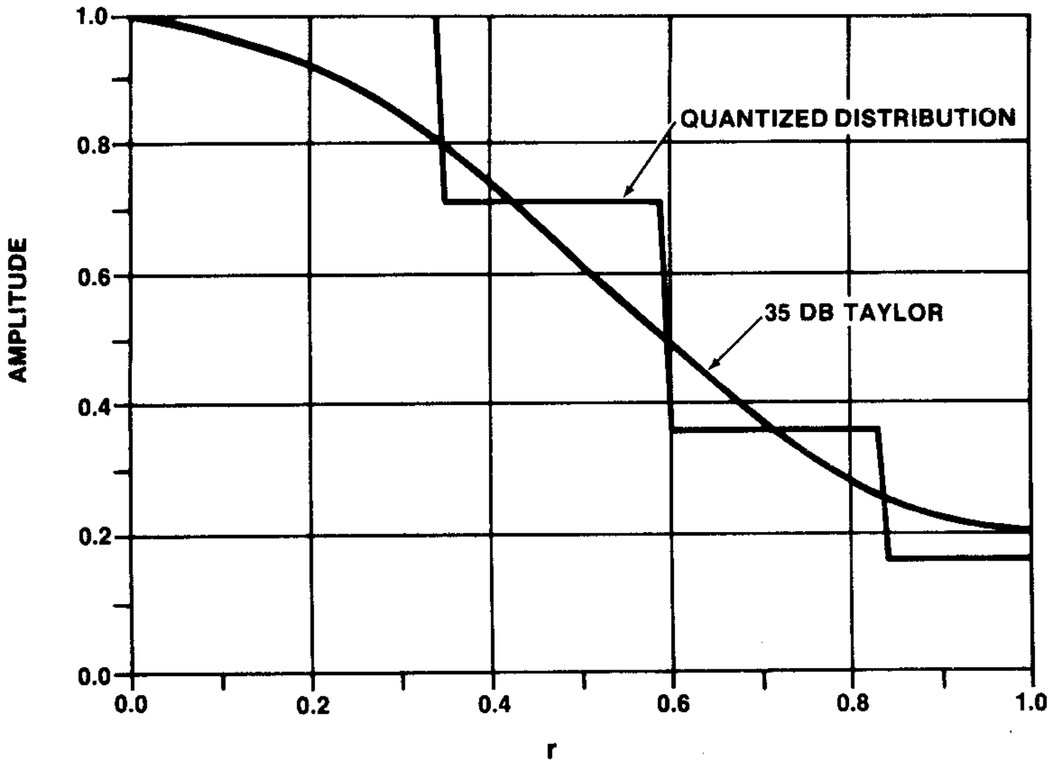


Figure 2. Quantized Aperture Distribution

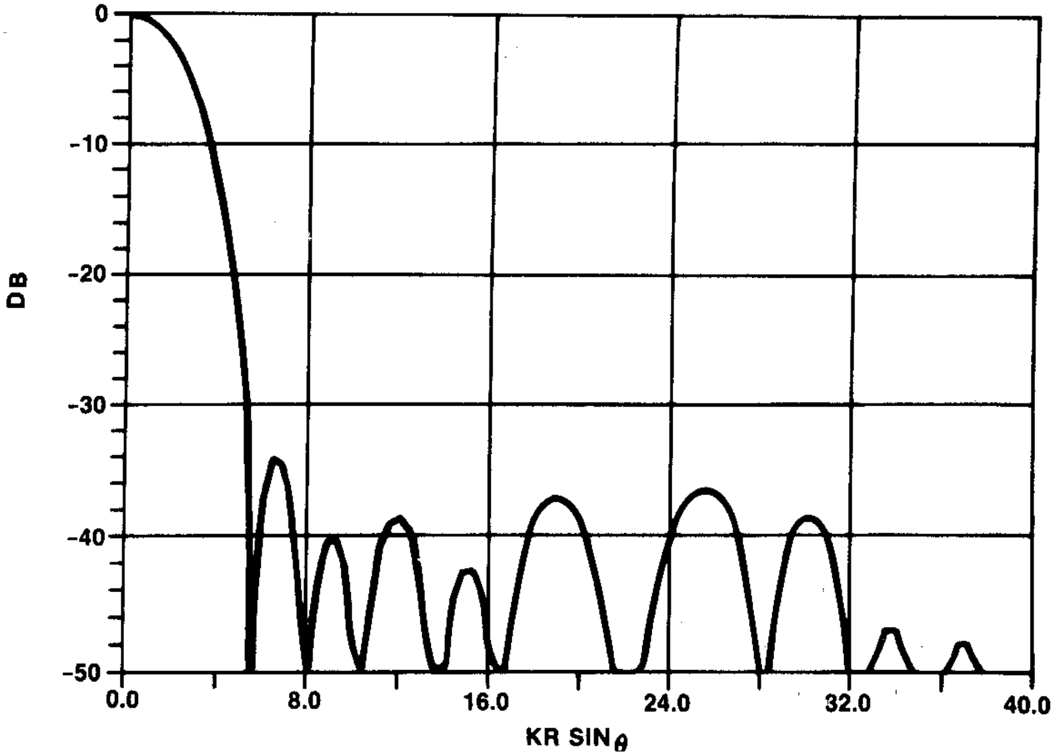


Figure 3. Antenna Pattern for Quantized Distribution

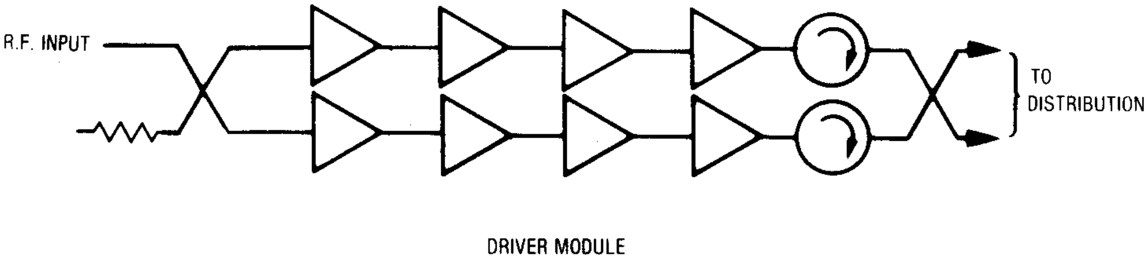


Figure 4. Redundant Amplifier

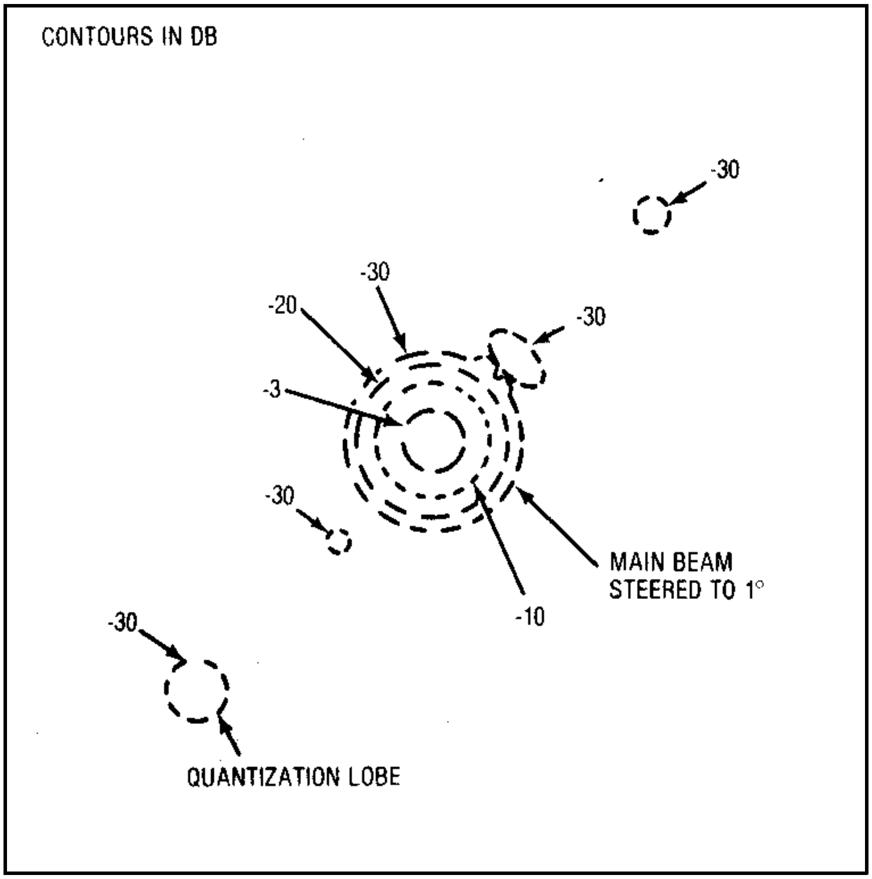
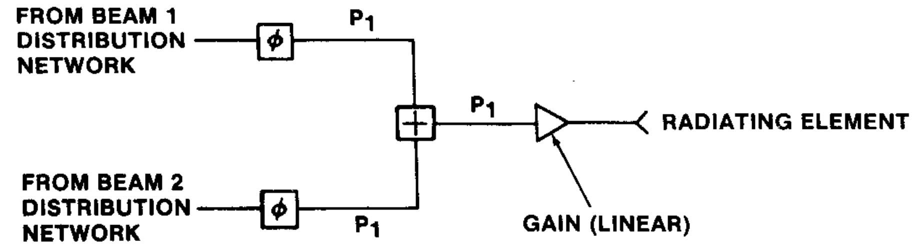
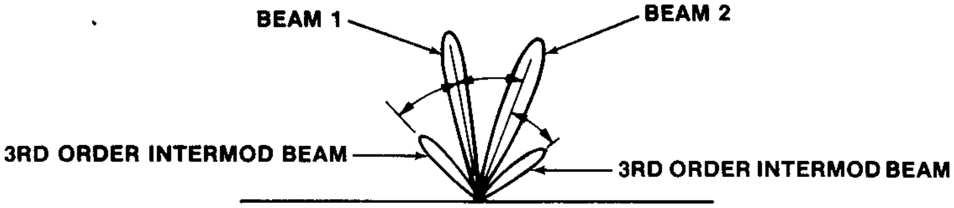


Figure 5. Quantization Lobe Example



TYPICAL ELEMENT



BEAMS

Figure 6. Multiple Beam Formation