RECTENNA ARRAY MEASUREMENT RESULTS

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ABSTRACT

The measured performance characteristics of a rectenna array are reviewed and compared to the performance of a single element. It is shown that the performance may be extrapolated from the individual element to that of the collection of elements.

Techniques for current and voltage combining have been demonstrated. The array performance as a function of various operating parameters is characterized and techniques for overvoltage protection and automatic fault clearing in the array have been demonstrated. A method for detecting failed elements also exists.

Instrumentation for deriving performance effectiveness is described. Measured harmonic radiation patterns and fundamental frequency scattered patterns for a low level illumination rectenna array are presented.

INTRODUCTION

Prior to a definite commitment for a significant application of Beamed RF Power, performance characteristic data must be obtained for use by design engineers and systems analysists. The operating performance of a rectenna array under various conditions of load, RF power input level, temperature, polarization, angle of incidence, state of maintenance, and frequency is required. Fundamental performance factors are the transfer efficiency, relating dc power output to available RF power input, and the level and distribution of scattered fundamental and emitted harmonic radiation from the array. Secondary performance factors are the output voltage and converter temperature. The existing measured performance data on rectenna arrays will be reviewed and recent results will be discussed.

MEASURED RECTENNA ARRAY PERFORMANCE

High efficiency (greater than 50%) rectenna array characteristics were documented in Ref. 1, for the condition of highest collection-conversion efficiency performance associated with a demonstration of overall system end to end dc transfer efficiency. The array consisted of 199 half wave gallium arsenide Schottky barrier diodes connected to half wave dipoles through a two section low pass filter projecting through a flat solid ground plane. The elements were arranged in a triangular lattice whose outline configuration was a hexagon. The collecting area per element was about 52 cm^2. The incident flux density ranged from 203 mW/cm^2 to 2.5 mW/cm^2 in a gaussian distribution over the aperture of the array. (A 19 dB taper.) The dc load collection consisted of 21 separate concentric rings of adjustable resistances tailored to the ring radius. A one tenth wavelength dipole probe in front of the array measured about 1.11 to 1 VSWR on axis under matched conditions.

The peak collection-conversion efficiency of an individual element was measured as 87 ± 1.5%, whereas the average efficiency of the entire array at approximately 0.5 KW output dc power was 82.7% of the available RF power incident upon the array (not counting the estimated 4% spillover energy). The array transfer efficiency decreased less than 2% for a 16.7% decrease in RF input power level.

The next large rectenna array was tested at Goldstone, CA (Ref. 2) and consisted of 4590 elements arranged in 17 subarrays of 270 elements each arranged in a triangular grid pattern. The subarrays were grouped in a three column arrangement with the top center subarray absent, as shown in Fig. 1. Fig. 2 and 3 are of the array performance characteristics and capabilities for use of the instrumented output data. The measured performance can in general be accurately predicted from general transmission line reflection coefficient theory as concerns the load variations, and the polarization and angle of incidence performance follows array theory. Computer models (Ref. 3, 4) for the diode and associated RF circuitry are able to predict the element performance as a function of the input RF amplitude, however, the array performance is poorer than predicted in most cases, by a few percent. This may be due to the effects of mutual coupling in the array, which are not modeled in a single element analysis. Nevertheless, over a 10 dB range of input power density, the rectenna array performance may be adequately predicted within a few percent, based upon measured diode characteristics.

Figure 4 compares the transfer efficiency performance of a single element, the average element in a subarray of 270 elements, and the average element in and array of 4590 elements over a 6 dB range of RF power density input. The performance of a large array may be extrapolated with confidence from the single element.

CURRENT AND VOLTAGE COMBINING AND PROTECTION

Figure 5 shows the wiring diagram of one of the 270 element subarrays. By insulating the dc buss from the subarray frame the paralleled rows of rectenna element outputs may be seriesed in order to raise the output voltage, while still presenting an adequate output impedance level to the individual element.

The subarray rows are self-clearing of short circuited diode faults by the fusing open of the one mil diameter gold bond wires in the packaged diodes under the combined short circuit current developed by 45 rectennas in parallel. The failed elements may be detected while operating by the increased reflected power at a VSWR probe over the element, or alternatively while the array is inoperative, by briefly individually illuminating each element while monitoring the dc output (termed "sniffing").

Overvoltage protection from loss of load, excessive RF input level or interruption of input, was accomplished in the Goldstone tests by the self actuated crowbar in Fig. 5. A voltage limiter would be less traumatic for the load than a crowbar however.

INSTRUMENTATION

Fig. 5 also shows the isolated load central element for a subarray, that is used to provide a measure of the input RF power flux density. An RF shielded thermistor is employed to measure the temperature of the central buss bar in the subarray. Calibrated shunts and precision voltage dividers were employed to sample the output current and voltage levels. A fixed track, movable probe positioned in front of the subarray to measure the reflected power would be an expensive, but useful instrument to monitor the subarray performance under various operating conditions. It could be integrated into a sniffing and maintenance positioning assembly perhaps, that travels over the array surface.

SCATTERED FUNDAMENTAL AND RADIATED HARMONIC CHARACTERISTICS

Figure 6 shows a 42 element rectenna array undergoing pattern recording of its emitted harmonics as a function of various operating parameters. Figures 7 and 8 show the measured harmonics and the scattered fundamental patterns for certain conditions. These patterns are typical for a wide range of parameters. The significant facts are that the scattered fundamental is distributed over a broad range of angles, and that the fourth harmonic is of higher magnitude than the third harmonic. The array was underexcited due to equipment limitations, with the peak RF to dc conversion efficiency being only 35%, however the results are expected to be applicable to a normally functioning array. Future designs will probably require more filtering of harmonics in order to control them and permit the array to meet applicable radio regulations (Ref. 5). The scattered fundamental frequency radiation may be controlled to a degree by varying the dc load value, the incident flux density level, or the dipole to ground plane spacing, each of which affects the impedance match of the array, and thus provides a potential parameter for control of the reflected fundamental magnitude. Figure 9 shows the variation in efficiency and dc power output for a particular subarray as the spacing is varied.

The RF frequency could also be varied to effect an impedance match. Figure 10 shows the bandwidth measurements for the 42 element array for two different illumination conditions. Such a design characteristic would have to be integrated with the harmonic filter design also.

CONCLUSIONS AND RECOMMENDATIONS

Adequate theory and design information exists that has been compared with full scale measurements, to provide engineers and systems analysts with the characterization of rectennas performance to within the order of a couple of percent. Particularly for high power level of incident flux density applications. The data for scattered fundamental and emitted harmonics could use some theoretical modeling to gauge the preliminary measurements. Also, bandwidth analysis and modeling for degraded modes such as partially obscured apertures and inadequate maintenance or repair need to be undertaken to round out the rectenna complete characterization.

Refinements such as automatic feedback control of rescattered fundamental by changing the ground plane spacing or load, frequency, or incident power density should be studied to evaluate their effectiveness and life cycle cost in meeting applicable radio regulations.

It should be stated that the above conclusions are based principally on measured results of half wave dipole arrays, and some of the conclusions are applicable to other elements such as yagis, only if the same array characteristics can in practice be achieved. The stipulation applies to any high gain element array.

Better harmonic filtering and active dc load management within a tapered density array along with an efficient and effective overvoltage limiter need to be developed, along with rapid repair techniques also. Long life environmental protection is still a continuing requirement for certain applications, along with light weight and waste heat dissipation for space and high altitudes.

REFERENCES

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4. Brown, W., "Optimization of the Efficiency and Other Properties of the Rectenna Element," 1976 IEEE MTT-S International Microwave Symposium Digest of Technical Papers, pp. 142-144.
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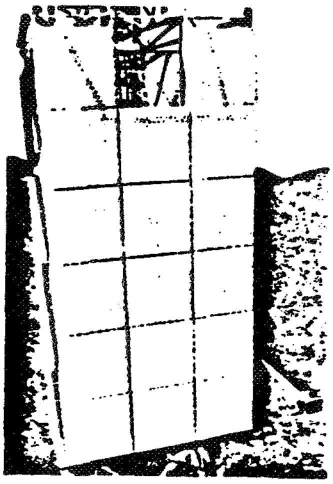


Fig. 1. The RXCV Array

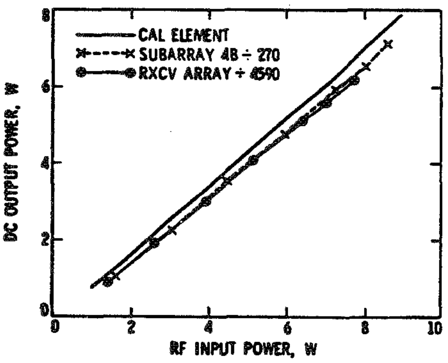


Fig. 4. Transfer Efficiency Performance Comparison

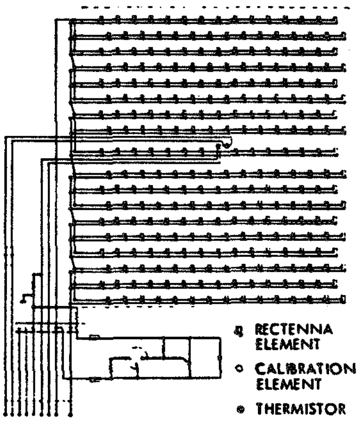
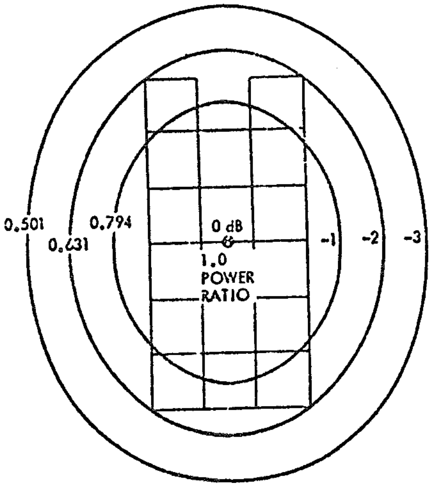
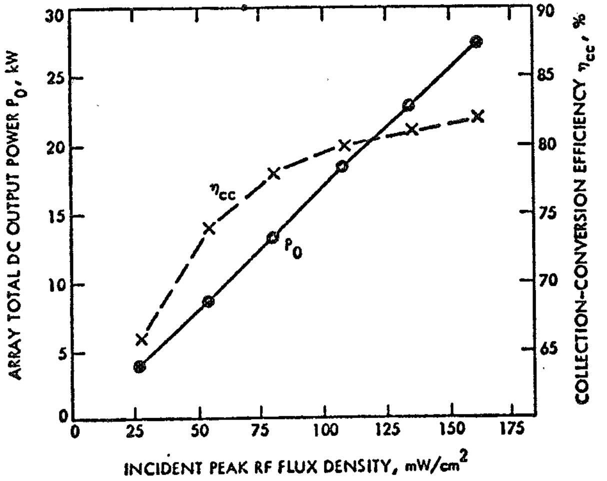
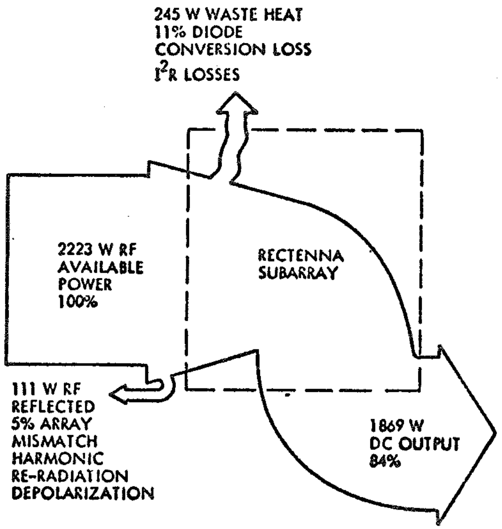


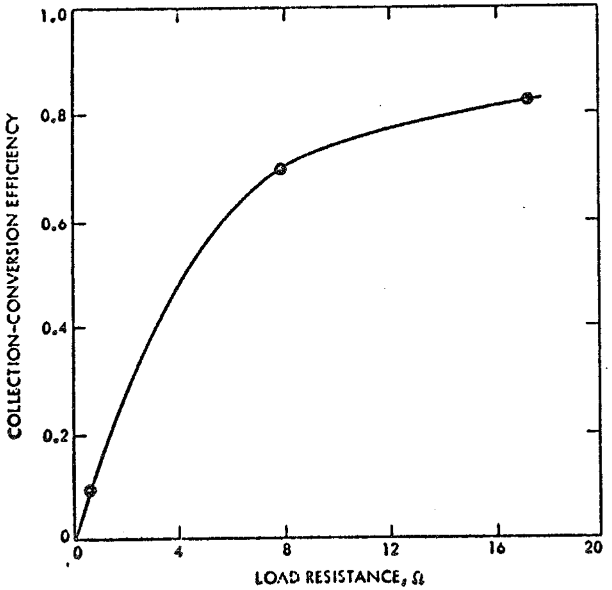
Fig. 5. Subarray Wiring Diagram

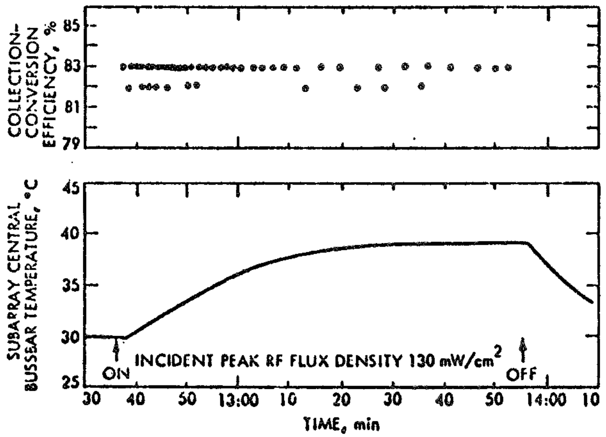
MICROWAVE RECEPTION-CONVERSION ARRAY PERFORMANCE I











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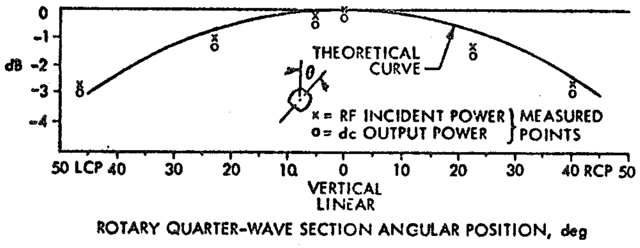
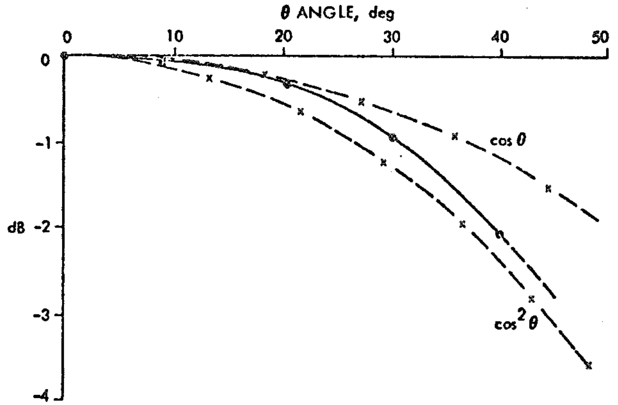
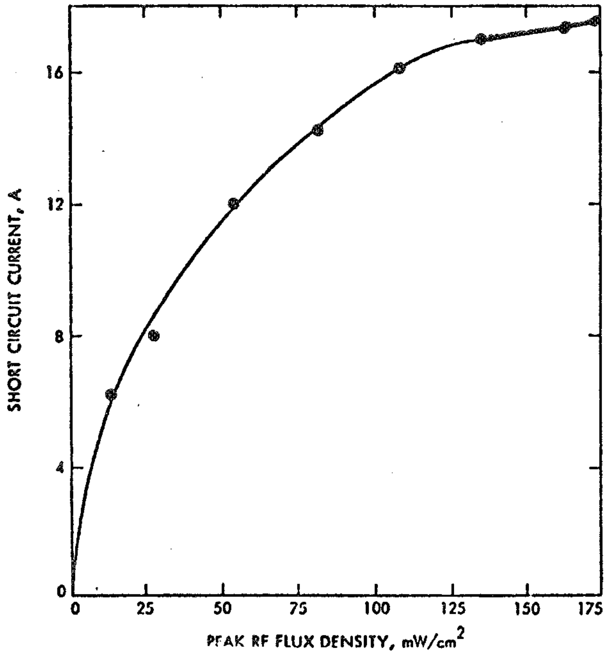
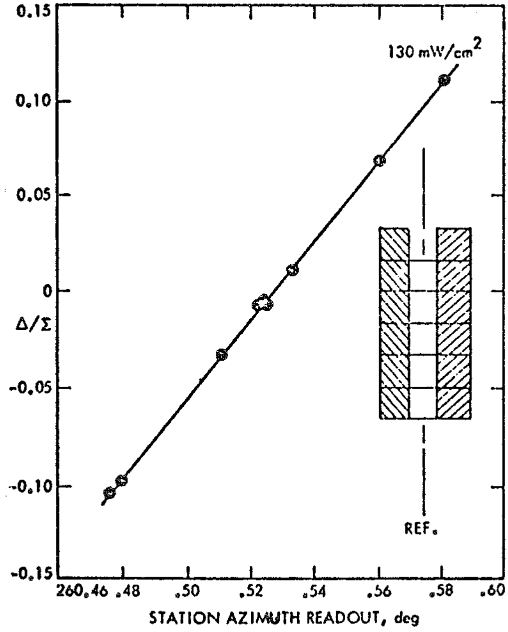
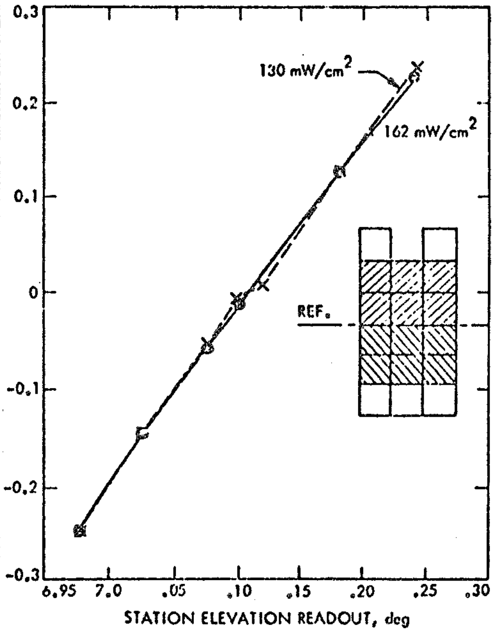
MICROWAVE RECEPTION-CONVERSION ARRAY PERFORMANCE II











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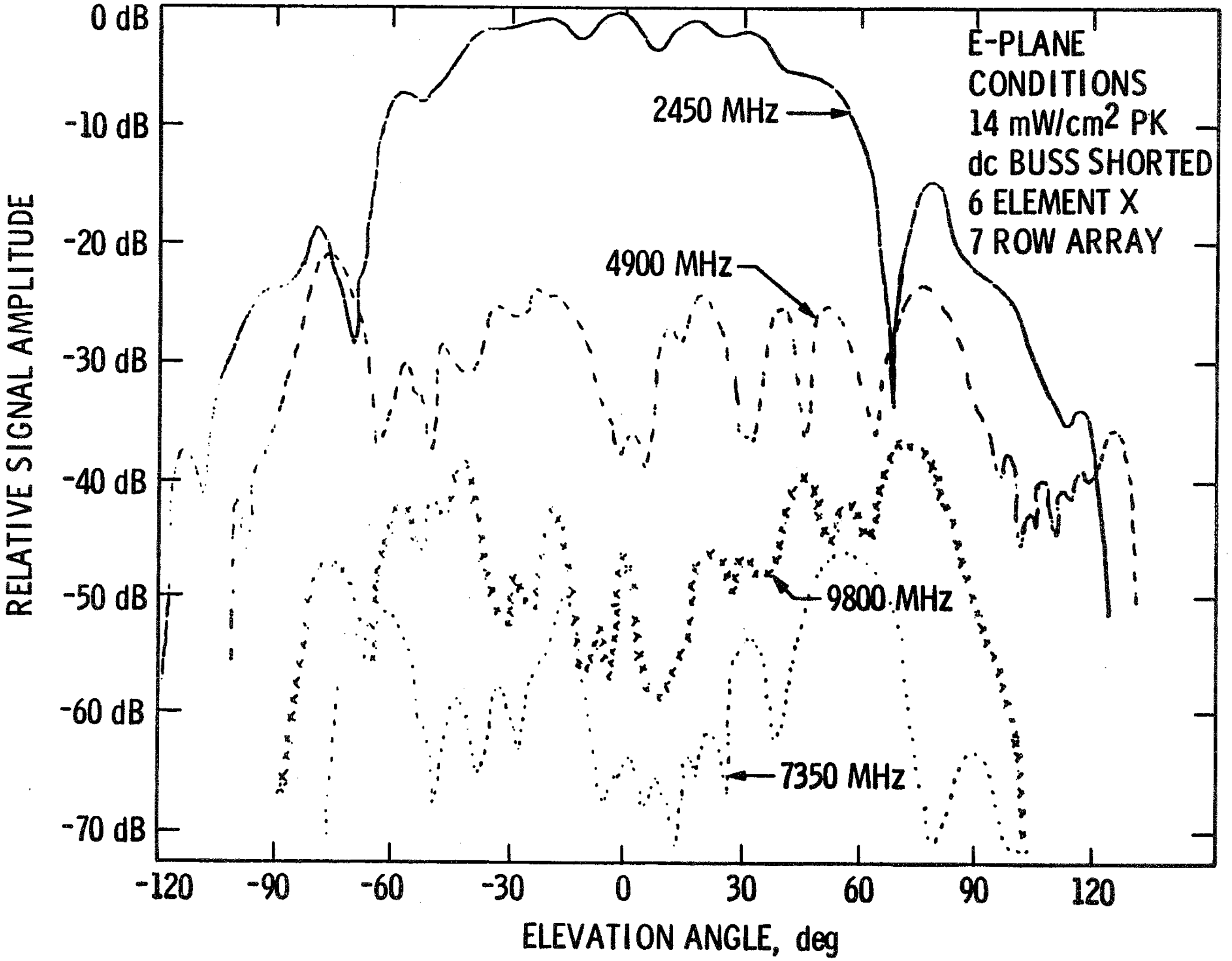
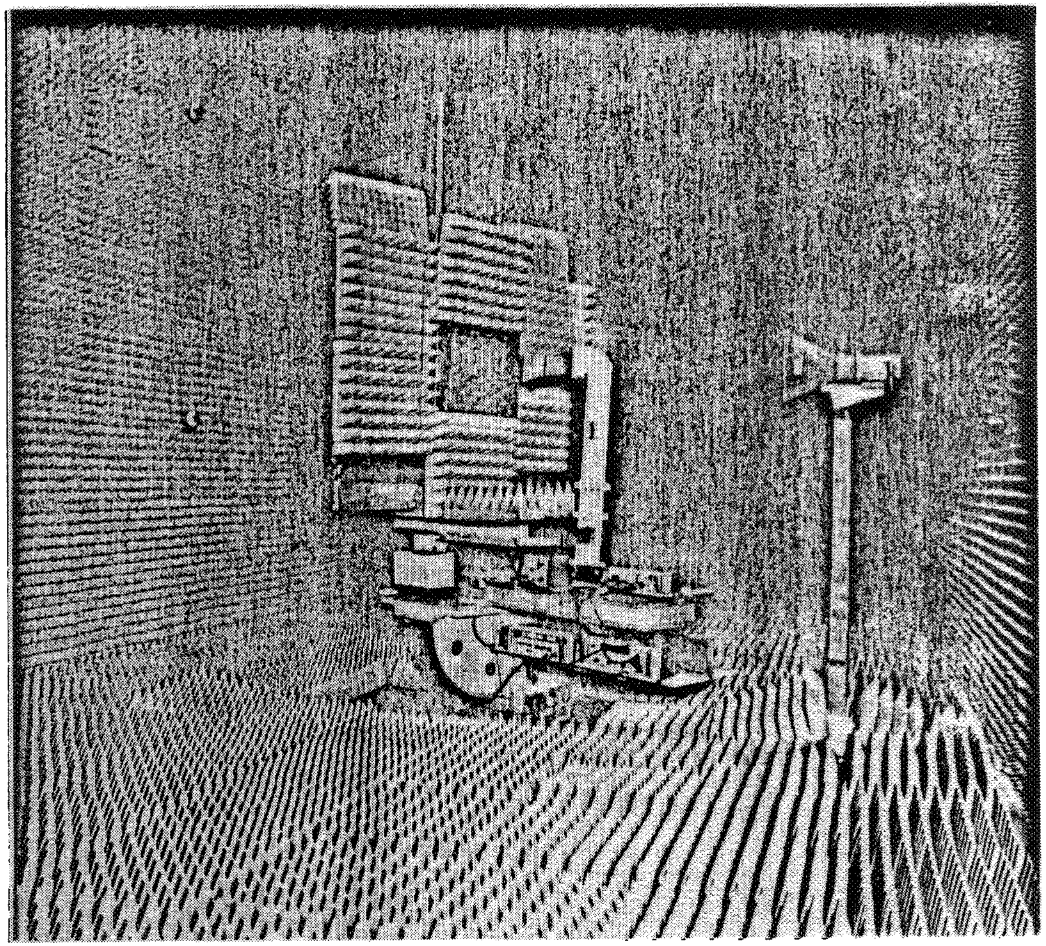
BEAMED RF POWER TECHNOLOGY

RECTENNA RESCATTER AND EMISSIONS



BEAMED RF POWER TECHNOLOGY

RECTENNA SUBARRAY FUNDAMEMTAL SCATTER & HARMONIC EMISSION RADIATION PATTERNS



BEAMED RF POWER TECHNOLOGY

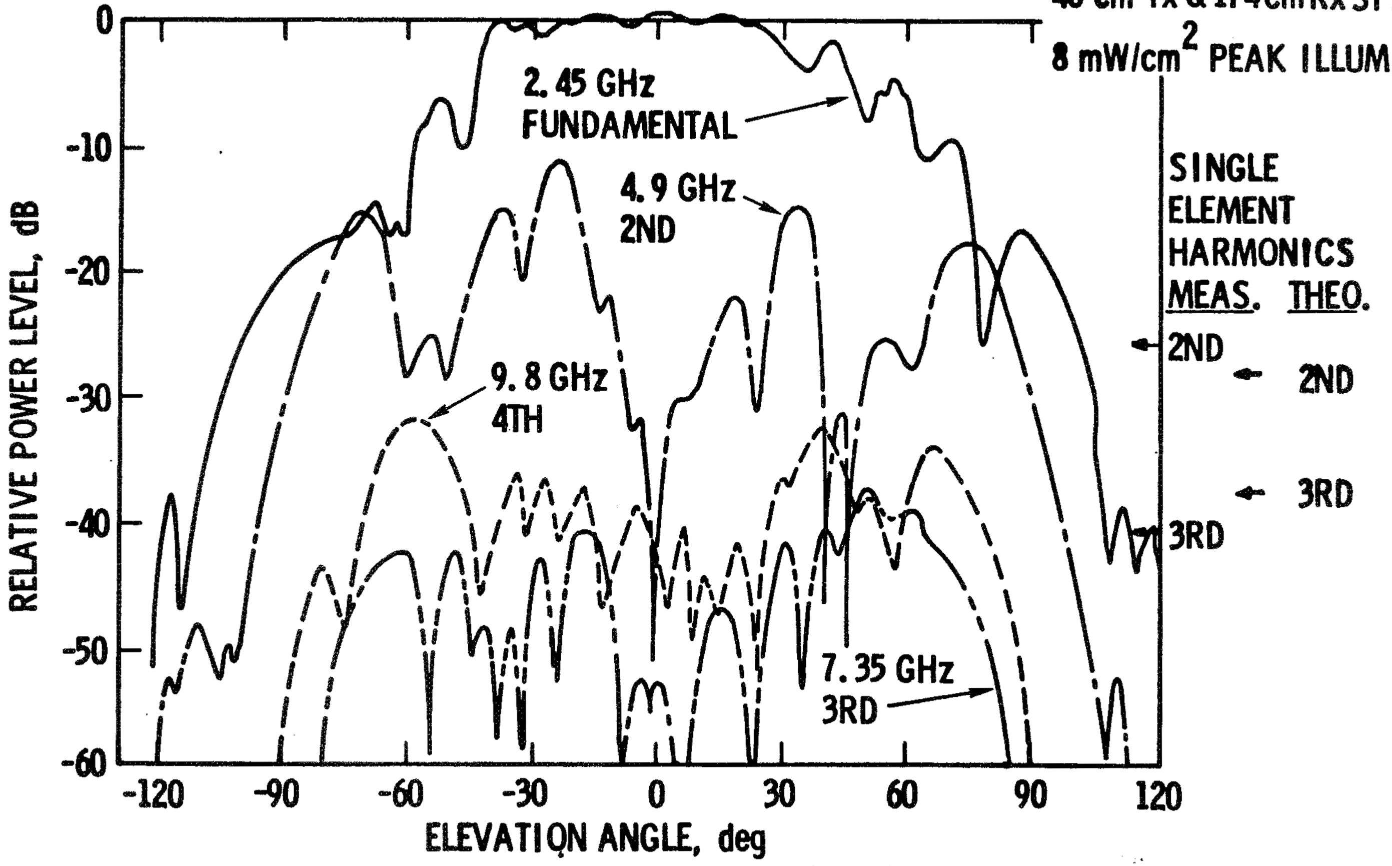
RECTENNA RESCATTER AND EMISSIONS

E-PLANE CONDITIONS

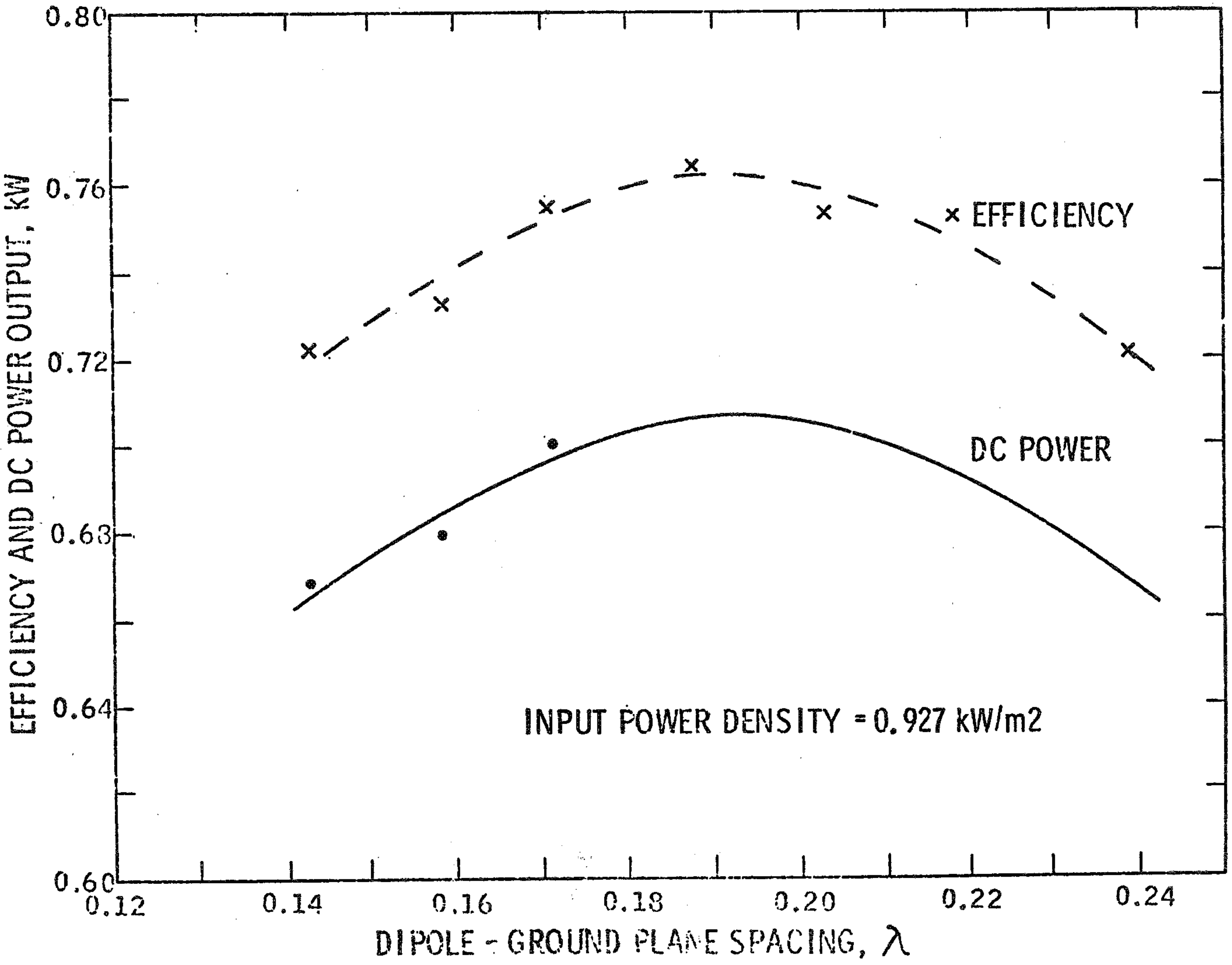
R_L = 15Ω/ROW 6 x 7 SUBARRAY

40 cm Tx & 174 cm Rx SPACING

8 mW/cm^2 PEAK ILLUMINATION



POWER OUTPUT AND EFFICIENCY
VS GROUND PLANE SPACING



CONCLUSIONS PRESENTED AT THE RECTENNA SESSION

1. Concept - The rectenna concept (individual antenna elements feeding directly into a rectifying circuit) has been shown by analysis and research to be the most technically effective and economically feasible RF-to-DC power converter for providing electrical power.

2. Harmonic Suppression - RF filtering will be required for harmonic suppression in the rectenna.

3. Higher Gain Antenna Elements - In areas of low power density higher gain antenna elements can increase conversion efficiency and reduce the parts count.

4. Collection Techniques - Analysis of rectenna collection techniques indicates that parallel and series combining inefficiencies are nearly identical.

5. Power Combining - It is preferable, from the standpoint of combining inefficiencies, to combine rectenna power in concentric rings rather than in continuous rows.

6. Demonstration - High power output at a long range with high combined collection/conversion efficiency has been demonstrated with a rectenna design that is tolerant to angle of incidence, temperature, polarization, flux density levels and load resistance magnitude changes.

   System Definition studies have integrated microwave system requirements into a typical rectenna array. The conclusions resulting from these studies and the characteristics of a typical array are discussed below.

1. Rectenna Configuration
   a. The RF collecting array consists of a group of serrated flat panel subarrays of vertically polarized half-wave dipoles ($\sim 11/m^2$), tilted with respect to the earth's surface so as to be perpendicular to the incoming RF beam. (Total area perpendicular to the beam of 78.5 km^2).
   b. An 80% optically transparent, steel mesh with less than 1% RF leakage is employed as the ground plane.

2. Incident RF Energy
   a. The normal incident RF energy is gaussian distributed across the rectenna with a peak intensity of 23 mW/cm^2.
   b. Studies to date have only considered rectenna configurations which receive RF energy from one SPS satellite.

3. Rectenna Area - The rectenna collecting area is to extend to the normal incident flux density level of 1 mW/cm^2. (Approximately 5 km radius E-W, variable with latitude in N-S direction) and the rectenna is to be fenced to exclude transient intrusion.

4. Type of Rectifiers - Half wave Schottky barrier Ga-As diodes are preferred as RF-to-DC rectifiers.

5. Efficiencies - The collection efficiency is projected to be 88% and the conversion efficiency is 89%.

6. Costs -

   a. The currently estimated rectenna cost is a large part of the total SPS program cost (approximately 20%).

   b. The rectifier is the largest cost element in the rectenna.