

SYSTEM PERFORMANCE CONCLUSIONS

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1. System Sizing

- o Reduced Power Levels
- o Antenna Diameters Smaller than 1 Km

The initial sizing for the satellite power station was a 1-kilometer transmit array with 5 gigawatts of DC power out of the rectenna. There are, however, some advantages in having a smaller system size. Commercial utility companies can probably handle 1-gigawatt increments easier than 5 gigawatts; the implementation cost of 1-gigawatt system is lower; and the sidelobe radiation levels near the rectenna are lower. Disadvantages of smaller systems include lower end-to-end microwave transmission efficiency and an increase in the overall cost of electricity (mills per kilowatt-hour).

The downlink operating frequency is another trade-off consideration. The SPS reference system operates at 2.45 gigahertz, which is the center of a 100-megahertz band reserved for government and nongovernment industrial, medical, and scientific (IMS) use. This band has the advantage that all communication services operating within the 2450 ± 50 megahertz limits must accept any interference from other users. There is another IMS band at 5.8 gigahertz which should be considered. One way to reduce the terrestrial land usage requirements for the SPS rectenna is to increase the operating frequency while maintaining the same antenna size. This reduction in rectenna size must, however, be traded off against the large temporary degradation in transmission efficiency under extremely adverse weather conditions at the higher frequency.

The end-to-end microwave transmission efficiency for smaller SPS systems operating at different frequencies will not be determined. The nominal microwave transmission efficiency, from the rotary joint in the satellite to the DC/DC power interface at the output of the rectenna, is shown in figure 1. This end-to-end efficiency, for a frequency of 2450 megahertz, may be written

$$\text{Microwave Eff} = 0.805 \text{ Eff}_{\text{coll}} \times \text{Eff}_{\text{conv}} \quad (1)$$

For the reference system, $\text{Eff}_{\text{coll}} = 0.88$ and $\text{Eff}_{\text{conv}} = 0.89$, and the microwave link efficiency is 63 percent. This efficiency will be used as a reference for comparing smaller SPS systems. In equation 1, the rectenna collection efficiency Eff_{coll} is a function of incident power density and incremental rectenna area while the conversion efficiency Eff_{conv} varies only with power density. The RF-DC conversion efficiency

Figure 1. - Nominal efficiencies for the microwave system (2450 MHz)

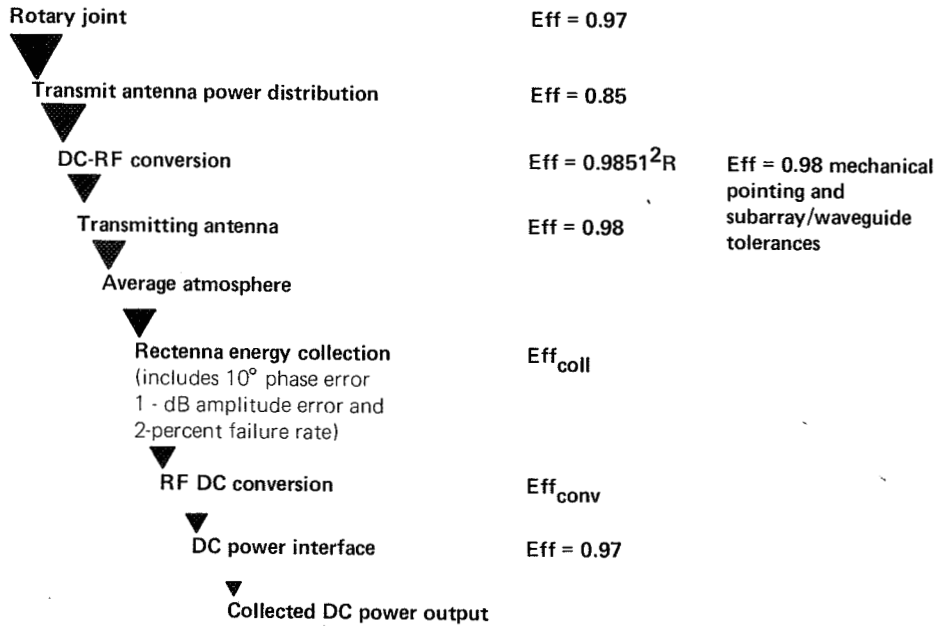
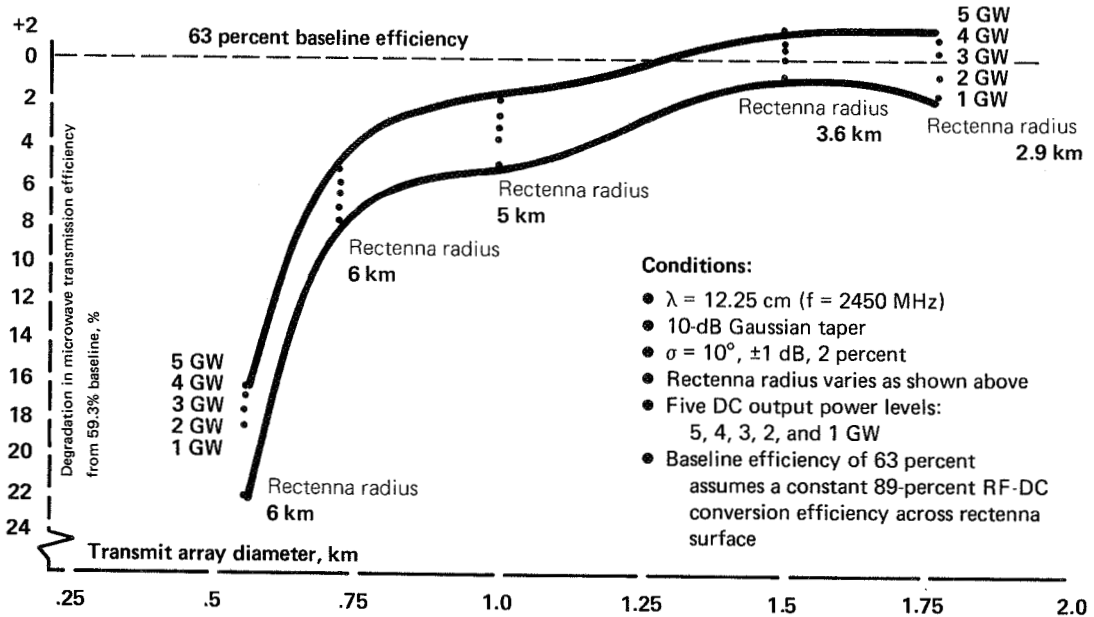


Figure 2. - SPS performance at 2450 MHz as a function of antenna size and power



depends on the input power level to the rectifying diodes connected to the half-wave dipole elements in the rectenna. During the past several years, excellent progress has been made in developing higher efficiency diodes, particularly at lower levels. This RF-DC conversion efficiency, which is the collection efficiency of the individual dipole elements times the diode rectifying efficiency, varies from 70 percent at 0.04 milliwatt per square centimeter to 90 percent at 10 milliwatts per square centimeter as a function of incident power density. These data assume a 3 percentage point improvement in the next decade over the present achievable conversion efficiency.

The degradations in end-to-end microwave efficiency for smaller SPS sizes are summarized in figures 2 and 3 for operating frequencies of 2450 and 5800 megahertz respectively. The 63 percent reference efficiency is that performance expected for a 1-kilometer, 5-gigawatt SPS system operating with a constant 89 percent RF-DC conversion efficiency in the rectenna. The difference in performance between the 5-gigawatt and the 1-gigawatt systems as shown in figure 2 is due to a reduction in rectenna conversion efficiency at the reduced power density levels associated with the 1-gigawatt system. Also, for transmit arrays with a diameter less than 1 kilometer, the power beam is dispersed over a wider area at the ground due to reductions in antenna gain. This dispersion reduces the amount of energy intercepted by the rectenna and further reduces the RF-DC conversion efficiency. The data indicate that smaller SPS powers are feasible, provided the antenna size is not reduced; that is, a 1-kilometer, 1-gigawatt SPS system will have only a 4 to 5 percent (percentage points) reduction in microwave transmission efficiency as compared to a 5-gigawatt system.

The transmission efficiency for systems operating at 5800 megahertz as given in figure 3 is interesting in that there is very little degradation in performance at the reduced power levels. The reason is that the power density levels at the rectenna are considerably higher for the 5800-megahertz systems, and hence little degradation in RF-DC conversion efficiency occurs as the power is reduced. There is also a constant degradation relative to the 59.3 percent reference efficiency due to lower efficiencies in several of the microwave subsystems operating at the higher 5800-megahertz through a heavy rain, rectennas for these systems could have intermittent power reductions unless located in dry, southwest regions.

There is a significant reduction in rectenna size at the higher frequency as shown in figure 3. If rectenna costs and land usage requirements become major factors, operating at 5800 megahertz should be seriously considered.

2. Startup/Shutdown Operations

- o Three sequences for startup/shutdown provide satisfactory performance

An SPS in synchronous orbit experiences solar eclipses by the earth, moon, and other SPS. The most important of these eclipses are by the earth, both in occurrence and duration. The satellite will be eclipsed daily by the earth for approximately six weeks during the spring and fall equinoxes, March 21 and September 21, respectively. Specifically there will be 43 eclipses centered around the spring equinox and 44 in the fall, for a total of 87 times per year. These eclipse periods will vary each day, with the time building up to a maximum of 75 minutes at the equinox. Except for the first and last days of each series, the satellite is totally eclipsed.

Because of switching conditions and transients in the DC power distribution system, the microwave system will be brought up (or shutdown) in controlled increments, rather than having on-off switching of 7 GW of power. The resultant microwave radiation patterns can vary greatly, depending upon the sequencies used for energizing the antenna. The beam patterns have been evaluated in order to reduce the environmental effects of the microwave radiation from the antenna under transient operating conditions.

Let us now examine what happens to the solar array during an eclipse. Both the solar cells and the structures will cool off quickly. The structure will drop to 70°K (-335°F) during the longest (72 minutes) occult period (Ref. 5). The solar cell temperature drops from its normal operating value of 310°K to 110°K at the end of 70 minutes. After emerging from the earth's shadow, cell temperatures rise quickly, particularly if the cells are open-circuited. A solar cell's output is a function of temperature and the cells will produce a higher output power for a few minutes until the temperature stabilizes. Since the voltage regulation to the klystron tubes is +5%, the tubes cannot be energized until near steady-state operating temperatures are reached in the solar array.

The operational procedure would be to open-circuit the solar cells prior to emergence from occultation, close to the DC power circuits in the solar array after the solar cell temperatures have stabilized near 310°K (a few minutes depending the length of the eclipse period), and then sequentially energize the klystron tubes in an optimum manner to minimize radiation effects.

The pattern characteristics for the main beam, sidelobes, and grating lobes were examined for eight types of energizing configurations which include:

1. Random - the antenna is starting at the center and progressing outward
2. Concentric rings - starting at the center and progressing outward
3. Concentric rings - beginning at the outer and progressing to the center
4. Line strips - center to the outside edge
5. Line strips - outside edge to the center

Figure 3. - SPS performance at 5800 MHz as a function of antenna size and power

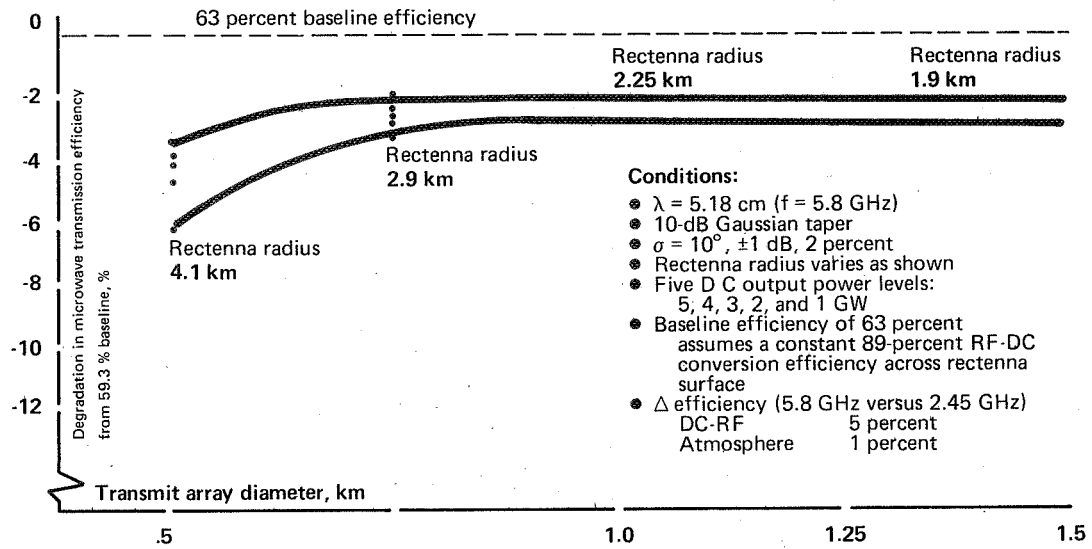
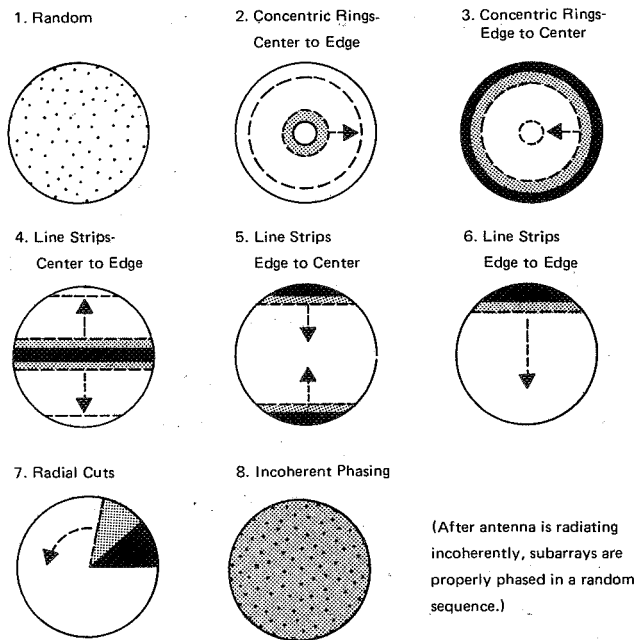


Figure 4. - Antenna startup/shutdown configurations



Note: Increments of 10 % power are used for all sequences. Antenna illumination is a 10 dB gaussian taper.

Figure 5. Sidelobe Patterns for the Random Sequence

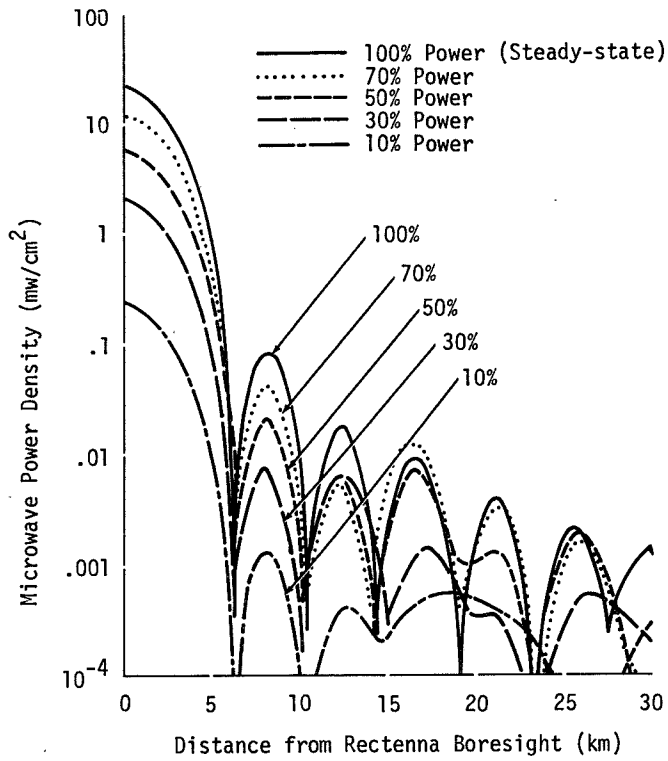
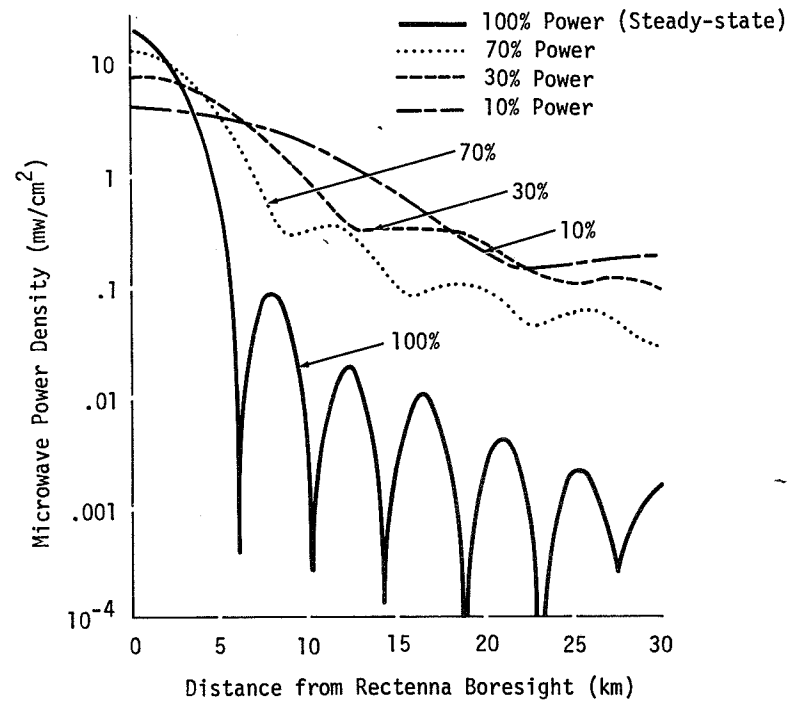


Figure 6. Sidelobe Patterns for Line Strips- Edge to Edge



6. Line strips - edge-to-edge
7. Radial cuts
8. Incoherent phasing

In each of these sequences shown in figure 4, the amount of antenna power is increased in ten discrete steps. For each of the configurations the reference error tolerances for random amplitude and phase errors throughout the antenna are included. The results are obtained through computer programs which simulate the 7220 subarrays as individual radiators properly phased together.

To briefly summarize the results, three sequences provided satisfactory performance in that the resultant sidelobe levels during startup/shutdown were lower than the steady-state levels present during normal operations. These three sequences were:

- o random
- o incoherent phasing
- o concentric rings - center to edge

As an example of the performance of the random sequence, the random startup is well-behaved in that the partial power patterns closely resemble the full power characteristics, only reduced in amplitude as shown in figure 5. As the radiated power is decreased the effective antenna area decreases, and the far sidelobe levels increase. The peaks and nulls of the sidelobes remain spatially stationary as the antenna radiating area changes.

An example of a poor startup/shutdown sequence is shown in figure 6, i.e., line strips - edge to edge. By taking successive vertical strips at one edge of the antenna and progressing to the other edge, the peaks and nulls of the sidelobes moves inward towards the rectenna with additional power. These patterns have sidelobe levels several orders of magnitude greater than for steady-state. In conclusion a proper choice of sequences should not cause environmental problems due to increased microwave radiation levels during the short time periods of energizing/de-energizing the antenna.

3. Antenna/Subarray Mechanical Alignments

- o Alignment requirements determined by grating lobe peaks and scattered power levels
- o Antenna alignment requirement is 1 min or 3 min depending upon phase control configuration.

There are two types of mechanical misalignments: (1) a systematic tilt of the entire antenna structure produced by attitude control system errors, and (2) a random tilt of the individual subarrays produced by antenna bending or subarray alignment errors. The rectenna collection efficiency (which is an indication of the amount of scattered power) as a function of systematic (structure) and random (subarray) tilts is shown in figure 7. It is interesting to note that the two tilts have the same degradation in collection efficiency per arc

Figure 7. - Antenna tilt (min)

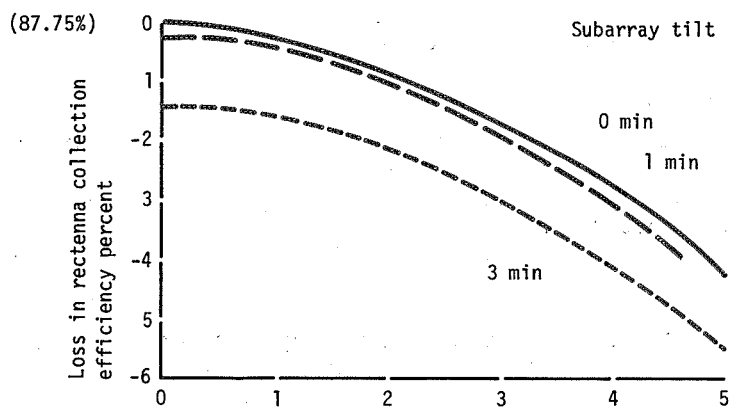
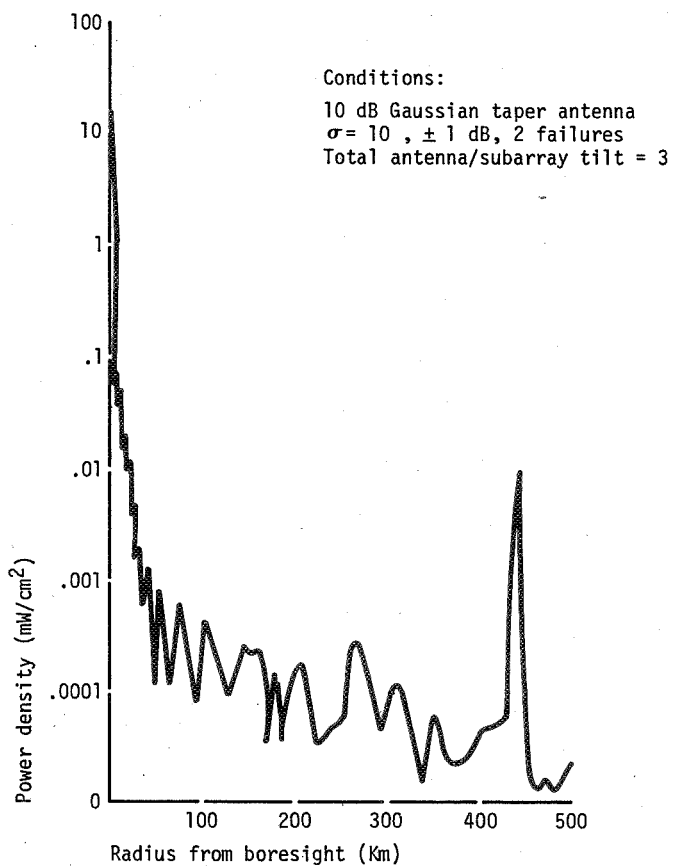


Figure 8. - Peak density for sidelobes and grating lobe as a function of range from rectenna.



minute of misalignment. It will be shown later that the systematic tilt has an order of magnitude greater effect on grating lobe levels than the random tilts.

The antenna and subarray/power module misalignments produce well-defined grating lobes. The grating lobes occur at spatial distances corresponding to angular directions off-axis of the antenna array where the signals from each of the subarrays add in-phase. When the mechanical boresights of the subarrays are not aligned with the pilot beam transmitter at the rectenna, the phase control system will still point the composite beam at the rectenna; however, some of the energy will be transferred from the main beam into the grating lobes. The grating lobes do not spatially move with misalignment changes but their amplitudes are dependent upon the amount of mechanical misalignment. The distance between maxima for the grating lobes is inversely proportional to the spacings between phase control centers on the transmit antenna. If the phase control is provided to the 10.4 meter X 10.4 meter subarray level, grating lobe peaks occur every 440 Km. If the phase control system is extended down to the power module level, the grating lobes will be spatially smeared and the peaks greatly reduced in amplitude. This improvement in grating lobe pattern would be due to differences in spacings between the power tubes within the antenna. An example of the first grating lobe peak for a total antenna/subarray tilt of 3.0 arc-minutes is shown in figure 8.

Based upon environmental considerations, the grating lobes are constrained to be less than $.01 \text{ mw/cm}^2$. The total mechanical alignment requirements for both the subarrays and the total antenna can be determined from this constraint. The amplitudes of the grating lobes for phase control to the power module level and an antenna tilt of 1 min is shown in figure 9. The locations and spacings of these grating lobes across the continental United States with the rectenna centrally located are shown in figure 10.

Conclusions from the antenna simulation studies are:

- (1) Systematic (antenna) tilt has an order of magnitude greater effect on grating lobe peaks than random (subarray) tilt.
- (2) The systematic tilt must be less than 1 min for phase control to the 10 meter square subarray level and 3 min for phase control to the power module level in order for the grating lobe peaks to meet the guideline of $.01 \text{ mw/cm}^2$.
- (3) Random (subarray) tilt is limited to 3 min in order to maintain a 2% or less drop in rectenna collection efficiency. The random tilt has a profound impact on the amount of scattered microwave power but only a very small contribution to the grating lobe peaks.

4. Scattered Microwave Power

- o System error parameters have been defined to minimize scattered power

Figure 9. - Grating lobe peaks for 10 meter subarrays and phase control 10 power modules (tubes)

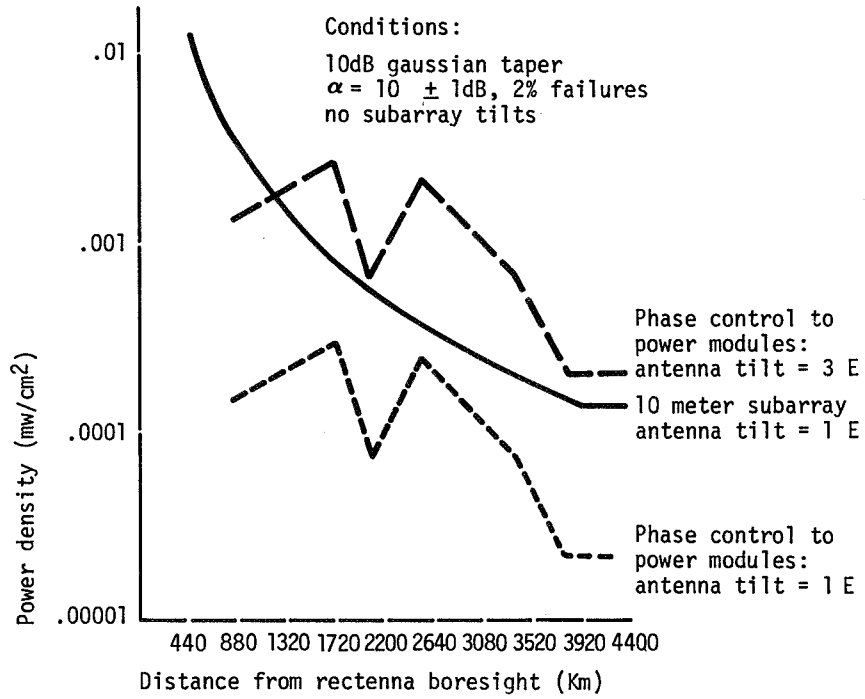
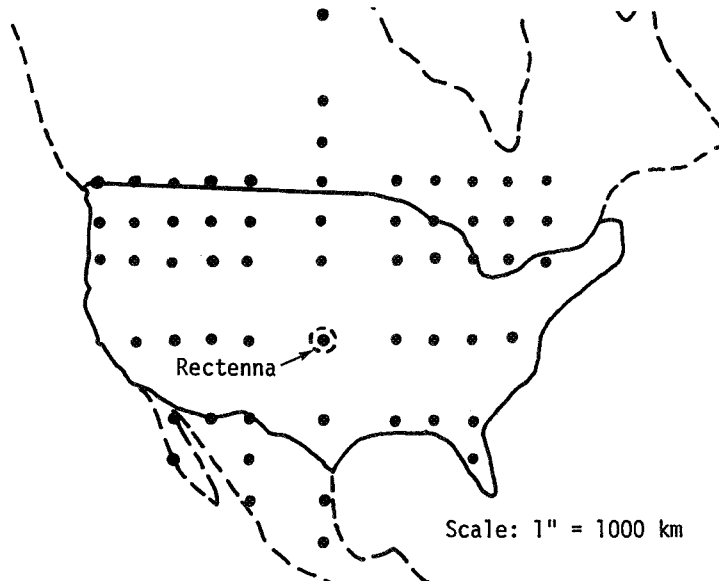


Figure 10. - Grating locations for a single beam.



The relative importance of the electrical and mechanical tolerances on the rectenna collection efficiency is summarized in figure 11. The baseline error parameters are $\sigma = 10^\circ$ rms phase error, ± 1 dB amplitude error, 2% failures, .25 inch mechanical gap between the 10. meter X 10. meter subarrays, antenna tilt < 1 min (attitude control) and subarray tilt < 3 min. The scattered microwave power is the extra power lost (not incident upon the rectenna) due to the error tolerances. The rectenna would intercept 95.3% of the total power transmitted by a perfect system; the error tolerances reduce this amount of received power to 86.0% of the transmit power.

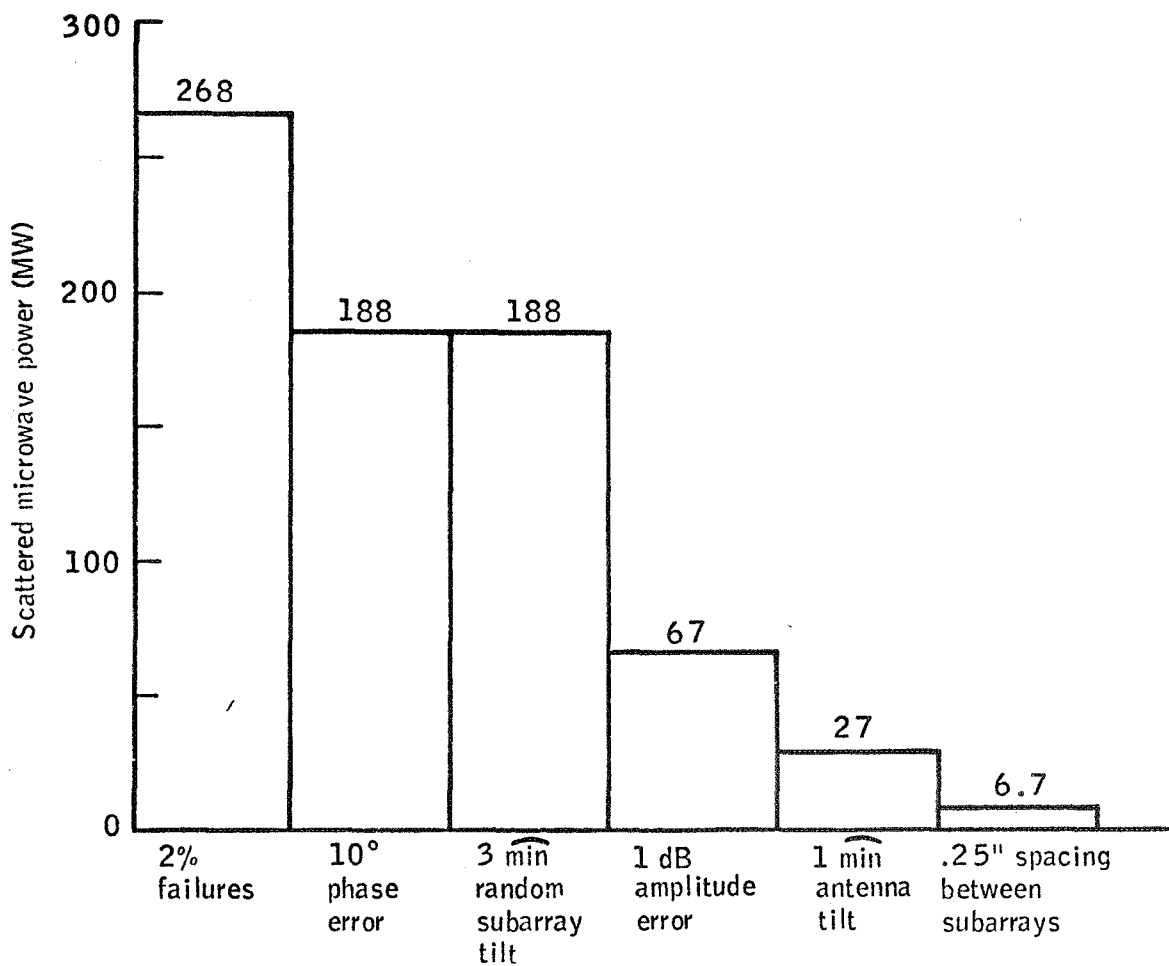


Figure 11.- Scattered microwave power due to electrical and mechanical errors. (10 meter subarray).