MICROWAVE SYSTEM PERFORMANCE SUMMARY

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Introduction: The SPS microwave system as defined in the October 1978 Reference System Report, DOE/ER-0023, has a 1 Km diameter phased array antenna with a 10 dB gaussian taper illumination which focuses the beam at the center of the ground antenna/rectifying system (rectenna). The power beam has approximately 88% of its energy within a 5 Km radius from the rectenna boresight, with a resultant beam width of 1.2 arc-minutes. Mechanical alignment of the 1 Km antenna is maintained within one arc-minute while electronic alignment has a 1.8 arc-second accuracy. The DC-RF power converters within the antenna are 70 KW klystrons fed by 40 KV power lines from a series/parallel solar array configuration. The antenna is divided into 7220 mechanical subarrays, 10.4 meters x 10.4 meters on a side, having slotted waveguides as the radiating surface. Slotted waveguides were selected because of their high power handling capabilities and low I^2R losses.

The klystrons will be phase controlled at the individual tube level through the use of a retrodirective pilot beam signal transmitted from the center of the rectenna and phase conjugated in receivers in each power module. An onboard phase reference signal is distributed through the antenna to provide the same reference in each conjugating receiver. The reference phase distribution system is implemented in the form of a four level tree structure with electronic compensation for minimizing phase shifts due to unequal path lengths from the center of the transmit antenna to each phase control receiver. The uplink pilot beam signal has a double sideband, suppressed carrier with code modulation to provide link security and anti-jamming protection from radio frequency interference.

he ground rectenna converts the RF energy to DC electricity using halfwave dipoles feeding Schottky barrier diodes. Coherence of the incoming phase front needs to be maintained only over the area associated with a small group of dipoles. Physically the present rectenna configuration is a series of serrated panels perpendicular to incoming beam and covers approximately 75 square kilometers. A 75-80% optical transparency of the panels allows other utilization of the area beneath the rectenna if so desired.

The SPS sizing of the 1-Km transmit antenna and 5 GW of DC output power from the rectenna is based upon a 23 KW/m^2 heat dissipation limit in the antenna and a hypothetical 23 mW/cm^2 peak power density limit in the ionosphere to prevent nonlinear heating. System sizing tradeoffs given in another paper in this session indicate the ionospheric limit is a critical design and costing parameter. This limit may be revised upward pending the completion of the Department of Energy Environmental assessment studies on ionospheric heating.

Recent Study Results: Several changes in the microwave system are now recommended as a result of recent NASA and contractor studies. These modifications to the reference system documented in the aforementioned October 1978 DOE/NASA report include:

- Phase control to the power module (tube) level. It is recommended that phase conjugation be performed at each of the 101,000 power modules rather than at the 7,220 subarrays. The advantages of phase control at the tube level is a reduction in the antenna and subarray mechanical tilt requirements (or a reduction in scattered microwave power if the same tilt requirements are maintained) and a reduction in the effects of distributed phase errors within the subarrays. The disadvantage is increased costs due to the 94,000 additional phase control receivers. In the May 1979 SPS Microwave Symposium in Washington, D. C. it was reported that an overall cost savings could be achieved (i.e., the cost benefits of less scattered power were greater than the additional receiver costs) if the phase control receivers were less than $600 each. A later Boeing Aerospace Company study indicates that these receivers can be built for less than $600 in high volume quantities. There is also an environmental advantage in phase controlling at the power module level in that the grating lobes incident upon the earth are reduced in amplitude and in quantity. Figures 1 and 2 show the locations and amplitudes of the grating lobes from a single 5 GW SPS system with phase control to the power module level. Recent simulation results indicate the off-axis grating lobes may be considerably reduced from the data shown in the figures.

The location jitter or the error in path length from the pilot beam transmitter to each radiating slot in the antenna is reduced by going to the smaller antenna size associated with an individual tube rather than to the larger subarray. This location jitter, which appears as a phase error, scatters 6 MW of power at the tube level as compared to 87 MW at the subarray level.

- A reduction in allowable amplitude jitter. The reference SPS system has a ±1 dB amplitude jitter across the surface of each subarray or power module. Analysis results indicate that power transfer efficiency (88% for the reference system) is relatively insensitive to amplitude jitter. However the voltage and amplitude regulations for the high efficiency, high gain klystron tubes have to be maintained to approximately 1% for satisfactory operation. Therefore a ±1% amplitude tolerance is recommended for the antenna error parameter. This change will not affect the microwave transmission efficiency budget.
- Metal matrix waveguides. The SPS reference system has aluminum for the subarray distribution and radiating waveguides. Because of thermal distortion problems a graphite/aluminum metal matrix composite is now being developed as a possible replacement for the aluminum.

The antenna structural members are composed of a high-temperature graphite plastic material for rigidity. The antenna primary structure has a 1040 meter x 1040 meter x 100 meter pentahedral truss configuration which suppors a secondary structure. This secondary structure provides a base for mounting and aligning the transmitter subarrays. Both the primary and secondary structures must maintain a high degree of stability over wide operating temperature fluctuations to preserve the three arc-minute flatness requirement, hence the need for low coefficient of thermal expansion materials.

- Startup/Shutdown Procedure. The satellite will have to shut down 87 times per year due to solar eclipses by the earth. In addition there will be eclipses by the moon and other SPS, as well as scheduled shutdowns for maintenance. A number of possible sequences for energizing/deenergizing the microwave system were investigated. 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: random, incoherent phasing, and concentric rings-center to edge. Thus no microwave radiation problems are anticipated during startup or shutdown operations, either scheduled or unscheduled.

<u>Shaped Beam Synthesis</u>: Studies into reshaping the beam pattern to improve overall rectenna collection efficiency and to provide additional means of sidelobe control were undertaken. These studies included: (1) Adding phase reversal at the klystron input as a first step towards a continuously variable phase distribution across the antenna surface. The results showed that reshaped beam patterns

into "squared" main beams are possible with both reverse and continuous phase tapers. However the penalty is an increased antenna size or a larger rectenna. (2) Adding suppressor rings to the antenna for reducing the first few sidelobe levels. Results indicate a 5 dB reduction in sidelobe levels at the expense of a loss in rectenna collection efficiency. Larger antennas or rectennas are again needed to retain the 88% rectenna collection efficiency. (3) Quadratic phase tapers. The analyses showed a decrease in on-axis power density (i.e., a squared beam) with a corresponding loss in beam transfer efficiency, dependent upon the amount of phase taper introduced. (4) Multiple antenna beams. The transmission of multiple beams from a single antenna is possible by spatially modulating the illumination function. Results for a simple two-beam SPS system were as predicted except for a small residual central lobe. Elimination of the central peak is a goal for future studies in this area.

Summary: The characteristics and error parameters of the updated microwave transmission system may be summarized as follows:

Frequency	-	2.45 GH_Z
Output Power to Power Grid	-	5 GW (DC)
Transmit Array Size	-	1 Km Diameter
Power Radiated from Transmit Array	-	6.72 GW
MPTS Efficiency	-	63% (DC/RF Input to RF/DC Output)
Array Aperture Illumination	-	10 step, truncated gaussian amplitude distribution with 10 dB edge taper
Peak Microwave Power Density in Ionosphere	-	23 mW/cm^2
Phase Control	-	to power module level
Waveguide material	-	metal matrix composite

Error Budget:

Total RMS phase error per power module	=	10°
Amplitude tolerance per power module	=	±1%
Failure rate of DC-RF power converter tubes	=	2% (a maximum of 2% failed at any one time)
Antenna mechanical alignment	-	one arc-minute
Subarray mechanical alignment	-	three arc-minutes

The relative importance of these electrical and mechanical tolerances upon scattered microwave power (extra power not incident upon the rectenna) is summarized in Figure 3.

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FIGURE 1. GRATING LOCATIONS FOR A SINGLE BEAM

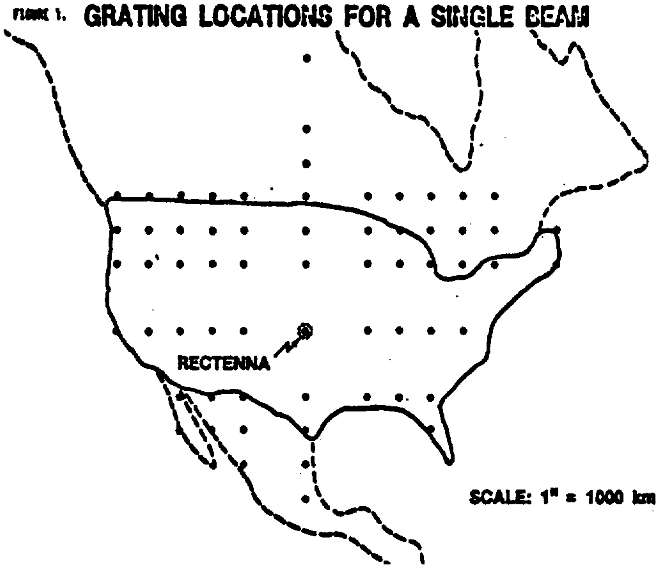
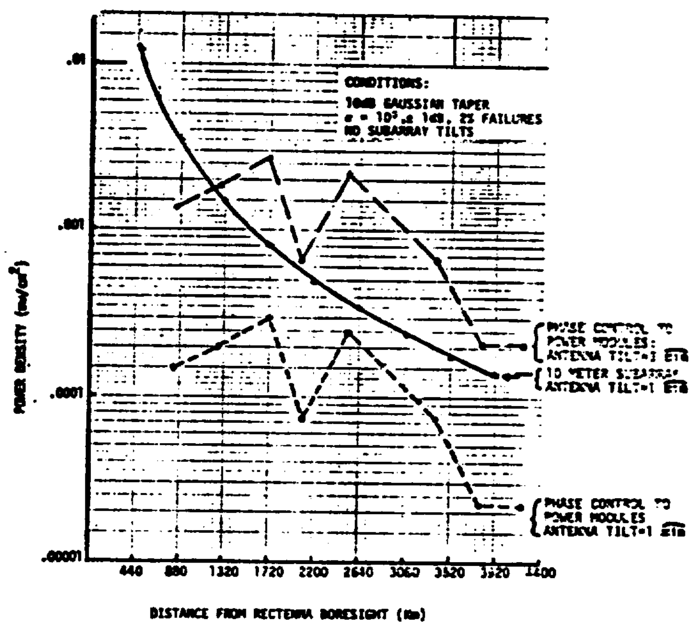


FIGURE 2.

GRATING LOBE PEAKS FOR 10 METER SUBARRAYS AND PHASE CONTROL TO POWER MODULES (TUBES)



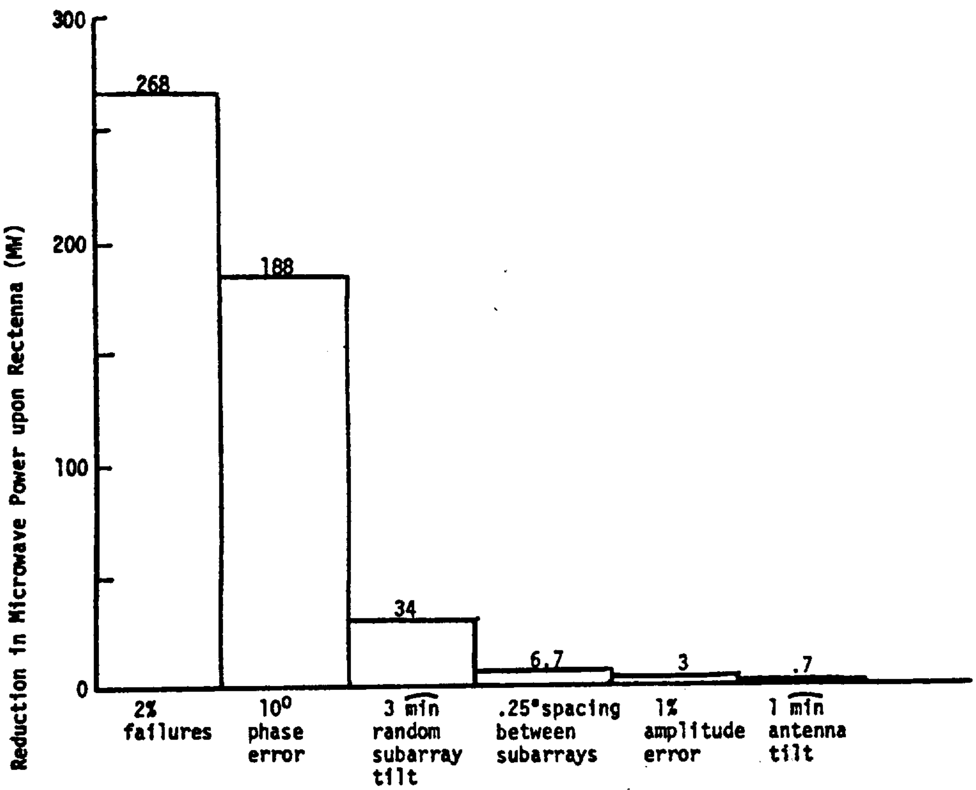


Figure 3. Reduction in Microwave Power due to Electrical and Mechanical Errors (Power Module Level Phase Control)