SMALLER SPS SYSTEM SIZING TRADEOFFS

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Introduction- The present solar power satellite (SPS) system was optimized to provide 5 GW of electrical power at the ground using a 1 Km diameter antenna and a 10 Km diameter rectenna. This antenna sizing and maximum power transmission were determined by two constraints; a 23 KW/m^2 thermal limitation in the transmit antenna and a 23 mW/cm^2 maximum RF power intensity in the ionosphere. This paper considers technical and economic tradeoffs of smaller optimized SPS systems configured with larger antennas, reduced output powers, and smaller rectennas. The advantages of smaller systems are two-fold: (1) commercial utility companies prefer to integrate lower power levels into their grids, and (2) smaller rectenna sizes than the 10 Km diameter reference configuration may be preferred from a land utilization and site location viewpoint.

The differential costs in electricity for seven antenna/rectenna configurations operating at 2.45 GHz and five satellite systems operating at 5.8 GHz have been determined and are described in detail in a report to be published. Because of space limitations only the results are summarized in this paper.

Microwave Systems and Cost Considerations

The thermal limitation at the center of the transmit antenna is due to the heat radiated by the DC-to-RF power converters, i.e., klystrons. The present configuration has 72 KW klystron tubes operating at 85% conversion efficiency and cooled by passive heat - pipe radiators. This thermal limitation is a severe constraint on higher frequency (5.8 GHz) systems which have lower efficiency klystrons (80%) and smaller antenna areas. An improved thermal design using graphite composite materials with high emissivity coatings which provide a 33% increase in heat rejection is proposed in the report and used in these calculations.

The ionospheric power density limitation, a critical parameter in the 2.45 GHz systems, is to prevent possible nonlinear interactions between the ionosphere and the power beam. These nonlinear heating effects are of concern because of possible disruptions in low frequency communications and navigation systems produced by radio frequency interference (RFI) and multipath effects. Theoretical studies of the ionosphere completed in the early phases of the SPS evaluation program indicated the power density should be limited to 23 milliwatts per square centimeter or less in order to prevent nonlinear heating effects. This theoretical value, 23 mw/cm^2, was taken as the SPS design guideline. Subsequent ionospheric heating tests conducted at Plattville, Colorado, and Arecibo, P. R. during the past year (the results of which are reported elsewhere at this conference) have indicated this 23 mw/cm^2 threshold may be too low.

The 2.45 GHz downlink power beam frequency is in the center of a 100 MHz IMS (Industrial, Medical and Scientific) band which allows users to interfere with other users in that frequency region. This 2400-2500 MHz band is not particularly affected by weather conditions and an SPS system should not suffer weather outages. Another IMS band (5800 ± 75 MHz) is also available for possible SPS usage. However an SPS system operating in this frequency region may have to be shut down under very poor weather conditions.

The microwave systems were resized with higher gain antennas and considering various ionospheric and thermal power density limitations. A 10 dB gaussian antenna illumination provides maximum rectenna collection efficiency while minimizing sidelobe levels. Other illumination tapers were investigated but the 10 dB gaussian was the most efficient as was true for the reference SPS system.

The groundrules for sizing the new microwave systems included using the present SPS antenna error parameters, i.e., 10^{o} phase error, ±1% amplitude error, 2% tube failures, ±1 min antenna tilt, ±3 min subarray tilt, .25" mechanical spacing between subarrays, etc., and the rectenna was sized to receive 88% of the transmit power. The relative antenna/rectenna sizes for 2.45 GHz and 5.8 GHz operation are shown in Figure 1.

A detailed analysis of subsystem costs and masses for the reference 5 GW solar power satellite with silicon solar cells is given in the Boeing Aerospace Final Report D180-25461-2, November 1979. These values are used as a baseline for computing costs for the different antenna/rectenna configurations. Since the purpose of this study is to determine the relative or differential costs for the various configurations, any future changes in the absolute costs for the reference system should not have a great impact upon the conclusions herein stated.

The principal elements in the SPS recurring costs are satellite hardware, transportation, space construction and support, rectenna, program management and integration, and cost allowance for mass growth. These cost calculations also included the following guidelines: 30 year operating lifetime, plant factors of .92 and .90 for 2.45 GHz and 5.8 GHz operation respectively, 15% rate of return on investment capital, 22% mass growth factor to cover potential risks in solar array and microwave system performance estimates, 17% of net SPS hardware cost factor to account for mass growth, and 10 GW per year power installation. The cost and mass for each of twelve satellite subsystems were varied according to total power, antenna size, frequency, efficiency, etc, of the candidate antenna/rectenna systems. The electricity costs in mills per KWH and the differential cost increases for 2.45 GHz and 5.8 GHz systems are summarized in Figures 2 and 3, respectively. The data indicates costs for the 2.45 GHz systems are heavily dependent upon ionospheric power density limitations. The 2.45 GHz and 5.8 GHz alternate configurations can provide smaller rectenna sizes at the expense of added electricity costs.

Summary

The satellite and associated microwave system have been reoptimized with larger antennas (at 2.45 GHz), reduced output powers, and smaller rectennas. Four constraints were considered: (1) the 23 mw/cm^2 ionospheric limit (2) a higher (54 mW/cm^2) ionospheric limit (3) the 23 KW/m^2 thermal limit in the antenna, and (4) an improved thermal design allowing 33% additional waste heat. The differential costs in electricity for seven antenna/rectenna configurations operating at 2.45 GHz and five satellite systems operating at 5.8 GHz have been calculated. The conclusions are:

- o Larger antenna/smaller rectenna configurations are economically feasible under certain conditions.
- o Transmit antenna diameters should be limited to 1-1.5 Km for 2.45 GHz operation and .75-1.0 Km for 5.8 GHz.
- o Three configurations were selected for minimum impact on electricity costs (See next page)
- o The present ionospheric limit of 23 mw/cm^2 is probably too low and should be raised after the ionospheric heating tests and studies are completed. For SPS cost considerations, it is very important to ascertain the true upper limit.
- o The 5.8 GHz configurations are constrainted by antenna thermal limitations, rather than ionospheric limits. Potential utility grid impacts of 5.8 GHz

system which has to be shut down on an unscheduled basis due to localized weather conditions are not known.

o Multiple (two to four) antennas on a single solar satellite as shown in Figure 4 are definitely recommended regardless of the particular antenna/rectenna configuration chosen. This is a means for maintaining the same amount of power supplied to the ground while reducing the geosynchronous slots (spacings) required for the satellites.

	2.45 GHz 23 mW/cm² Ionospheric Limit	2.45 GHz 54 mW/cm² Ionospheric Limit	5.8 GHz Improved (33%) Thermal Limit
Antenna Diameter	1.36 Km	1.53 Km	.75 Km
Rectenna DC grid power	2.76 GW	5.05 GW	2.72 GW
Rectenna Diameter	7.6 Km	6.8 Km	5.8 Km
Relative Rectenna Area	56%	46%	33%
Electricity Cost Increase	50.2%	17%	36%
Electricity Cost (mills/KWH)	70.6	55	64

Note: The rectenna areas and electricity costs are in comparison to those for the reference SPS system.

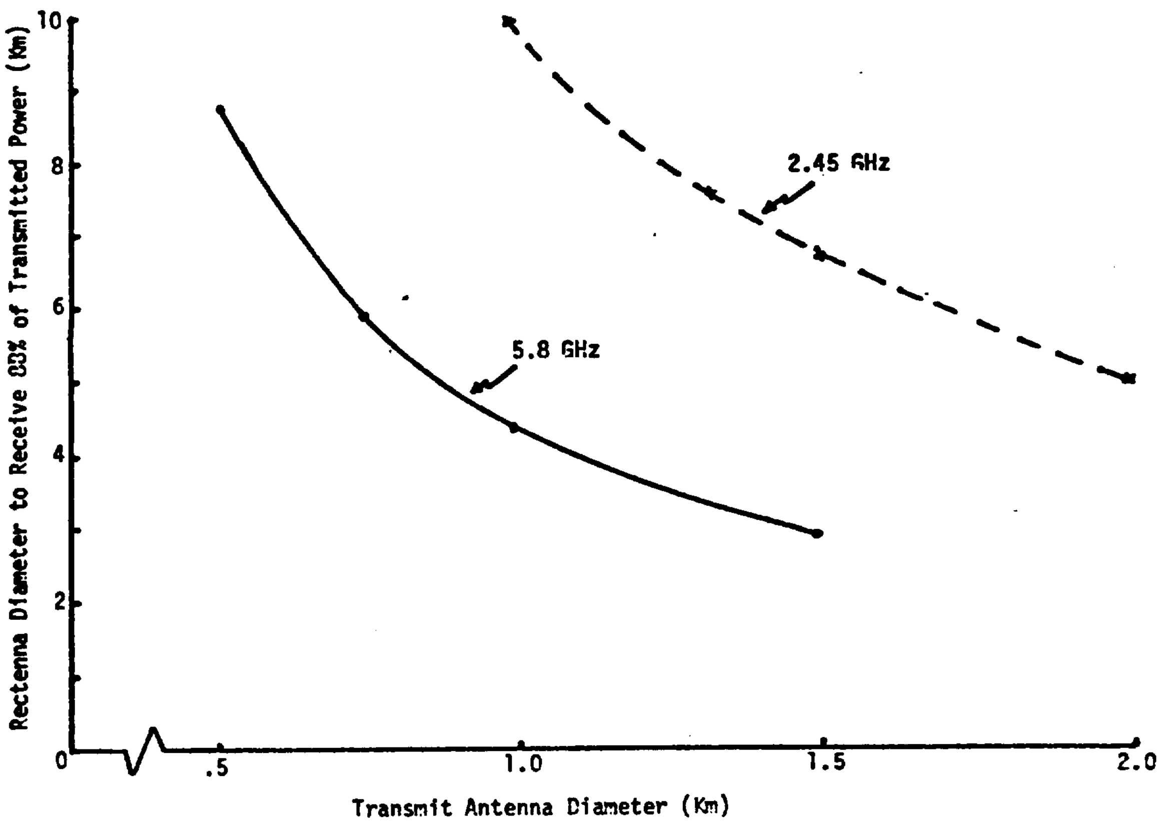

Figure 1. Antenna/Rectenna Sizing Summary

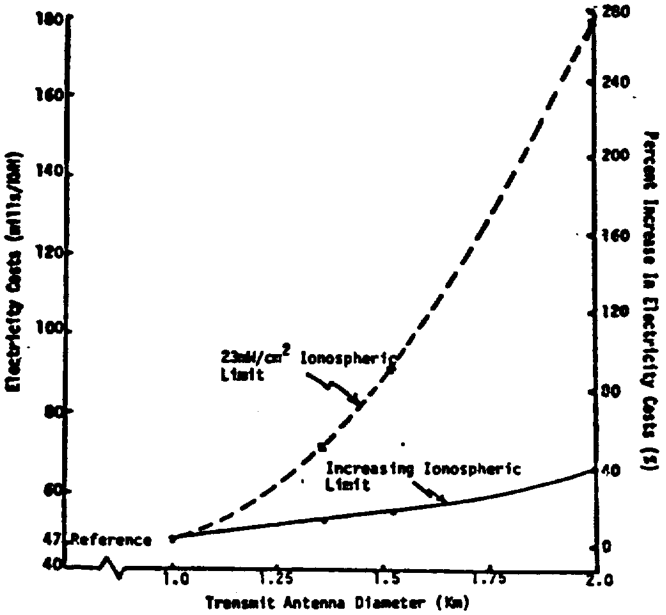

Figure 2. Electricity Costs for 2.45 GHz Systems

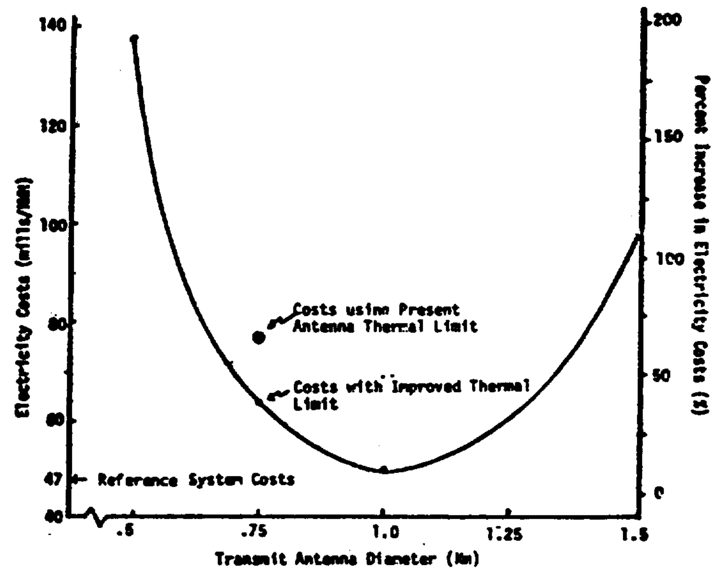

Figure 3. Electricity Costs for 5.8 GHz Systems

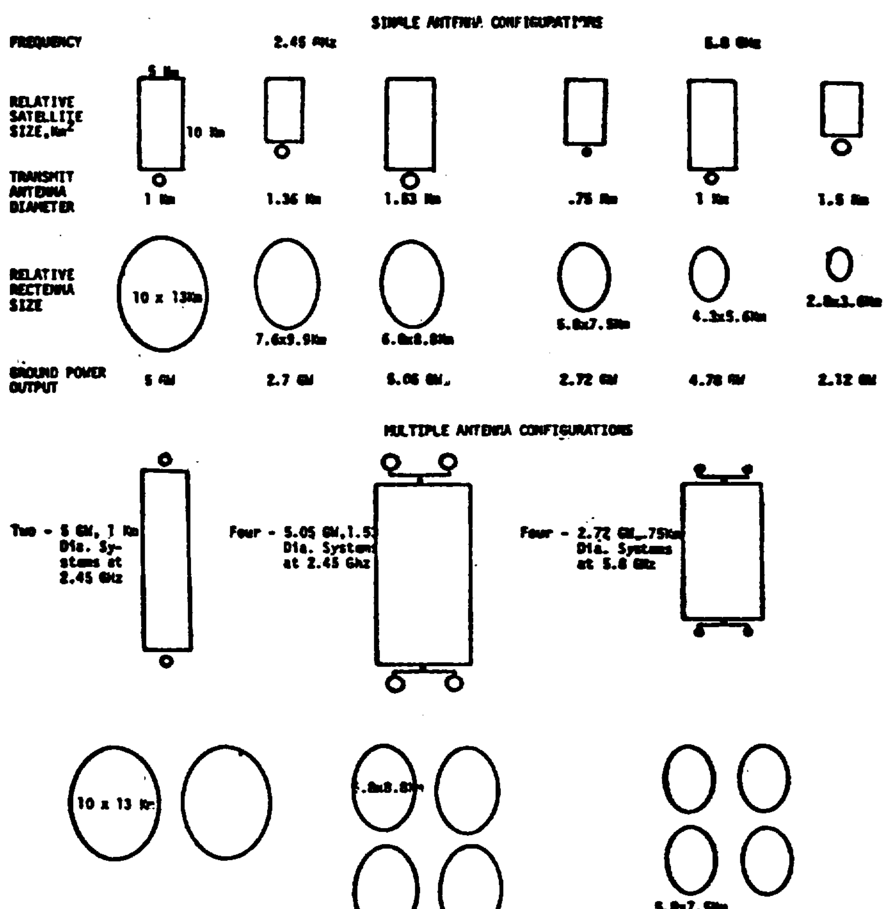

Figure 4. Relative Antenna/Rectenna Sizing Configurations