MICROWAVE TRANSMISSION CHARACTERISTICS OF SOLAR POWER SATELLITES

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ABSTRACT

A summary of the analyses and performance characteristics of a high-power microwave system for transferring energy from solar power satellites in geosynchronous orbit to the earth is given. Design tradeoffs, problem areas, and simulation results for various configurations are presented.

Introduction

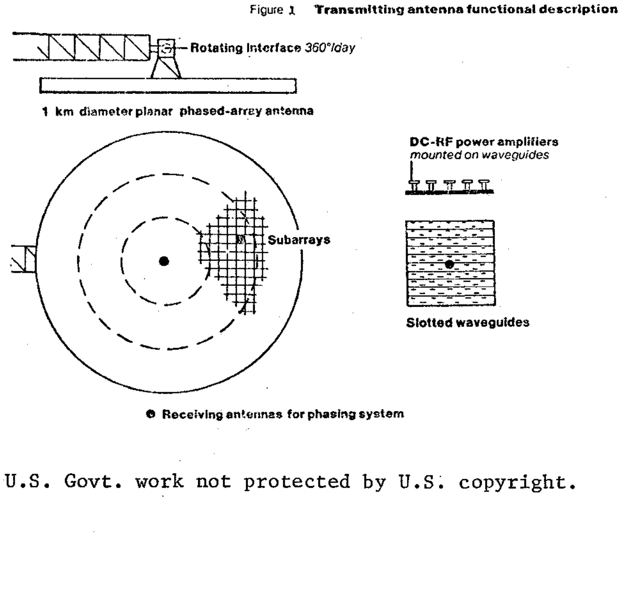
Studies of microwave power generation, transmission, and reception are underway to determine the feasibility of high-power microwave transmission from geosynchronous orbit. The concept of solar power satellite (SPS) systems involves collecting and converting solar energy to electrical energy either by photovoltaic processes or by solar thermal converters. This power is transmitted via a microwave beam to earth's surface. Each microwave system, consisting of DC-RF converters, a 1 Km retrodirective phased array, and a 10 Km ground antenna/rectifier scheme, is capable of providing 5 GW of electrical power to the commercial utility power companies.

This report gives a summary of the performance and hardware parameters for the microwave system. The tradeoffs and relative performances of various system configurations are presented. Simulations of antenna performance considering such parameters as phase and amplitude errors, subarray and array tilt angles, and sizing/power tradeoffs are included.

Microwave System Parameters

Definition of the microwave power transmission system has evolved over the past several years from a number of SPS system studies (Ref. 1-4). These parameters were developed considering environmental effects, antenna size tradeoffs, constraints imposed by thermal heating of the antenna, and ionospheric propagation effects. The present microwave system has DC-RF power converters feeding a 1-kilometer-diameter retrodirective phased array with a 10-decibel Gaussian taper illumination across the array surface. This antenna, shown in figure 1, is composed of small subarrays having slotted waveguides as the radiating surface with DC-RF power tubes mounted upon the backside of the array.

Figure 1 **Transmitting antenna functional description**



Each subarray has its own RF receiver and phasing electronics to process a pilot beam phasing signal from the ground. The subarrays are phased together to form a single coherent beam focused at the center of the ground antenna/rectifying system (rectenna). This power beam has approximately 88% of its energy within a 5 Km radius of boresight, with a resultant beamwidth of 1.2 arc-minutes. The beam steering system must be capable of pointing to within hundredths of an arc-minute. Some of the pertinent parameters of the SPS microwave system related to environmental effects include:

- Output DC power: 5 GW at the rectenna
- Transmit array size: 1 Km in diameter
- Array aperture illumination: A 10-step, truncated Gaussian amplitude distribution with 10 dB edge taper
- Subarray size: 108 m^2 (10.4m X 10.4m)
- Number of subarrays: 7220
- Error budget:
  - Total root-mean-square phase error for each subarray = 10^o
  - Maximum mean-phase error at edge of transmit array = 2^o
  - Amplitude tolerance across subarray = $\pm$ 1 decibel
  - Failure rate of DC-RF power converter tubes = 2%
- Phase control: An active, retrodirective array with a pilot beam reference for providing phase conjugation
- Antenna radiators: Slotted waveguides
- Power converters: 72-Kw klystrons
- Antenna mechanical alignment requirements: $\pm$ 3 arc-minutes
- Rectenna dimensions: 10Km X 14Km (for a 36^o latitude)
- Atmospheric attenuation: 2% for the S-band (2450 MHz) operating frequency
- Power density levels:
  - Center of transmit antenna = 22 Kw/m^2
  - Edge of transmit antenna = 2.4Kw/m^2
  - Center of rectenna = 23mw/cm^2
  - Edge of rectenna = 1.0mw/cm^2

The total microwave system efficiency, from the DC power output at the rotary joint to the collected DC power output of the rectenna, is 59.3 percent. A breakdown of the efficiencies of the microwave subsystems is shown in figure 2. It is highly desirable to maximize these efficiencies because, for each 1% loss in overall transmission efficiency, there is a loss of $50,000,000 in revenue over the thirty-year lifetime of the satellite.

Figure 2. -Microwave Transmission Link Efficiency

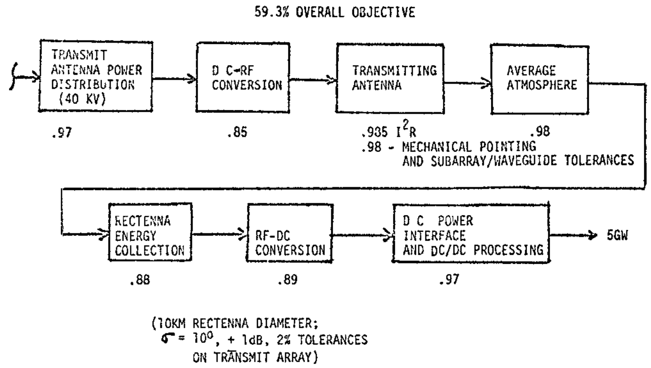
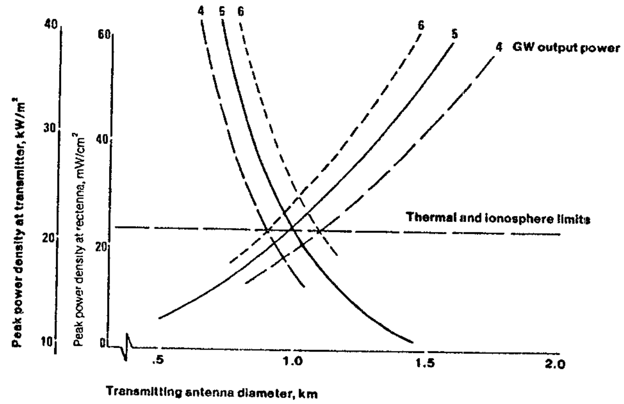


Figure 3 Ground power output limit



System Sizing Tradeoffs

The power capability of the SPS system was sized by: 1) thermal limitations of 22Kw/m^2 in the transmit array, 2) a peak power density limitation in the ionosphere of 23mw/cm^2 to prevent non-linear heating interactions between the ionosphere and the microwave beam, and 3) microwave transmission efficiency considerations (particularly the RF levels into the rectenna). The thermal limitation in the transmit antenna is due to waste heat from the DC-to-RF power converter tubes. Passive heat-pipe radiators, with mercury as a candidate working fluid, are used to cool the tubes. Composite materials, such as graphite-epoxy and graphite-polymide, are being considered for the antenna structure to reduce the effects of waste heat. The solid state control circuits for the tubes and the phase control electronics will also require thermal insulation to maintain a 70°C operating temperature.

Studies into the microwave beam/ionosphere interactions indicate that non-linear thermal self-focusing instabilities in the F-region (200 to 300 kilometers altitude) and thermal runaway conditions in the E-region (110 kilometers) will limit the maximum power density at the center of the beam to approximately 23mw/cm^2 at the 2450MHz operating frequency (refs. 5 to 9). Above this threshold power density level (which is a theoretical number, not yet verified by experiments), non-linear interactions between the power beam and the ionosphere begin to occur. These non-linear heating interactions are of concern because of possible degradations to existing HF and VHF communication and VLF navigation systems due to RFI effects and multipath degradations. The heated ionosphere may also introduce phase jitter and/or differential phase delays on the uplink pilot beam signal. The phase jitter will degrade the performance of the phase control system by spreading the downlink power beam and increasing the sidelobe levels; the differential phase delay will produce a boresight shift (misalignment) of the power beam. The effects of the ionosphere/microwave beam interactions are now being studied, both theoretically and experimentally.

In summarizing the system sizing tradeoffs, thermal limitations due to waste energy from the DC-RF power converter tubes heating the waveguides and antenna structure and economic/efficiency considerations in the ground rectenna favor larger transmit antennas; ionospheric/microwave beam interactions favor smaller transmit antennas and lower power levels. The tradeoffs in antenna size and power handling capability are given in figure 3. By adjusting the thermal and ionospheric limits to coincide, the allowable combinations of antenna powers and sizes may be determined. For these limits, an output power of 5 gigawatts from a 1 Km diameter antenna was selected.

Antenna Illumination Characteristics

The transmit antenna has an optimized aperture distribution across the array surface to maximize the RF power intercepted by the ground rectenna and to minimize the sidelobes and grating lobes. A number of antenna illumination functions, operating in the presence of phase and amplitude errors and element (subarray) failures, have been examined. These functions include various gaussian tapers, cosine on a pedestal, and quadratic functions. Their relative performance was evaluated in terms of maximum power density (at the transmit array and the rectenna), sidelobe suppression, and rectenna collection efficiency. The rectenna collection efficiency is the amount of flux (or power) intercepted by the rectenna. The optimized antenna functions are summarized in figure 4 in terms of their relative performance. The exponent weighting and pedestal height were varied to maximize collection efficiency and reduce the peak-power densities. The same error parameters, i.e., σ = 10°, ± 1 dB, and 2% failures are applied to each function. For these simulations the electric field at each point on the ground is calculated from the sum of individual radiative patterns from each of the 7220 subarrays on the transmit antenna. It is interesting to note that each of the optimized functions have a power density at the edge of the transmit array which is approximately one-tenth (1/10) of the maximum density at the center of the array. Summarizing the results, the 10 dB Gaussian taper has the best overall performance of the three optimized illumination functions when considering the two constraints for maximum power density in the transmit array and at the rectenna.

Function	Amplitude Distribution E(r)	% Collection Efficiency for 10, 250m Rectenna σ = 10°, ± 1 db, 2%	Max. Power Density at Rectenna (boresight) (mw/cm²)	First Sidelobe Level Referenced to Main Beam	Maximum Power Density at Transmit Array (Kw/m²)
Gaussian (10dB taper)	$-1.15\left[r/r_o\right]^2$	87.76	22.0	-24.7db	20.88
Cosine	$\cos^2\left[90°\left(r/r_o\right)\right]+.4$	87.95	20.8	-30.9db	27.61
Quadratic	$\left[1-\left(r/r_o\right)^2\right]^2+.4$	88.23	21.0	-28.7db	25.15

Figure 4. - Antenna Illumination Functions

The radiation pattern of the 10dB gaussian taper, 1 Km array at the ground rectenna is shown in figure 5. for two conditions: 1) for a perfect antenna, i.e., $\sigma = 0^o$, 0dB, and0%; and 2) for the baseline error parameters, σ = 1dB, and 2%. The effects of the antenna errors are to produce a wider, lower intensity main beam with higher sidelobes. For the SPS system concept, only a portion of the main lobe will be collected; the sidelobe energy occupies a very large area at minimal density levels and is not economically feasible to collect. For the antenna with the baseline error parameters, the first sidelobe has a peak of $.08 mw/cm^2$, which is two orders of magnitude lower than the U.S. radiation standard of $10mw/cm^2$. In addition grating lobes will appear at 440 kilometer intervals with peak levels of $.01mw/cm^2$. The grating lobe levels, which are highly dependent upon mechanical pointing of the 10 meter square subarrays, constrain the mechanical boresight alinement to be within ± 3 arc-minutes (Ref 8).

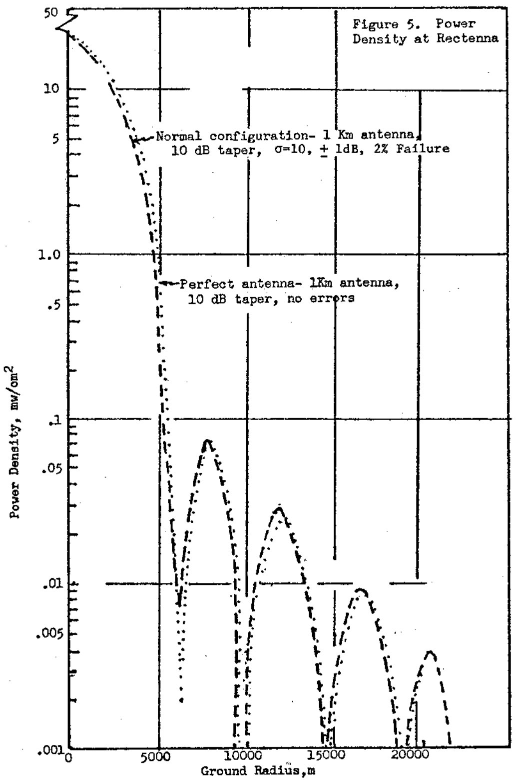


Figure 5. Power Density at Rectenna

High Power DC-RF Transmitters

The candidate DC-RF power converter tubes are the medium-power amplitrons and the high-power klystrons. For purposes of the SPS baseline, the klystron has been chosen but the ultimate choice will be made on the basis of reliability, length-of-life, efficiency, spurious radiation, integration with the phase control system, and maintenance.

The design objective for the klystron is to have high efficiency (approximately 85%) at 40 kV with a power output of 72 kW. This can be achieved with a 5-segment depressed collector, six cavity design using beam-focusing field with the body-wound solenoid. The thermal design would encompass heat pipes with passive radiators, a modulating anode for rapid shutoff protection, and a 2-port output to operate at a temperature below 200^oC. The advantages of a klystron are its high gain of 50 decibels which allows phase control at drive levels of 1 watt; potential high efficiency; low noise; high power outputs; small efficiency change with temperature variations; and bake-out in space with its own solenoid. Disadvantages include high beam voltage of 40 kilovolts; multiple voltages required for the collector stages; hot cathode; and requirement of a depressed collector for the tube to exceed 75 percent efficiency.

Solid-state microwave devices were investigated to determine their potential as replacements for power converter.tubes. Since the high voltages associated with the operation of the SPS power tubes may lead to plasma leakage currents and/or arcing problems and since solid-state devices were considered. Devices that generate power in excess of 1 watt and have efficiencies greater than 25 percent are required. The candidate amplifiers included the impatt diode, trapatt diode, bipolar transistor and field effect transistor. At the present time, the efficiencies and power-handling capacities of state-of-the-art solid-state microwave devices suitable for use as power amplifiers are well below the levels of those projected for the tube designs. However solid-state circuitry remains an attractive alternative candidate for the SPS microwave system, requiring further analysis and laboratory work. The characteristics of the FET and klystron are summarized in figure 6.

CHARACTERISTIC	KLYSTRON	FIELD-EFFECT TRANSISTOR
Frequency, MHz	2450	2450
Bandwidth (3 dB) MHz	3	-
Beam Voltage	40 kV	10 V
Power Output	72 kW	1-10 W
Overall Efficiency, Percent	84 to 86	80 to 85
Gain, dB	40 to 50	10 to 20
Amplitude Modulation (AM) Noise, dB	-130	<100
Phase Modulation (PM) Noise, dB	-115	<100
Specific Weight, kg/kW	0.7	0.1
Cooling	Heat-pipe Radiation	Passive Radiation
Reliability, Years	30	100

Figure 6. Estimated Operating Characteristics of the Klystron and Field-Effect Transistor

Rectenna

The microwave power is received on the ground and collected into a useable form for interfacing with the electric utility grid system. The reference configuration of the receiving antenna consists of: half-wave dioples plus a ground reflector to receive the energy; low-pass filter for harmonic suppression; half-wave rectifier (Schottky barrier diode) which is fed by multiple dipoles; rectifier output filter; and a DC bus.

Alternative types of rectenna elements have been proposed to either increase the efficiency of reception or lower the cost of production and installation of the rectenna elements. (Ref 3 and 4). These configurations include: hogline high-gain antennas - a cylindrical parabola with a horn and a line feed between parabola and horn; slot arrays with modified cavities beneath the slots; yagis; and strip-line antennas.

Since the rectenna is presently the largest single cost item within the microwave system, considerable optimization and improvements are warranted.

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