SOLAR POWER SATELLITES — THE PRESENT AND THE FUTURE

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ABSTRACT

The concept of using large satellites in neosynchronous orbit to collect solar energy for earth use, first proposed in 1968, is being evaluated by the Department of Energy and the National Aeronautics and Space Administration. A reference system has been defined to provide a basis for evaluating alternate technical approaches and for assessing environmental impacts. This reference system is described with emphasis on the microwave subsystems and possible alternatives. Other considerations, including study guidelines, system sizing tradeoffs, mass and cost projections, and environmental factors, are discussed. An outline of a ground-based exploratory development program which could follow the present evaluation study (now scheduled for completion in 1980) and answer key technological issues is given. Several space technology projects as further steps towards develoning an SPS system are also discussed.

INTRODUCTION

The solar power satellite (SPS) system first proposed in 1968 by Dr. Peter Glaser is envisioned as a means of using extraterrestrial solar energy to supply power for earth use. This concept has a large satellite in geosynchronous orbit converting, solar energy to electrical energy either by a photovoltaic process or by solar thermal conversion. The energy is transmitted to the earth by a high-power microwave transmission system. This summary paper describes the present reference SPS configuration, the projected masses, alternative configurations, and some details of a proposed ground-based research program.

The SPS concept is now being evaluated under a joint Department of Energy (DOE)/ National Aeronautics and Space Administration (NASA) program which has four major study areas:

1. System Definition
2. Evaluation of Environmental, Health, and Safety Factors
3. Evaluation of Socioeconomic Issues
4. Comparative Assessment of Alternative Energy Systems

Based upon the results from these studies a decision will be made in 1980 as to whether the solar power satellite program should be continued, and if so, in what manner.

The environmental assessment studies would be included with emphasis on specifically defining the environmental factors and limitations.

A set of evaluation guidelines were established based upon the results from earlier SPS system studies. These guidelines, used primarily in sizing a reference SPS configuration and determining its costs, are as follows:

- Construction materials obtained totally from earth resources
- Geosynchronous orbit
- Microwave system operating frequency - 2.45 GHz (center of a 100 MHz industrial, medical and scientific band)
- Microwave power density not to exceed 23 mw/cm^2 in the ionosphere
- Microwave system sized to provide 5 GW output from the rectenna
- Satellite implementation rate of two 5-GW satellite systems per year
- Thirty (30) year satellite lifetime

REFERENCE SYSTEM CONFIGURATION

A reference system configuration has been defined to provide a basis for evaluating alternate technical approaches and as a guideline for assessing environmental impacts. This configuration, developed through both NASA in-house and contractor system studies, is not intended as a final design. Alternative concepts will also be pursued. The reference system as documented in reference 1 has the following general characteristics:

Generating Capacity
    Each solar power satellite system sized for 5 GW D.C. power output
Operational Configuration
    Flat solar array with transmitting antenna on one end
    Orientation - antenna main rotational axis perpendicular to orbit plane
Energy Conversion-Two Baseline Options
    Single-crystal gallium aluminum arsenide Photovoltaic - CR = 2
    Single-crystal silicon photovoltaic - CR = 1
Microwave Power Transmission
    2.45 GHz operating frequency
    One-kilometer diameter planar phased-array transmitting antenna
    Klystron power amplifiers
    Slotted waveguide radiating elements
    Active retrodirective phase control

Structural Materials
 Graphite-fiber reinforced thermoplastic
Attitude Control
 Argon ion electric thrusters panels
Array Power Distribution
 Thin sheet conductors
 40 kv to microwave power amplifiers

The SPS sizing of a 1-kilometer transmit antenna and 5 gigawatts (GW) of DC power output at the rectenna was based upon:

(1) achieving a maximum output power due to cost effectiveness and efficient reception by the rectenna.
(2) a thermal limitation of 22 kilowatts per square meter in the transmit array, and
(3) a peak power density of 23 milliwatts per square centimeter in the ionosphere to ensure no nonlinear heating of the ionosphere.

From thermal considerations larger antennas are desirable while the ionospheric limitation is satisfied by smaller antennas. Tradeoffs in antenna size and power-handling capability are summarized in Figure 1. After the thermal and ionospheric limits are adjusted to coincide, the final SPS sizing of a 1 Km antenna and 5 GW output power are obtained.

The solar array sizing is determined by the efficiency chain of the various elements in the system. Figure 2 shows the end-to-end efficiency chain for the GaAlAs and silicon solar cell options. A satellite providing 5 GW out of useful power at the ground and an overall efficiency of approximately 7% must intercept about 70 GW of solar energy.

Energy Conversion

A number of different energy conversion techniques were investigated. These included silicon and gallium arsenide photovoltaics with concentration ratios of 1 and 2, thermal conversion using rankin cycle turbines with potassium as the working fluid and Brayton systems using helium gas, and thermionic systems. The overall conversion efficiency, satellite area, and mass are comparable for the thermal and, the photovoltaic systems. However the photovoltaic systems have the advantages of simplicity in space construction and higher reliability due to the lack of moving parts. The thermal systems also have the disadvantage of requiring large movable solar reflectors to concentrate the sunlight.

Two photovoltaic systems, silicon with a concentration ratio (CR) of one and GapAlAs (CR=2) were chosen for the reference energy conversion devices. The silicon cell option has no concentration (CR=l) with a blanket area of 52.3 Km^2 as shown in Figure 3. A tradeoff analysis indicated this simplier no-concentration configuration for silicon is cost effective due to a reduction in conversion efficiency at higher operating temperatures, increases in structural requirements for stretching the solar reflectors, and degradations in solar cell performance due to shadowing in the solar reflectors. The silicon blankets consists of 50-micrometer (2-mil), thick single silicon solar cells with an efficiency of 17.3% at 25°C. At the design operating temperature of 36.5°C, the efficiency drops to 16.5%. Details of the silicon cell are shown in Figure 4.

A problem associated with the silicon cells is degradation due to electron radiation at geosynchronous orbit associated with solar flares. Solar flares strong enough to create radiation damage in the silicon cells will occur a few times over the thirty year lifetime of the satellite. A laser annealing system usinq CO_2 lasers mounted on an overhead gantry structure can heat the cells to approximately 500°C. This temperature is sufficient to anneal out the radiation induced degradations to the cells while still being low enough to prevent damaging the cell interconnects and substrate materials. Annealing tests are underway to determine the cell recovery characteristics.

The GaAlAs option is shown in the array configuration in Figure 3 and the cell desion in Figure 4. A five-trough arrangement provides a concentration ratio of two which reduces the amount of gallium required. The solar cell has a 20% efficiency at 28°C, and 18.2% efficiency at the design operating temperature of 125°C. At 125°C, self-annealing of radiation damage occurs within the cells, so there is no need for a laser annealing system. Gallium arsenside cells have higher efficiency than silicon, are less susceptible to radiation damage, and can operate at the higher temperatures associated with a concentration ratio of 2 or greater. A problem with these cells which has not been fully resolved is the availability of gallium.

Microwave Power Transmission System

The reference satellite configuration has a 2.45 GHz microwave system for transmitting the power down to the earth as shown in Figure 5. A 1 Km diameter phased array antenna with a 10-decibel (db) Gaussian taper illumination focuses the beam at the center of the ground antenna/rectifying system (rectenna). This power beam has approximately 88% of its energy within a 5 Km radius from boresight, with a resultant beam width of 1.2 arc-minutes. Mechanically the antenna is divided into 7220 subarrays, approximately 10 meters X 10 meters on a side, having slotted waveguides as the radiating surface. The DC-RF power converters, i.e., 70 KW klystrons, are mounted on the backside of the subarrays. A retrodirective phasing scheme is used to provide phase information to each subarray or each power module (antenna area associated with an individual klystron). This system has a pilot beam transmitter at the center of the rectenna and RF receivers/phasing electronics at each subarray or at power module to process the pilot beam phasing signal. The characteristics and error tolerances of the microwave power transmission system may be summarized below:

Frequency - 2.45 GHz
Output Power to Power Grid - 5 GW D.C.
Transmit Array Size - 1 Km. Diameter
Power Radiated from Transmit Array - 6.85 GW
MPTS Efficiency - 63%
Array Aperature Illumination - 10 step, truncated gaussian amplitude distribution with 10 db edge taper

Error Budget:
Total RMS phase error for each subarray = 10°
Maximum mean phase error at edge of transmit array = 2°
Amplitude tolerance across subarray = ± 1 decibel
Failure rate of dc-rf power converter tubes = 2% (a maximum of 2% failed at any one time)
Antenna/Subarray Mechanical Alignment:
± 3 arc-minutes th the grating lobes constrained to ≤ .01 mW/cm^2
Subarray Size: $108m^2$
Number of Subarrays: 7220

The antenna pattern at the rectenna for the 10 dB Gaussian taper reference system is shown in Figure 6. The antenna illumination function was optimized to provide the maximur amount of RF power intercepted by the ground rectenna (88%) and to minimize the sidelobe levels. Other illumination functions were investigated, includling uniform, various Gaussian tapers, cosine on a pedestal, quadratic and inflected Bessel, but the 10 dB Gaussian taper provided the best overall performance after considering the maximum power density constraints in the transmit array and rectenna. Studies are now underway on the feasibility of producing a flattened, widebeam pattern at the ground by using a continuously variable phase reference across the transmit array. This technique requires a much larger antenna which is amenable to the solid-state configuration to be discussed later.

Grating lobes will also be present; the intervals or spacings between the lobes are dependent upon the subarray or power module sizes and the amplitudes are a function of the mechanical alinement of the antenna and subarrays. The grating lobes are stationary and do not spatially move with misalignment changes. The locations of the grating lobes for a main beam rectenna site in the central United States are shown in Figure 7. The spacings are determined by the phase control system.; if phase conjugation is performed at the power module (tube) level, then the grating lobe peaks are as shown in Figure 7. However if phasing is performed at the subarray level , (10.4 meters X 10.4 meters), then grating lobes occur at 440 Km intervals. Based upon an environmental constraint of having grating lobe peaks less than .01 mw/cm^2, the mechanical misalinement of the 1 Km array has to be less than 3 arc-minute if phasing is performed at the power module level and 1 arc-minute if phasing is done at the subarray level.

Rectenna - The around rectenna, which receives and rectifies the nower beam, has half-wave dipoles feeding Schottky barrier diodes. The rectenna is a series of serrated panels perpendicular to the incident beam and covers approximately 75 square kilometers. The panels have a wire mesh screen for a ground plane with 75-80% optical transparency. This mesh is mounted on a steel framing structure, supported by steel columns in concrete footings. The DC electrical power from the diodes is transferred via dedicated aluminum conductors into 40 megawatt DC/AC converters. The power is then transmitted to 200 megawatt transformer stations where the voltage is stepped up to 230 KV, then collected in 100 megawatt groups for interface with the outside transmission system for commercial usage.

Space Transportation

The space transporation system required for the SPS program has four types of vehicles.

- Heavy Lift Launch Vehicle (HLLV)
- Electric Cargo Orbit Transfer Vehicle (COTV)
- Personnel Launch Vehicle (PLV)
- Personnel Orbit Transfer Vehicle (POTV)

The heavy lift launch vehicle (HLLV) is a two-stage, vertical takeoff, horizontal landing, fully reusable winged launch vehicle. It has a gross liftoff weight of 11,000 metric tons with a payload to low earth orbit (LEO) of 425 metric tons. This vehicle, as shown in Figure 8, uses methane and liquid oxygen in the first stage (booster) and liquid hyrodgen and oxygen in the second stage (orbiter). The booster also has an airbreather propulsion system (aircraft jet engine) for a flyback capability to the launch site. At the present time the Kennedy Space Center is expected to be the launch site.

The COTV moves SPS construction material and cargo from the LEO staging area to the GEO construction site. It is also fully reusable vehicle with the main source of propulsion being electric power from solar arrays driving argon ion thrusters. There are two electric power options - GaAlAs and Si photovoltaic arrays. Both types of solar cells will suffer radiation damage during each trip through the Van Allen belts and will require annealing. Supplementary chemical thrusters will be available to provide power during times when the solar arrays are shadowed. One scenerio of a typical COTV transfer to GEO and return is shown in Figure 9.

The personnel launch vehicle (PLV) transports personnel and priority cargo from the launch site on earth to LEO. The vehicle, derived from the present space shuttle system. has a 75-passenger capacity personnel compartment in the orbiter payload bay. It has a winged liquid propellant fly-back booster instead of the present solid-state booster. The POTV carries personnel and priority cargo from the LEO to the GEO construction base. This vehicle can transport 160 personnel in a passenger module, 480 man-months of consumables in a resupply module, and a two-man flight crew in a trip time of approximately one day. The propellants are liquid hydrogen and oxygen for the two common stage vehicle. The transporation sequences for both personnel and cargo from ground ↔ LEO and LEO ↔ GEO are summarized in Figure 10 using the four types of space vehicles.

Construction

Primary construction of the satellite is slated for geosynchronous orbit with a LEO staging base. A number of system studies evaluated LEO versus GEO construction bases, with each orbital location having advantages. The GEO location has continuous sunlight, the construction base can be optimized to build the satellite in its final form, and there is no need to transport large completed segments of the satellite from LEO to GEO. The LEO location has a more benign space environment with solar radiation particles being shielded the Van Allen Belt but has the problem of gravity gradient torques on the large satellite modules (the satellite was divided into eight modules for ease of construction and transportation). As stated previously the GEO site has been selected for the reference system report. The construction time for a satellite is six months, using a 550-man construction and support crew.

In order for the satellite to be built quickly and efficiently the construction process must be automated. Construction materials will be packaged in a very dense form to reduce transportation costs. Automated beam builders will take the rolls of construction materials and extrude long structural beams. These beam builders as shown in Figure 11 are not unlike the simple commercial aluminum gutter fabricators used today. the open-truss structure of the satellite is designed with regular uniform cross-section beams to expedite automatic fabrication. The basic structural element of the satellite has a triangular cross-section and is made of a graphite composite material for the antenna which requires a surface flatness of less than l arc-minute. The solar array does not have the stringent surface tolerance and may be constructed of aluminum beams.

The diagram of a satellite with the silicon solar cell array is shown in Figure 12. The antenna has a primary structure, 130 meters deep, with an octagonal shape over 1000 meters in width and length. The secondary structure is a cubic truss, approximately 10 meters in depth, which provides support for the microwave subarrays. These subarrays may be aligned using Az-El mounts to maintain a 3 arc-minute random flatness.

MASS

The satellite mass properties may be separated into three areas: solar array, microwave antenna, and solar array-antenna interface (rotary joint, sliprings and antenna yoke). A summary of these masses for a 5 GW satellite is as follows;

	CaAlAs Array		Silicon Array	
	(Millions of Kilograms)			
Solar Array				
Primary Structure	4.17		3.39	
Secondary Structure	.58		.44	
Solar Blankets	6.70	13.8	22.0	27.3
Concentrators	.96		0	
Power Distribution, Altitude Control, etc.	1.40		1.4	
Microwave Antenna				
Primary Structure	.25			
Secondary Structure	.79	13.4		13.4
Transmitter Subarrays	7.18			
Power Distribution	2.19			
Thermal Control	2.22			
Information Management Altitude Control	.76			
Array-Antenna Interface		.1		.1
Subtotal		27.3		40.8
25% Contingency		6.8		10.2
Total		34.1		51.0

The two largest mass contributors are the solar blankets in the solar array and the klystron/waveguide subarrays in the antenna. The large antenna and solar array structures are lightweight and comprise only 12-20% of the total satellite mass.

COMPARISON OF ELECTRICITY COSTS

The question arises - how does the electricity costs from an SPS system compare with the costs from a conventional power plant? The answer is that any comparison depends mainly upon the projected fuel cost of a conventional system. The cost data shown in Figure 13 are for an average U.S. plant in 1975. Assume the terrestrial transmission, distribution, and operating and maintenance (O&M) costs are the same (1.24¢ per kwh) for the conventional plant and the SPS system. The conventional plant investment cost is less than 14¢ per kwh of electricity, with the remaining expense being fuel costs. If we project a 5% per year increase in fuel, which is considerably less than the 18.7% per year average increase for the 1970-1975 time frame, then the rates for the two systems will be approximately the same (5.5¢ per kwh) in the year 2000. Larger fuel expenses will vary the conventional systems costs accordingly. The point is that the cost of electricity from SPS systems should compare favorably with those costs from other energy sources.

ALTERNATIVE MICROWAVE SYSTEMS

While the reference system has been defined in some detail, other alternative power transmission systems are presently being studied. These alternate concepts may be summarized as follows:

DC-RF Converters

- Solid state - The main advantage of low-power solid-state devices is reliability, which should be several orders of magnitude greater than klystrons. Two configurations are being studied - (a) a conventional antenna with the solid-state power converters mounted on the backside, and (b) a sandwich concept which integrates the solar array with the antenna.

- Magnetrons - A scheme of injection-locked magnetrons with the heaters turned off to reduce noise is being studied.

Phase Control System

- A ground-based phase control system, with the principal advantage of reducing spacecraft hardware complexity associated with the present phase conjugation system, is being evaluated. The error budget for the phase reference distribution system within the 1 Km array is now limited to less than 1°.

Laser Transmission

- New systems, including the free electron laser, the electric discharge laser, and optical pumped laser, could possibly replace the microwave power transmission system. The advantage of lasers is a greatly reduced ground receiver size while a disadvantage is the low conversion efficiency.

EXPLORATORY RESEARCH PROGRAM

A ground-based exploratory development program which could follow the present evaluation study now scheduled for completion in 1980 would focus on technology programs to provide definitive information on critical issues. This program would emphasize laboratory testing in key technical areas. The systems definition studies have provided guidelines and performance criteria; the technology development program would ascertain the feasibility and assessment of these requirements. Some typical areas which might be explored include:

1. System Definition Studies
   - Preferred Concept Definition - update reference system
   - Technology Program Impacts - integration of test and analytical results
   - Societal/Environmental/Comparative Assessment Impacts - integration of DOE study results
   - Alternative Concepts - solid state, lasers, etc.
   - Flight Project Definition - define follow-on space tasks

2. Solar Energy Conversion
   - Solar Array Resources - develop resources recovery techniques
   - Solar Cell Studies - high efficient Si and GaAlAs cells, annealing techniques
   - Cell and Blanket Testing - ground and space testing of solar cells
   - Blanket and Concentrator Development - develop and test GaAlAs and Si blankets

3. Integrated Microwave System
   - Power Amplifier Development - klystron, solid state
   - Integrated System Performance (Tube/Solid State) - define test requirements and conduct tests on integrated tube/phase control/subarray configuration
   - Phase Control System - develop and test phase control system using either phase conjugation or ground-based system)or hybrid)
   - Transmit Antenna Performance - slotted waveguide performance, materials selection, and subarray development
   - Rectenna Element - conversion efficiency, RFI characteristics, manufacturability of dipole/diode (and/or alternate configurations)

Since this is a microwave conference, a brief review of the microwave system requirements would be appropriate: DC-RF conversion efficiency of $\simeq$85%, rectenna collection efficiency = 88%, rectenna conversion efficiency = 89%, waveguide I^2R loss $\leq$ 2%, phase error budget of 10°RMS, noise output $\leq$ 2% failed power converters at any one time.

4. Space Construction
    - Operations and Support Functions - large system berthing, assess construction support capabilities.
    - Structure Fabrication - prototypes of beam builder and joiner, assembly techniques
    - System Installation - concepts for solar blanket, concentrator and conductor packaging, rotary joint installation, antenna/subarray integration.

5. Transportation
    - Rocket Engine Investigations - engine definition, design, component evaluation, critical technology assessment
    - Thermostructure/Cryo Insulation Investigations - materials development
    - Electric Propulsion - design goals and performance criteria, subscale propulsion system development and testing
    - Ballistic Booster Recovery - configuration design and testing
    - Vehicle Design/Analyses - analysis procedures for vehicle design
    - Operations - packaging concepts, launch site operations, payload handling
    - Airbreathing Engine Technology - multicycle engine performance and testing

6. Electrical Power Distribution
    - Power Processing - prototype of SPS power distribution system
    - Switchgear - prototype development
    - Rotary Joint - subscale design and testing
    - Power Conductors - thin sheet conductor develcpment
    - Energy Storage - battery storage for powered-down periods during solar eclipses
    - Integrated System Modeling - computer simulations and evaluation of test results
    - Space Environmental Impacts - spacecraft charging, plasma interactions, insulation degradation and arcing

7. Structure/Control and Materials
    - Structural/Control Studies - structural analysis, coupling modes through rotary joint, flight control systems and performance
    - Materials - lifetime characteristics in geosynchronous environment, outgassing, radiation damage.

FUTURE PROJECTS

If one assumes the technology development program successfully answers the key issues and prototype hardware is available, a series of space projects would be the next logical step in the SPS program. A number of space projects have already been suggested including:

- Component Testing Using the Shuttle

  This would encompass small “suitcase” experiments such as operation of a prototype SPS klystron on a slotted waveguide radiator. Plasma effects in the LEO environment could be studied.

- LEO-LEO Microwave System Tests -

  A microwave system test involving a 3 meter X 45 meter transmit array and a beam mapping satellite separated by 16 Km has been proposed. The transmit array has two configurations: one, with nine subscale subarrays in a 9 meter X 9 meter arrangement for thermal testing and two, in a 45 meter linear array with 15 subarrays to evaluate phase control system performance. The input power requirement to the tubes is 300-400 kW, depending upon the test configuration. The power is supplied from a solar array which also provides subscale testing of the SPS solar blanket configuration.

- Inverted Ground-GEO Test -

  Verification of the phase control system to electronically form and steer the microwave beam with its required accuracy (±200 meters) would be the goal of an inverted test as shown in Figure 14. The pilot beam, normally transmitted from the ground to the satellite, would now be transmitted from geosynchronous orbit to the ground. A narrow, 1 Km long prototype phased array would receive the phasing signal on the ground and transmit a fan-shaped beam directed to the pilot beam satellite. A small beam-mapping satellite in geosynchronous orbit would measure the uplink beam pattern from the linear array. In addition to a separate ground-based heating facility would be utilized to heat the ionosphere to simulate the operational SPS environmental conditions. This inverted test can be accomplished at a much reduced cost due to the small amount of hardware in space. There is however one problem which is now being studied. Due to Fresnel zone lens effects of the ionosphere on the downlink pilot beam signal, mit may not be possible to obtain independent phase measurements at the 1 Km array on the ground. If the measurements are not independent, then the phase control system cannot provide conjugation of the correct phase and the beam pattern would not be properly formed. This problem recently arose in the test planning of phase scintillation measurements through the ionosphere from existing geosynchronous satellites.

- Demonstrator -

  The last project prior to a full-scale SPS commitment could be a “demonstrator” which provides continuous power from geosynchronous orbit to a small rectenna system. These are varied opinions as to the objectives and the configurations of a demonstrator. However some of the objectives can be listed as follows:

- Demonstrate power transmission, space-to-ground
- Demonstrate a complete subscale system
  - Verify designs for microwave system, structures, power distribution, solar arrays, and attitude control systems
- Refine data on environmental effects on satellite
  - Spacecraft charging
  - Radiation effects (Van Allen Belt and geosynchronous orbit)
- Demonstrate productivity in space
  - "Large" satellite construction
- Establish satellite reliability and ascertain any failure modes
- Establish operational experience
  - High launch rates
  - Operations and maintenance

It is important to minimize the amount of power delivered on the ground due to costs. It can be shown that a system providing 1/20 of the power (250 megawatts) as that from a full-scale satellite (5000 megawatts) will cost about 80% of the full satellite. This small differential is due to applying the same DDT&E costs and the development of a heavy lift launch vehicle. By limiting the ground output to a few tens of kilowatts of less the total demonstrator costs can be minimized. Small amounts of power can still demonstrate the concept of continuous power from space to technical and lay persons as well as provide valuable experience in space operations and productivity.

It should be emphasized that the space projects have not been thoroughly developed but these projects have received varying degrees of consideration.

REFERENCE:

1. "Solar Power System - Reference System Report", DOE/ER-0023. U.S. Department of Energy and the National Aeronautics and Space Administration, October, 1978.

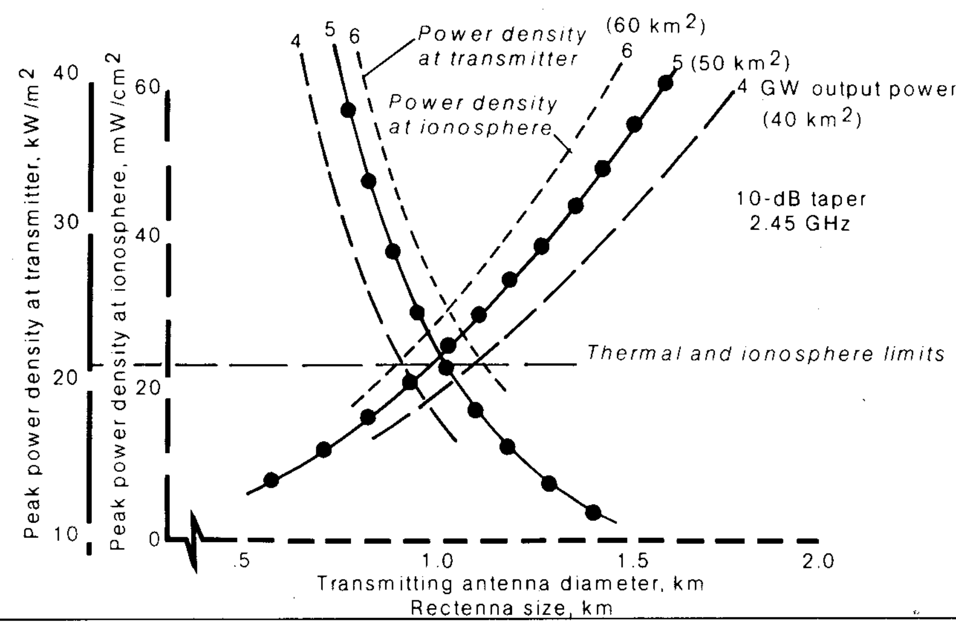

Figure 1 Satellite System Sizing

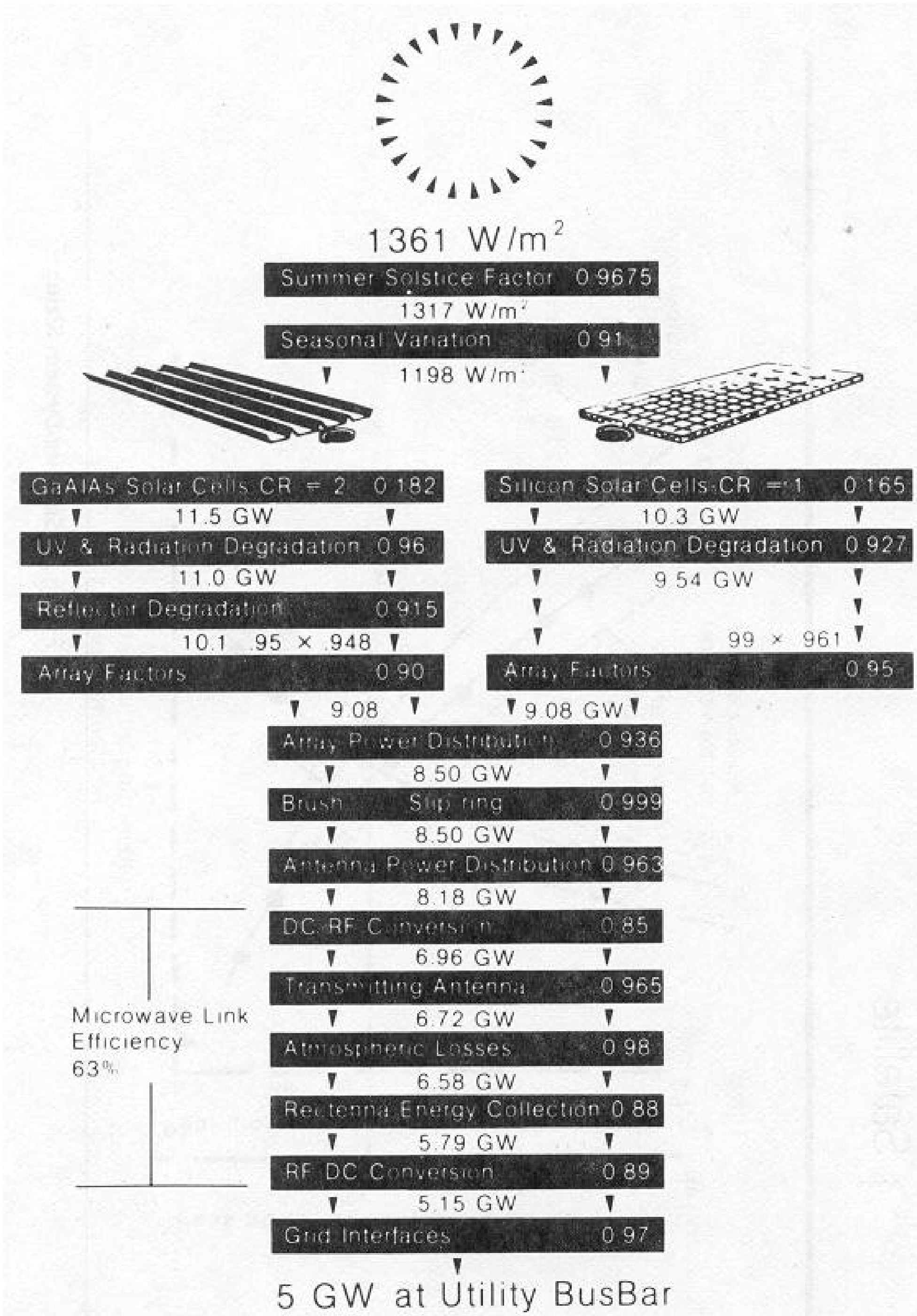

Figure 2 Solar Power Satellite Efficiency Chain

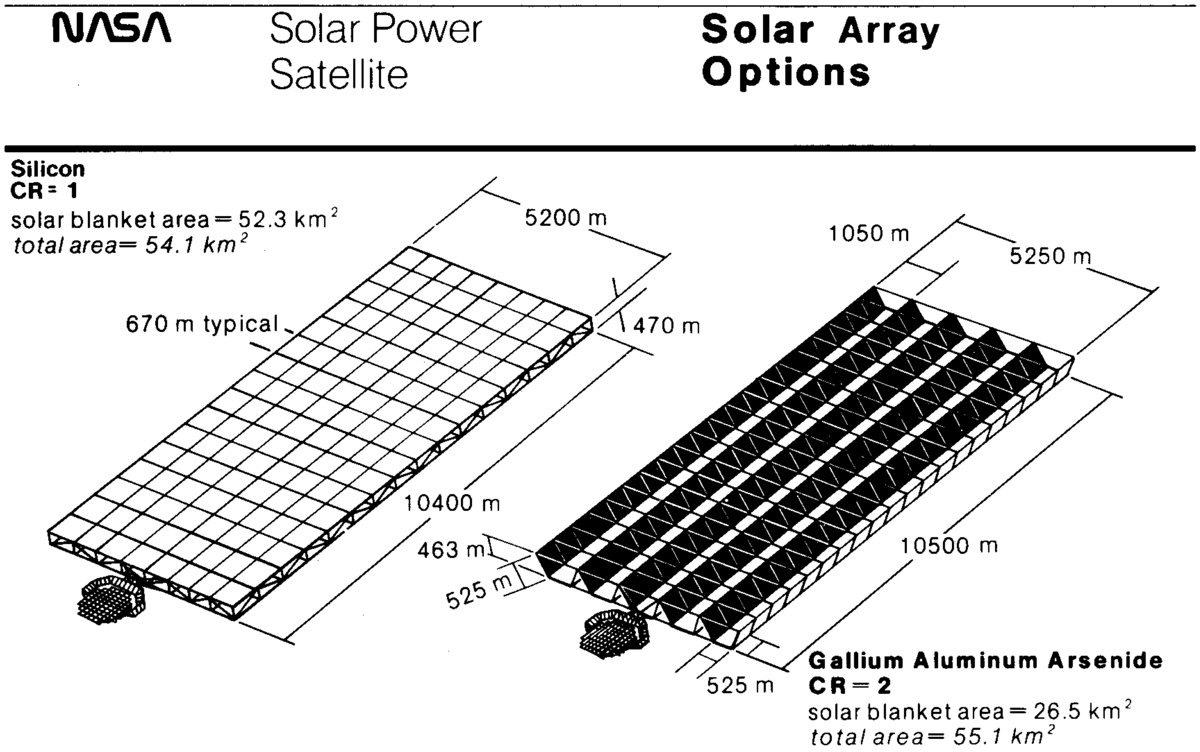

Figure 3 Solar Array Options

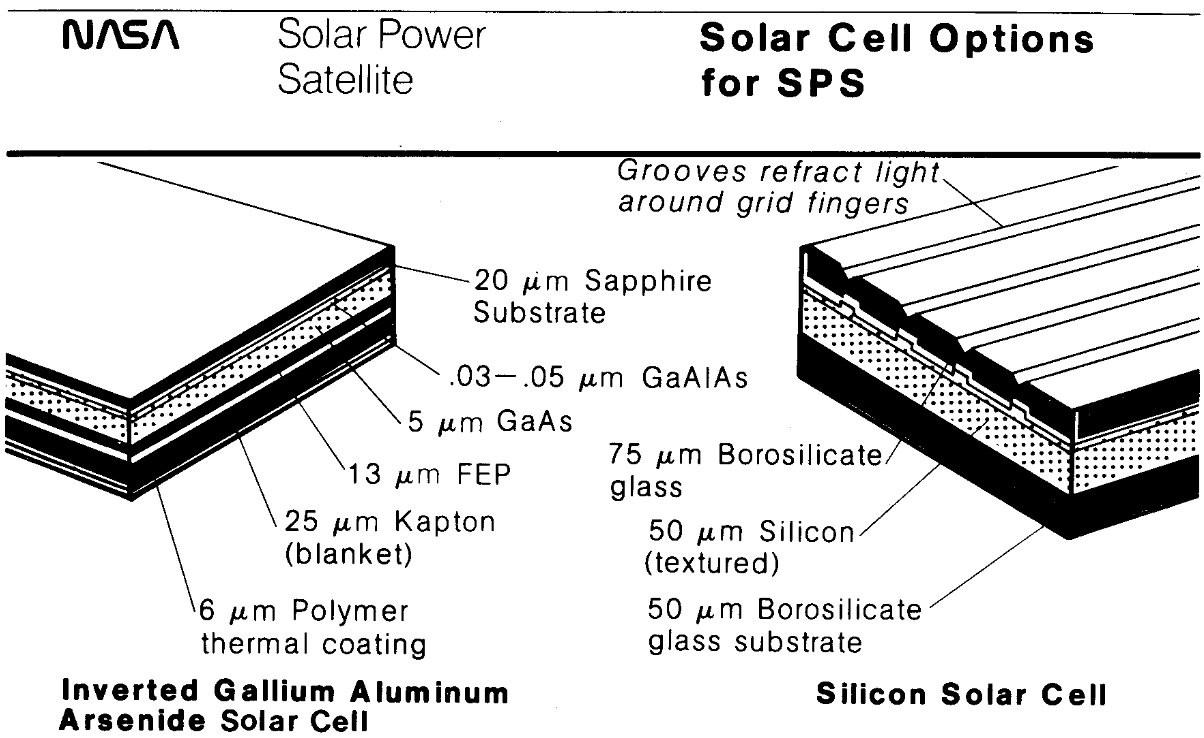

Figure 4 Solar Cell Options

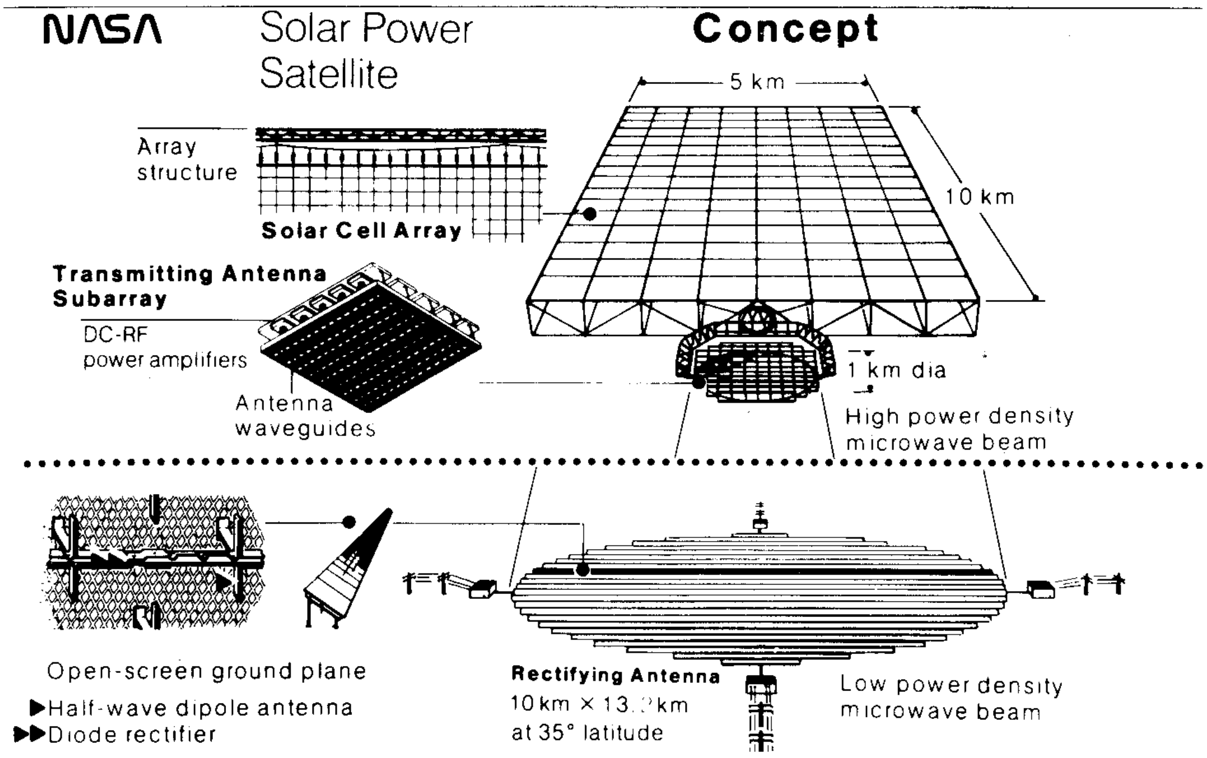

Figure 5 Microwave Power Transmission System

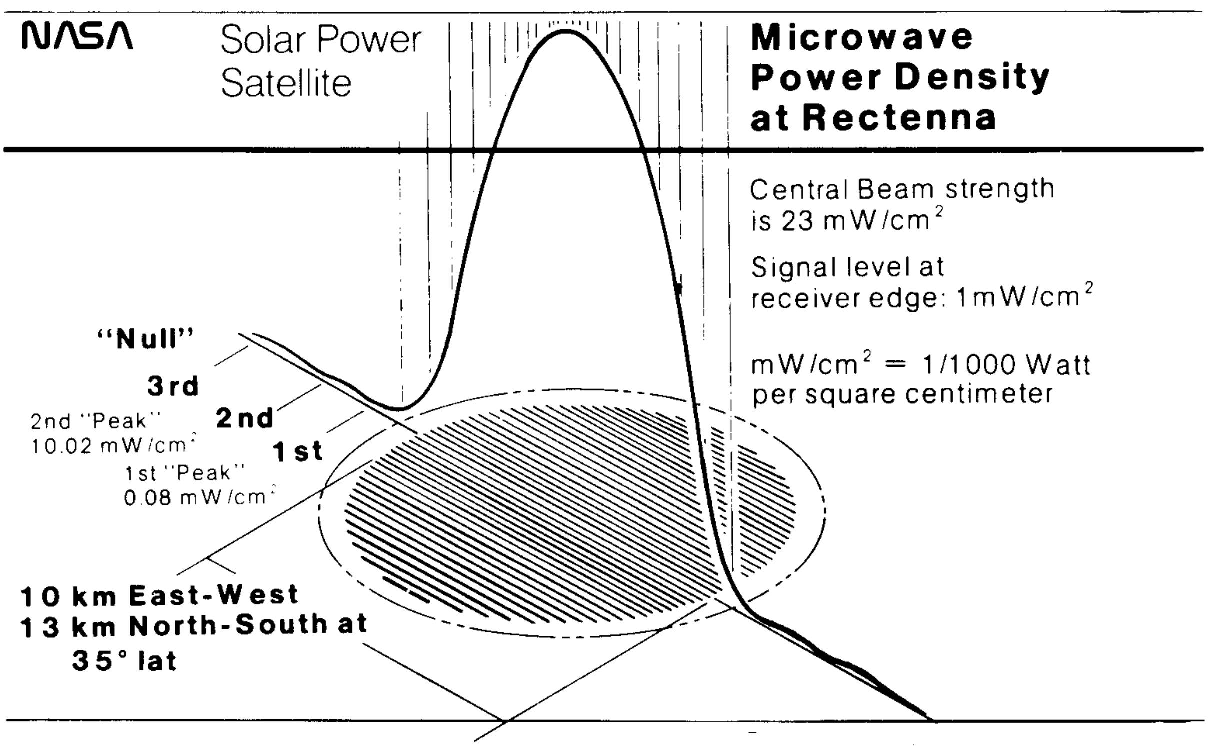

Figure 6 Microwave Power Density at Rectenna

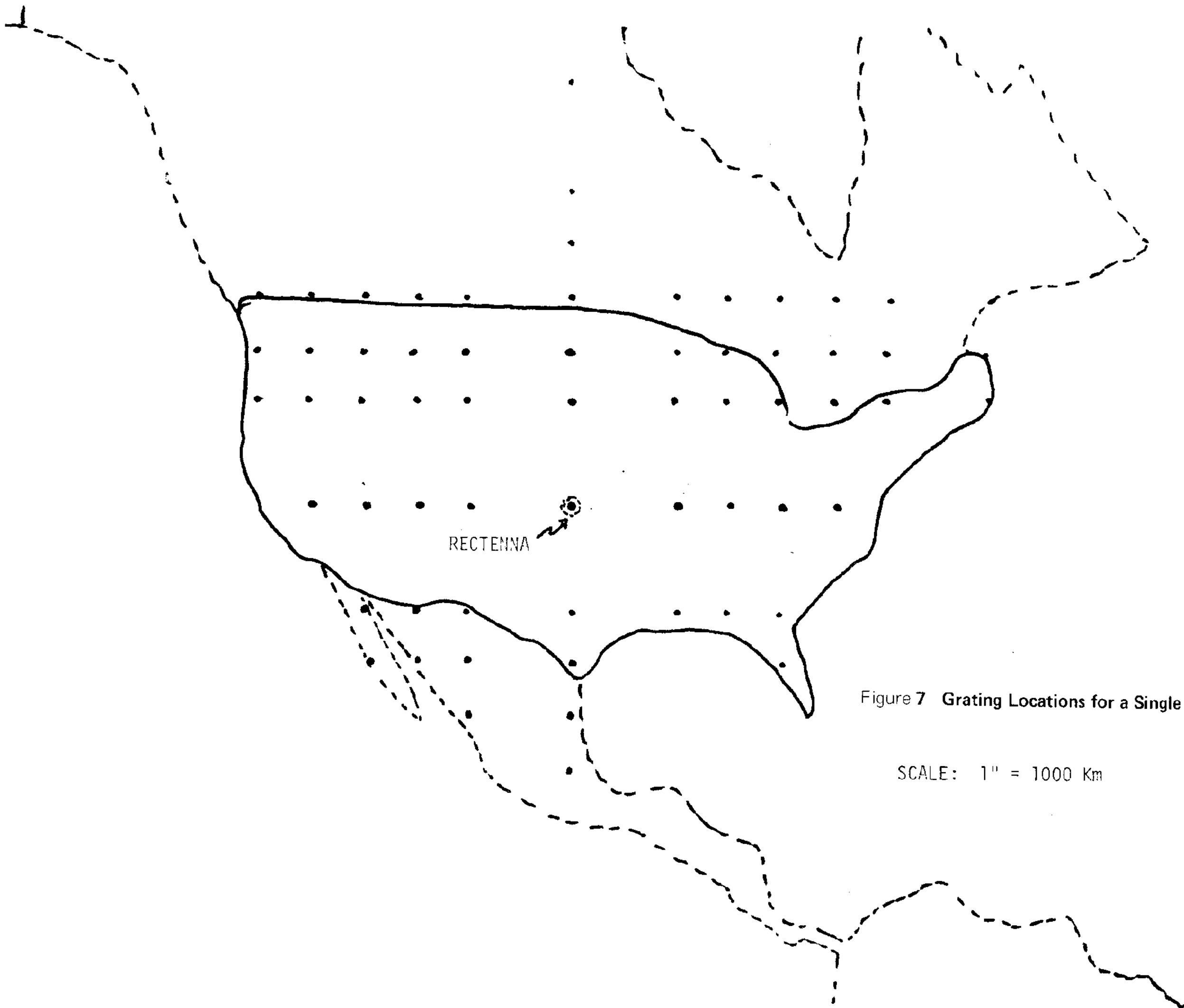

Figure 7 **Grating Locations for a Single Beam**

SCALE: 1" = 1000 Km

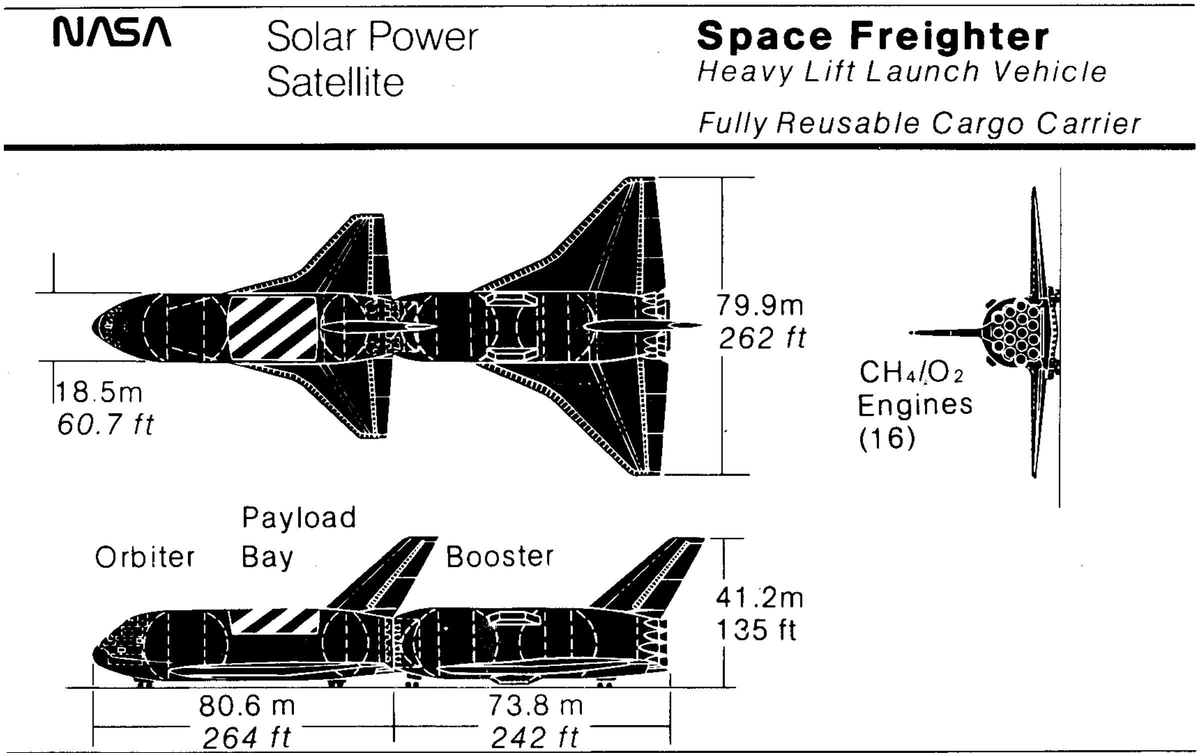

Figure 8 Heavy Lift Launch Vehicle (HLLV)

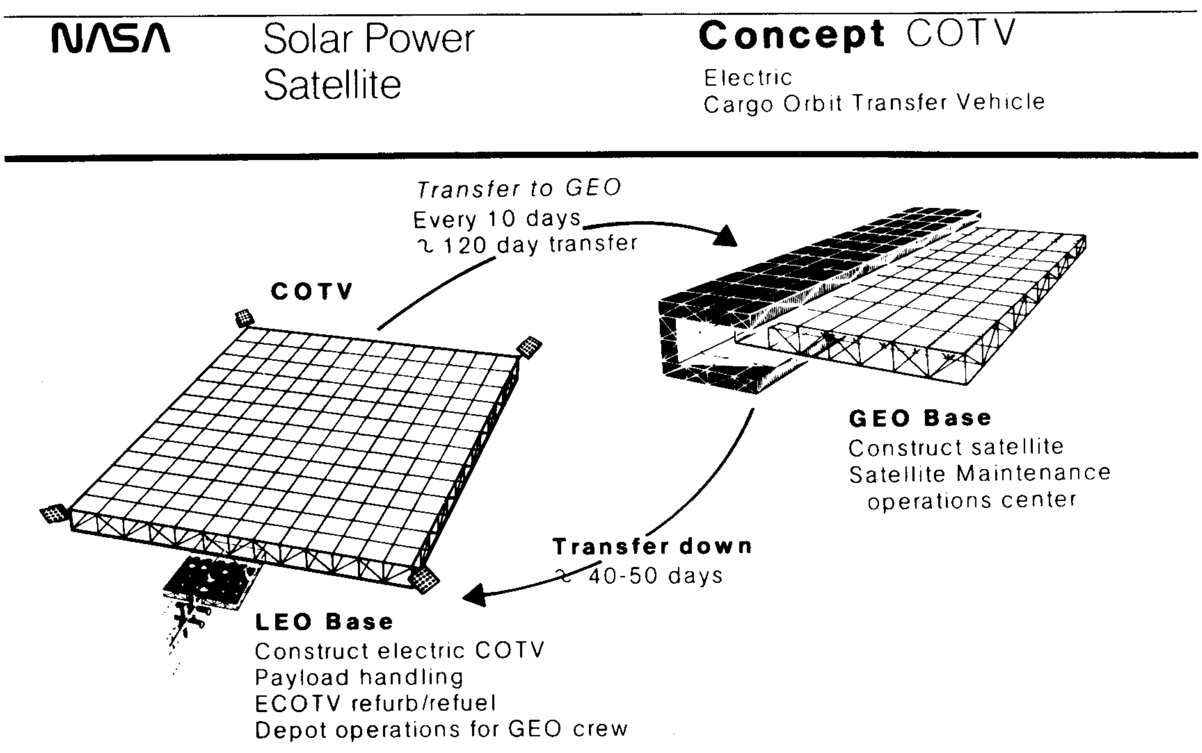

Figure 9 Cargo Orbit Transfer Vehicle (COTV)

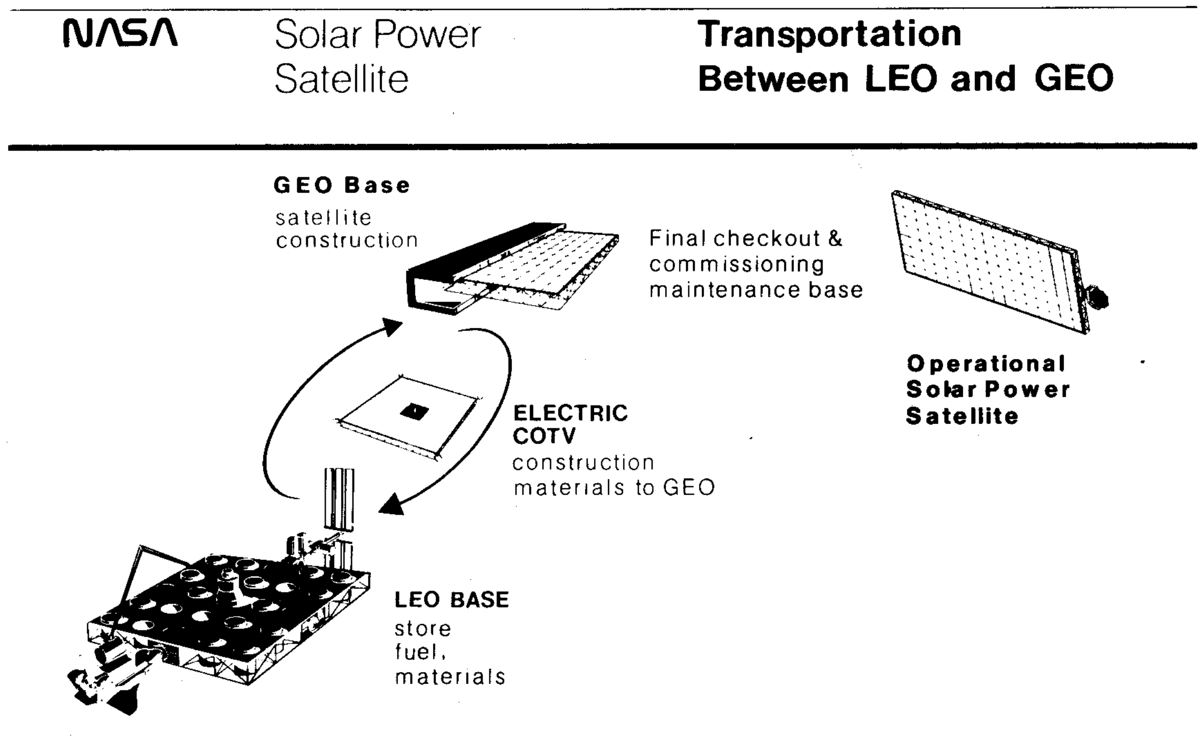

Figure 10 Transportation Between LEO and GEO

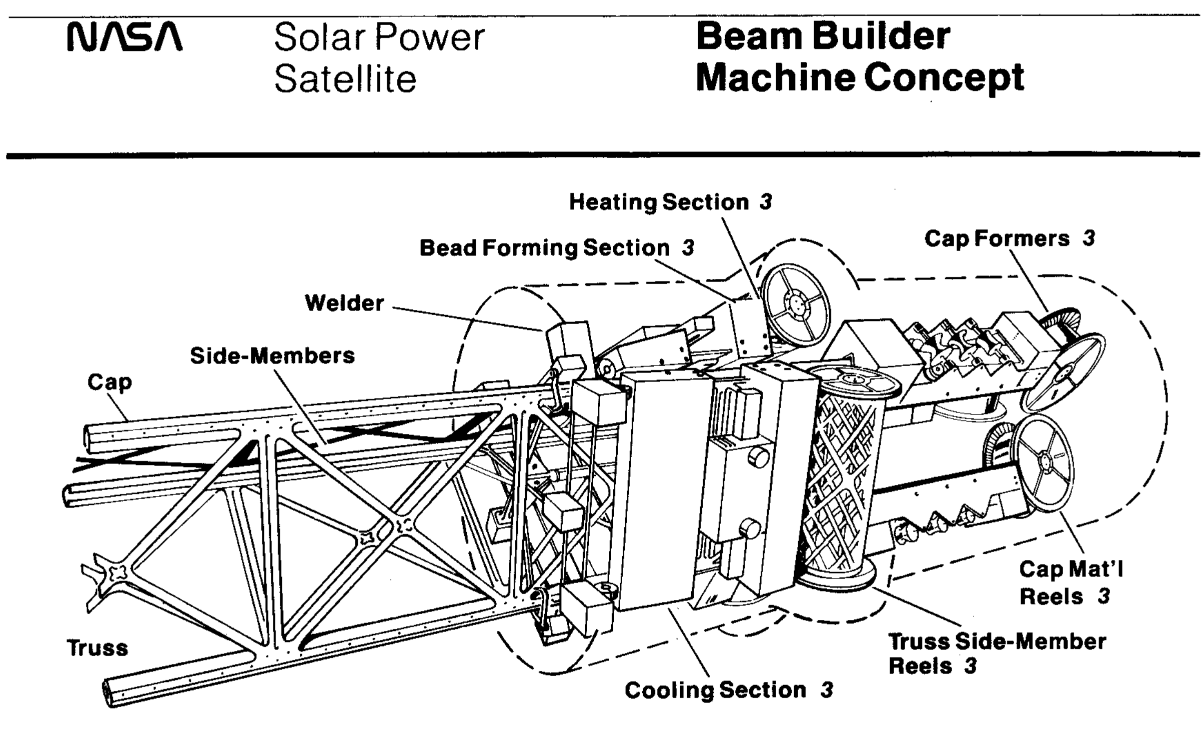

Figure 11 Automated Beam Builder

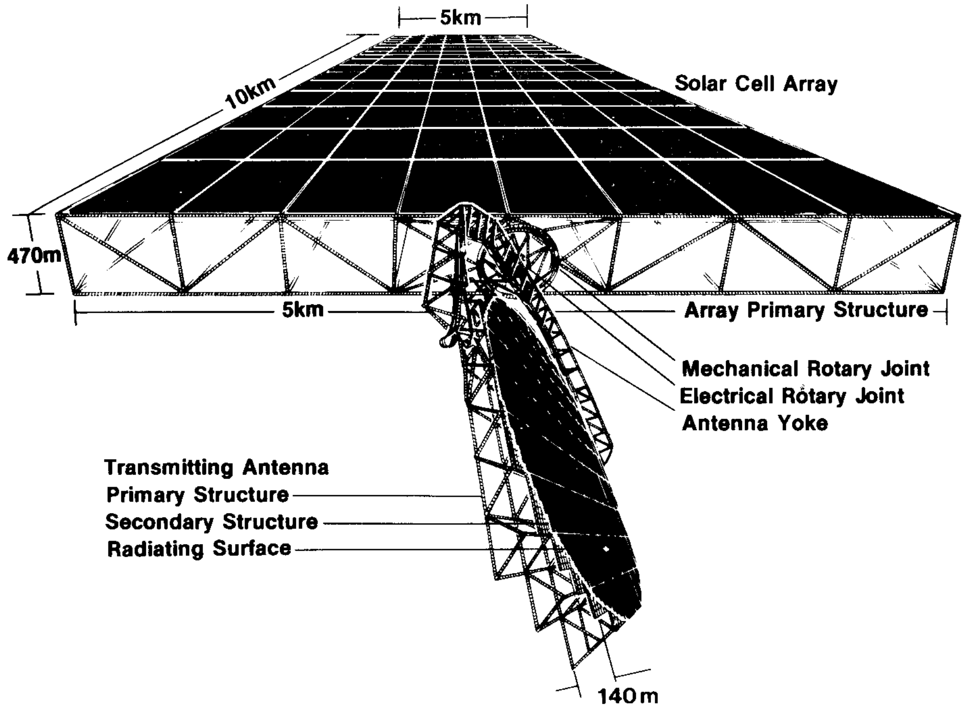

Figure 12 Satellite Structure

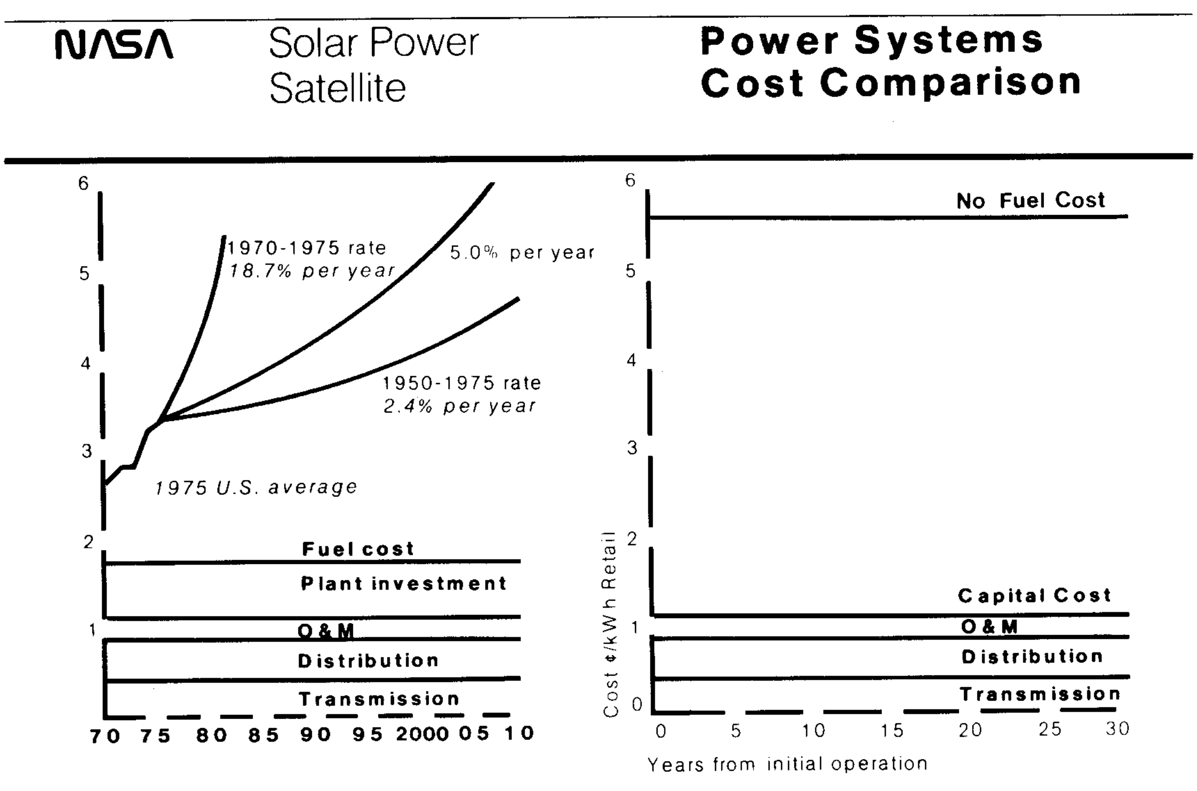

Figure 13 Power Systems Cost Comparison

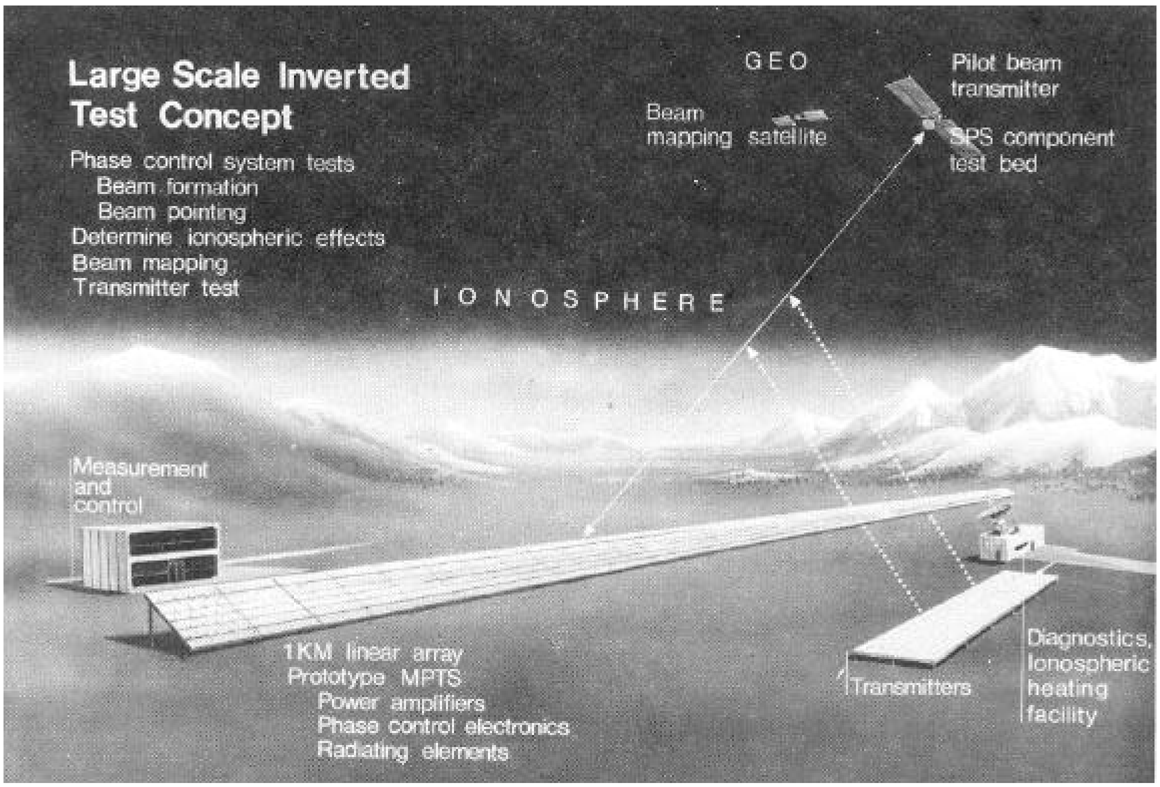

Figure 14 Large-Scale Inverted Test Concept