

SOLAR POWER SATELLITES: RECENT DEVELOPMENTS

Frank E. Little

*Texas A&M University, Center for Space Power
Center for Space Power, MS 3118, Texas A&M University
College Station, TX 77843-3118, USA
Tel: +1 979 845 8768, Fax: +1 979 847 8857, Email: f-little@tamu.edu*

ABSTRACT

Solar power is a reality. Today, increasing numbers of photovoltaic and other solar-powered installations are in service around the world and in space. The Solar Power Satellite has been hailed by proponents as the answer to future global energy security and dismissed by detractors as impractical and uneconomic. This paper reviews recent design and feasibility studies, advances made in enabling technologies (particularly wireless power transmission) and the development of supporting infrastructure. It identifies current progress towards practical demonstrations of space solar power technology that could lead to an economically viable Solar Power Satellite system.

INTRODUCTION

In 1990, the world demand for power exceeded 10 terrawatts (10×10^{12} Watts) thermal, with about 30% of the thermal energy being used to produce electricity [1]. In 1990, the nations of the Organization for Economic Cooperation and Development (OECD) used more than two-thirds of the world's total electrical power of >10.5 terrawatt-hours [2]. However, beginning in 2015, the DOE has forecast that the non-OECD countries' share of electric power usage will exceed fifty percent and will continue to rise [2]. Energy demand is estimated to increase by more than 60% from the present 382 Quads (1999) to 612 Quads in 2020 and electricity, with an annual growth rate of 2.7% between 1999 and 2020 will outpace growth of other energy use, reaching more than 22.4 terrawatt-hours [2].

Solar power is a reality. Today, increasing numbers of photovoltaic and other solar-powered installations are in service around the world and in space. These uses range from primary electric power sources for satellites, remote site scientific experiments and villages in developing countries to supplementing the commercial electric grid and providing partial power for individual businesses and homeowners in developed countries. In space, electricity generated by photovoltaic conversion of solar energy is the mainstay of power for low Earth and geostationary satellite constellations. Still, for all its acceptance as a benign and environmentally friendly energy source, terrestrial solar power has yet to be seriously considered a viable technology for providing base electrical generating capacity. The obvious reason is sunshine on earth is too unreliable. In addition to the diurnal and seasonal cycles, inclement weather reduces the average daily period and intensity of insolation. However, the sun shines constantly in space. The challenge is to harvest and transmit the energy from space to earth.

The Solar Power Satellite has been hailed by proponents as the answer to future global energy security and dismissed by detractors as impractical and uneconomic. The idea for a Solar Power Satellite that would help meet the growing energy needs of developed and developing nations was conceived by Dr. Peter Glaser in 1968 [3]. Dr. Glaser's concept was orbiting satellites converting solar energy and transmitting the energy to earth via a radio frequency energy beam. Solar Power Satellites placed in geosynchronous equatorial orbit 35,800 kilometers above Earth's surface would be continuously illuminated for most of the year. As a result of the orbit location, the amount of sunlight shining on the satellite during the year is five times more than is available to any terrestrial location. At geosynchronous orbit, satellites have the same rotational period as the Earth and are therefore fixed over one location at all times, enabling the satellite to deliver almost uninterrupted power to a ground receiving site.

Because the Earth's axis tilts 23° from the plane of the ecliptic, the satellites would pass either above or below the Earth's shadow except during the spring and fall equinox periods. During the 22 days prior to equinox, the satellite would experience a lengthening daily period of eclipse to a maximum of 72 minutes. The period of eclipse would then fall during the 22 days following equinox. The eclipse period occurs near local midnight when energy demand is at a minimum. The equinox eclipses will result in about a 1% decrease in the amount of solar radiation reaching the Solar Power Satellite and hence a 1% scheduled outage rate during the year.

SYSTEM ARCHITECTURES

Historic Studies

The first major attempt to conceptually design and evaluate a complete Solar Power Satellite system was by the US Department of Energy (DOE) and US National Aeronautics and Space Administration (NASA): the 1977-1980 DOE/NASA systems definition studies. The studies defined a Solar Power Satellite reference system including the satellite configuration and all of the supporting infrastructure [4]. The "completed" system would provide a generating capacity of 300 gigawatts from 60 satellites. The satellites were designed to have five gigawatt generating capacity; use photovoltaic cells for energy conversion; use wireless energy transmission at 2.45 GHz; be based at geosynchronous orbit; be assembled on-orbit with human support of automated machinery; and have a thirty-year operational life.

The purpose of the reference system was to be a basis for evaluating the Solar Power Satellite concept for environmental and societal impacts and as an alternative energy source. It was not a mature design to be used for manufacturing Solar Power Satellites. The estimated non-recurring cost of \$100 thousand million (for infrastructure and the first operational Solar Power Satellite system providing 5 gigawatts) contributed to the general impression of the Solar Power Satellite as an expensive program

The choice of five gigawatts per satellite was arbitrary and, in fact, may be seen as unduly restrictive for worldwide acceptance of the Solar Power Satellite concept beyond the industrialized nations of the G7. Very few countries in the developing world have the necessary transmission infrastructure to distribute 5 gigawatts of power from a single location to outlying regions and would be better served by smaller, more numerous distributed ground conversion sites.

Several independent assessments were made of the DOE/ NASA study. A report by the National Research Council of the United States National Academy of Sciences [5] concluded that while solar energy from space was technically feasible, the reference system assumptions were too optimistic, especially in the areas of photovoltaic cell performance and probable launch costs. The assessment recommended further relevant research be tracked and the situation assessed from time to time, but that implementation not be pursued at that time.

Japanese interest in Space Solar Power followed closely the 1981 establishment of the Institute of Space and Astronautical Science of Japan (ISAS) within the Ministry of Education. Japan recognized the enormous cost and technical difficulty of building the DOE/NASA system and decided to concentrate on the also costly problem of

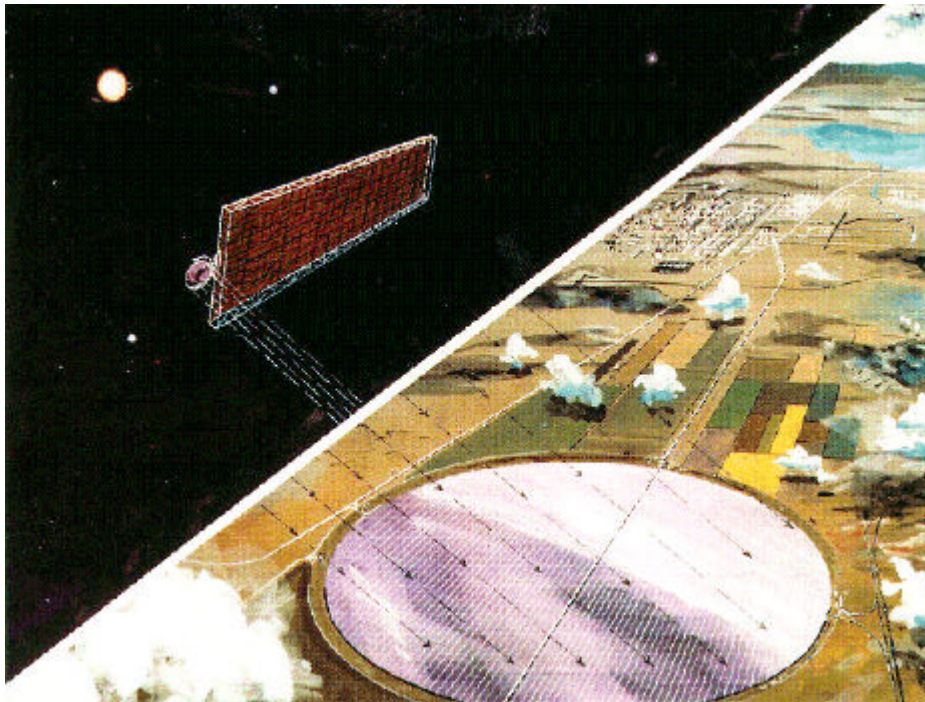


Fig.1. Artist rendering of NASA reference system showing satellite and ground rectenna

developing the ground receiving system, which led to an offshore, floating rectenna design [6]. Two prototype Space Solar Power Satellite designs were developed in Japan [6]. The first was a 10 MW photovoltaic derivative of the DOE/NASA Reference System developed by the Space Technology Committee of Japan Machinery Federation [7]. The second design was for a 70 MW solar concentrator, thermal energy conversion satellite with energy storage and periodic transmission developed by ISAS and Toshiba [8].

In the early 1990s, the idea of using the Earth's largest satellite as a platform for collecting solar energy with photovoltaic materials manufactured *in situ* and beaming the power to earth was proposed as a Lunar Solar Power option [1, 9]. In this proposal, several very large, although not very efficient, solar farms would be sited strategically to provide constant power to a large aperture microwave transmitter. Because the same face of the moon is always pointed at earth, transmitted power could be beamed to earth sites either directly and periodically or continuously through satellite relays.

Recent Studies

Since the completion of the DOE/NASA systems definition study in 1980, much progress has been realized in research and technology development. Progress has been made in photovoltaic cell efficiency, transportation, space structures, robotics and other areas. New studies were begun to reassess the feasibility of the Solar Power Satellite concept. The most notable of these is the "Fresh Look" study undertaken by NASA in 1995-1996 [10].

Of particular challenge and technical interest is the wireless transmission of power from the satellite to earth. Early proposals emphasized radio frequency transmission in the microwave spectrum, at 2.45 GHz, based primarily on the pioneering work of William Brown. While not abandoning 2.45 GHz, recent solar power satellite studies and transmission technology development projects have emphasized higher frequency microwaves (5.8 GHz) and visible and near IR lasers. While the energy delivered per satellite improves the economic competitiveness of solar power from space, there are practical and safety limits to the amount of power that can be delivered to a single site. Most current designs are typically in the range of 1 gigawatt rather than the 5 gigawatts delivered per site in the Reference Design.

Microwave Wireless Power Transmission Based Systems

The "Fresh Look" essentially consisted of a "brainstorming" exercise to elicit new design concepts followed by a critical review of the concepts to select the most promising for further study. Some 30 concepts were examined and two ranked highest. One was the "Sun Tower"; an innovative gravity gradient stabilized modular satellite. The satellite, which incorporated many new and innovative technologies, would be robotically assembled on orbit and could grow in size and power capability by adding new segments. One drawback of the design is its inability to fully track the sun, resulting in self-shadowing by the solar arrays, particularly at noon and midnight. In its preferred embodiment, the "Sun Tower" would be deployed as a constellation in a middle-earth-orbit that would supply energy to multiple sites. One of the chief attractions of the design was it would provide a cheaper path to initial satellite deployment and first power than the reference system design [10].

Based on interest generated by the "Fresh Look", the US Congress suggested a follow-on study. NASA began the Space Solar Power Concept Definition Study [11] in 1998 to evaluate the results from "Fresh Look". In addition to identifying, developing and analyzing system concepts and technologies for solar power satellites, and evaluating the potential commercial markets and economic feasibility of space solar power, applications of SSP concepts for space exploration and transportation were developed. The bulk of the system modeling and evaluation effort was applied to "Sun Tower" and derivative architectures, although a "Sandwich" concept [12], introduced by Professor Kaya of Kobe University, received some analysis in this study and continues to be investigated in Japan. The study validated much of the "Fresh Look" results, however, the "Sun Tower" middle-earth-orbit was found to be impractical.

The main design features of a sandwich design are the placement of the photovoltaic array directly behind the transmitter, which remains stationary, pointed at earth, and the concentrator/steering mirror system used to direct sunlight to the photovoltaic array. The main advantage of the design is the elimination of the majority of the power management and distribution system. The major disadvantages are increased demands on thermal management for the sandwich and the complexity of solar tracking with the concentrator system.

NASA began the Space Solar Power (SSP) Exploratory Research and Technology (SERT) Program in 1999. SERT continued the satellite concept definition and analysis work and funded fundamental technology research as well as a wireless power transmission demonstration project. In addition to defining SSP applications for science, exploration and

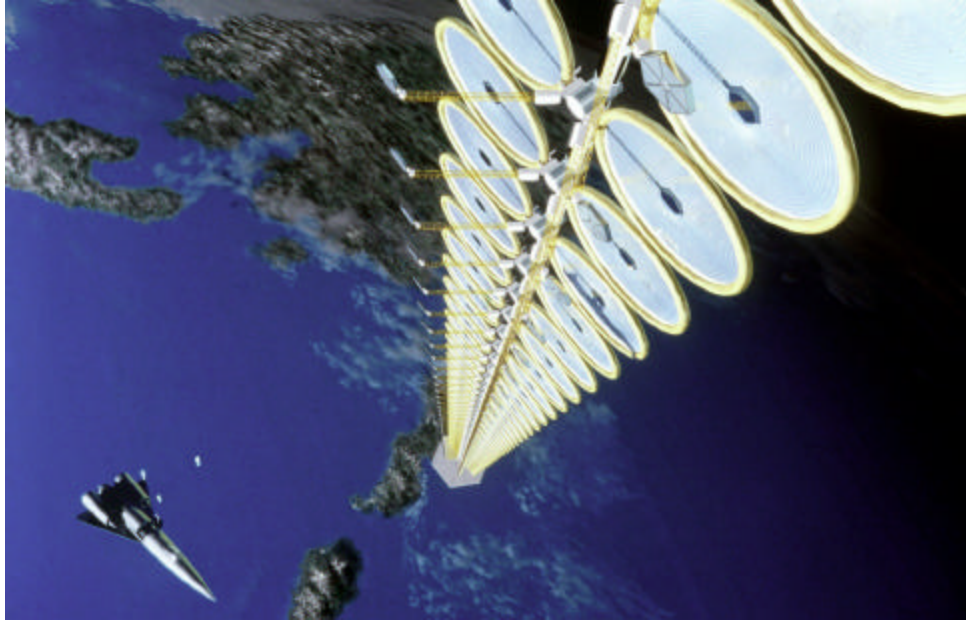


Fig. 2. Artist conception of “Sun Tower” solar power satellite

other commercial space uses, SERT addressed a number of critical technology elements for solar power satellites, including transportation (both earth-to-space and in-space), robotic assembly, power generation, power management and distribution, thermal management and wireless power transmission [13].

The principal microwave solar power satellite designs to emerge from the SERT studies were a traditional perpendicular to orbit plane (POP) configuration and the Integrated Symmetric Concentrator (ISC) configuration. The ISC design is loosely based on a modified sandwich concept, in which the photovoltaic array is moved from the back of the transmitter and two photovoltaic arrays are placed at the focus of the concentrator array. This compromise relieves much of the thermal management problems while slightly increasing power management and distribution complexity

Laser Wireless Power Transmission Based Systems

Satellite and system architectures based on laser wireless power transmission were first considered seriously during the SERT program. Laser systems have one major advantage for power transmission, which is aperture collection efficiency. Whereas microwave power transmitting and receiving antennas are sized in kilometers, laser systems can be sized in meters. A secondary advantage is that laser based systems lend themselves more readily to incremental development than microwave based systems. However, the major hurdle that laser based systems face is atmospheric losses, especially due to rain attenuation. To provide continuous power, which would be necessary to qualify as base load power generation, the laser system would either have to have massive ground energy storage capability or multiple sites located sufficiently far apart such that one site could be available at all times.

With the lower delivered power per site design criteria of the current studies compared to the DOE/NASA Reference System, beam safety has minimal influence on the design of a microwave based solar power satellite system, however, it has been a major factor for laser based systems [14]. To deal with laser eye and skin exposure limits, [14] proposes a system of a geostationary cluster of laser satellites distributed uniformly through a sufficient solid angle of space, with the beams from the satellites spread uniformly over the 600 meter diameter photovoltaic array receiving site. With such a system it is possible to maintain safety standards and still deliver IR light ($1.03 \mu\text{m}$ (Yb:YAG), $1.06 \mu\text{m}$ (Nd:YAG)) with a seven-fold increase in power density over natural sunlight [14]. Practical realization of such a system is through a HALO orbit in which the satellites appear to move in a circular orbit about a fixed point in space [15]. Individual satellites would have multiple solid state lasers powered by photovoltaic arrays. The lasers would be dispersed among the photovoltaic cells to minimize power management and distribution and the light beamed directly to earth or collected by mirrors or through fiber optics to a central steering mirror and beamed to earth.

A novel approach to overcoming weather interruption of laser based power beaming is to use the beamed power to store energy at the receiving site for later transportation [16]. A low-earth-orbit satellite would use a concentrator fed solar

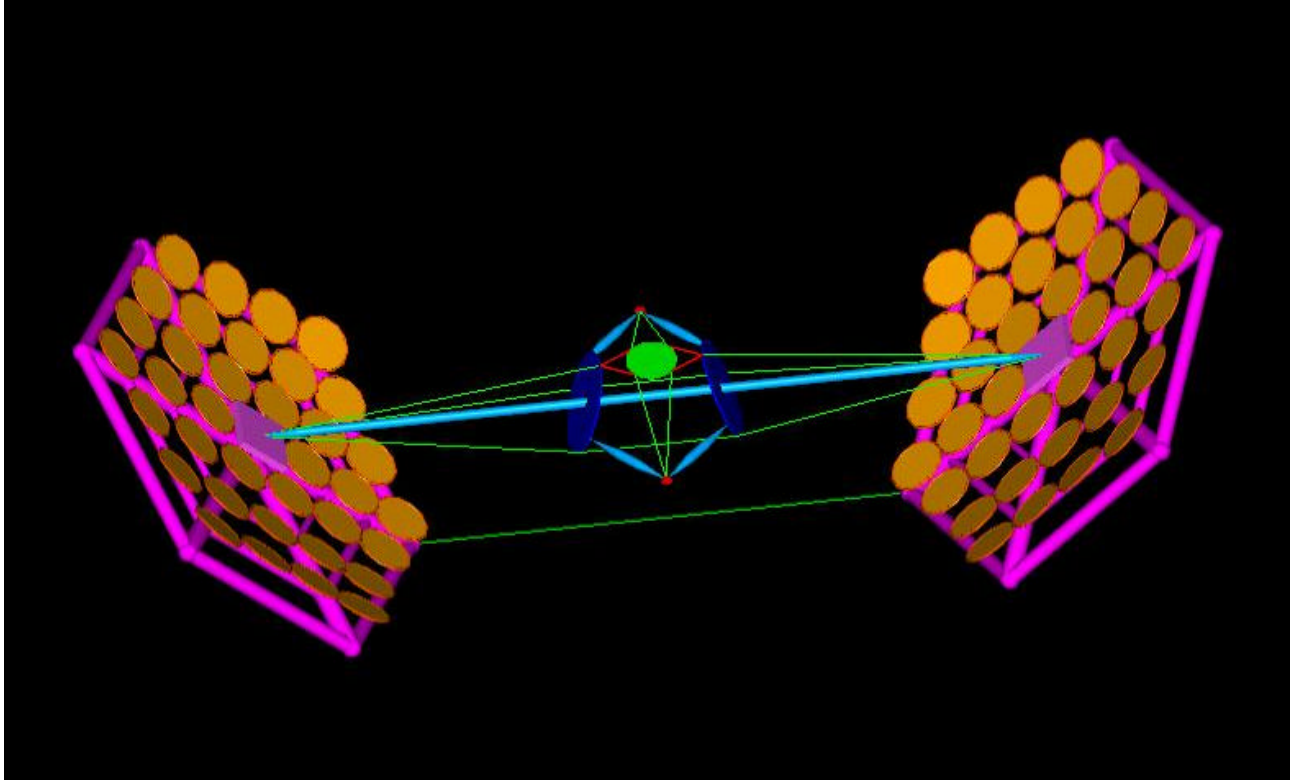


Fig. 3. Integrated Symmetric Concentrator concept showing concentrator mirrors in orange, photovoltaic arrays in dark blue and microwave transmitter disc in green (scale: transmitter disc is 500 m diameter)

pumped laser to deliver 10 megawatts of laser energy focused into a tank of seawater containing titanium dioxide as a catalyst to split the water into its component hydrogen and oxygen. The hydrogen could be used as a fuel directly, or reacted with CO_2 to make methane.

Hybrid Laser-Microwave Wireless Power Transmission Based Systems

Laser and microwave wireless power transmission each have unique advantages, lasers in requiring smaller apertures and microwaves in being nearly immune to rain and other atmospheric conditions. Proposals have been made to marry the two such that each would operate in the most advantageous environment. The key to the design proposal is a platform operating in the stratosphere at about 20 kilometers height [17, 18]. Lasers would be used to beam power from satellites at geostationary orbit through space (no atmospheric attenuation) to a photovoltaic array on the platform. The power would be retransmitted with microwaves from the platform to a ground rectenna. This would minimize both the size of the satellite transmitter and ground receiver for an all-weather transmission system. Drawbacks to such a system include efficiency losses due to the conversion/retransmission step and the likelihood of exceeding microwave beam power density safety standards.

TECHNOLOGY DEVELOPMENT

Progress has been made in a number of technologies relevant to space solar power and the development of an economic solar power satellite since the Reference System [13]. Photovoltaic cell efficiency has risen from approximately 14% for the single crystal silicon base-lined in the DOE/NASA study to 27.4% obtained with sunlight concentrated through a stretched lens array Fresnel concentrator onto a triple junction solar cell [19] and even higher efficiencies are being sought. Inflatable structures have been demonstrated in space [20, 21], lending credence to concepts for lower mass satellite structures. Propulsion, thermal management and power management technologies have all advanced [22]. Infrastructure technologies such as robotics for assembly and repair of modular structures have come of age [23, 24]. Space transportation scenarios necessary to support the massive launch requirements necessary to solar power satellite deployment are being developed along with the new, reusable launch technology necessary to bring transportation cost down to economically viable levels.

WIRELESS POWER TRANSMISSION

Historical Background

The first wireless power transmission was recorded in scientific experiments by Heinrich Hertz in which high-frequency power was generated, transmitted and received with parabolic reflectors, and detected at the receiver [25]. Wireless power transmission experiments were conducted by Nikola Tesla just before and during the early part of this century. Tesla envisioned wireless power transmission as an alternative to the terrestrial transmission line and distribution grid. Tesla hoped to use a central beaming station to set up a pattern of standing waves with optimally placed receivers. His idea, to transmit energy without wires, was far ahead of the technology. In 1899, Tesla first attempted to transmit power from a 200 foot tower at his laboratory in Colorado Springs, Colorado. The resulting level of power broadcast and collected are not recorded [25]. His final project, a demonstration transmission system on Long Island was discontinued in 1917 for lack of funding [26].

High power transmission of microwaves became possible with the invention of the magnetron and its subsequent improvement by Japanese researchers in the 1920s, and the invention of the klystron in the 1930s. However, wireless power transmission remained a distant possibility although in 1926 H. Yagi and S. Uda presented “Feasibility of Electric Power Transmission by Radio Waves” at the Third Pan-Pacific Academic Conference in Tokyo [27].

During the Second World War, the secret Japanese “Z-project” to shoot down aircraft with a ground-based high power microwave beam resulted in the development of a 100 kW magnetron [27].

A demonstration of point-to-point wireless power transmission was finally achieved by the Westinghouse Electric Company in their laboratory in the 1930s [25], but it was not until the work of William Brown at the Raytheon Company in the 1960s, that point-to-point, focused power beaming with microwaves became practical [28-30].

The development of the laser (light amplification by stimulated emission of radiation) in 1960, following the earlier microwave maser (microwave amplification and stimulation through the emission of radiation) in 1953 [31], led to a potential reduction in the size of power beaming equipment, since the diameter of the transmitter and receiver is proportional to the wavelength of radiation.

Although lasers have existed in the laboratory for more than 30 years and have recently been incorporated into most aspects of human life (*e.g.*, communications and personal electronics), little effort was put into developing high average power lasers until the concept of beam weapons seized the military. Beginning in the 1980s, military research efforts such as the Strategic Defense Initiative included research into high energy and high power laser weapons [32].

Recent Progress

Microwave

For direct microwave wireless power transmission to the surface of the earth, a limited range of transmission frequencies is suitable. Frequencies above 6 GHz are subject to atmospheric attenuation and absorption, while frequencies below 2 GHz require excessively large apertures for transmission and reception. Efficient transmission requires the beam have a Gaussian power density. Transmission efficiency η_b for Gaussian beams is related to the aperture sizes of the transmitting and receiving antennas:

$$\eta_b \sim 1 - \exp(-\tau^2) \quad (1)$$

and

$$\tau = \pi D_t D_r / (4\lambda R) \quad (2)$$

where D_t is the transmitting array diameter, D_r is the receiving array diameter, λ is the wavelength of transmission and R is the range of transmission.

Frequencies other than 2.45 GHz, particularly 5.8 GHz and 35 GHz are being given greater attention as candidates for microwave wireless power transmission in studies and experiments. The mass and size of components and systems for the higher frequencies are attractive. However, the component efficiencies are less than for 2.45 GHz, and atmospheric attenuation, particularly with rain, is greater.

Work by Brown [33] has resulted in the conversion of a common 2.45 GHz magnetron oscillator, with the addition of external circuitry, into a high-gain, phased-locked amplifier with independent control of the operating frequency and of

the power output level. This control was achieved over a broad range of power output and operating frequency. In addition, an amplitude control system using a buckboost coil is incorporated into the packaging of the magnetron. This controls the microwave power output level within narrow limits despite a wide variation in the DC voltage applied to the magnetron, functioning as a low loss power conditioner when the magnetron is paralleled with other magnetrons on a common high power bus. It also functions as an electronic filter to help counter the effects of a current ripple on the power supply. This magnetron has been coupled with a slotted waveguide antenna element to form the basis of a phased array antenna.

Development of more efficient microwave tube devices has been stimulated primarily by commercial applications. Conversion efficiency (DC-RF) of a 2.45 GHz magnetron operating at 800 Watts output has been measured at 85% [34].

Although conversion efficiency is not yet as high as for magnetrons, solid state radio frequency transmitting systems show promise and are improving. The Japanese in particular continue development of solid state devices for the Solar Power Satellite systems and experiments they are planning [35,36].

Improvements are being reported for RF to DC conversion devices such as higher frequency rectennas, including circularly polarized rectennas, [37-42] and cyclotron wave converters [43, 44].

Laser

Except for those laser power beaming missions which use thermal energy from the beam, it is necessary to convert the light to electricity. This means developing photovoltaic cells which are capable of efficiently converting multiple sun intensity coherent monochromatic light into electricity. Photovoltaic research has shown an increase in conversion efficiency of 2 to 3 times for photocells illuminated with laser light near the bandgap of the semiconducting material as compared with sunlight [45].

The photovoltaic materials most seriously considered for laser power converters are, naturally enough, those most commonly in use with current solar photovoltaic space power systems. These are gallium arsenide (GaAs) and crystalline silicon (Si) [46, 47]. To a lesser extent indium phosphide (InP) has received attention because its conversion efficiency approaches gallium arsenide and it is more radiation tolerant than either gallium arsenide or silicon [48]. Copper indium diselenide (CIS) and gallium antimonide (GaSb) have been considered for IR wavelength beaming, but suffer from significantly lower conversion efficiency with monochromatic light [48]. Cadmium telluride/cadmium sulfide and amorphous silicon seem not to have been investigated to this point. Multi-bandgap cells offer no advantage with monochromatic light and have the disadvantage of being generally heavier and more complex and costly to manufacture.

Maximum efficiency for a photovoltaic cell with monochromatic light is achieved at a wavelength that is just short of the cutoff wavelength for the semiconductor [48]. The cutoff wavelength (λ_c (μm)) is given by

$$\lambda_c = 1.24/E_g \quad (3)$$

where E_g is the semiconductor bandgap energy in eV. Peak wavelength efficiencies for steady state monochromatic light illumination have been calculated for GaAs (>58% for 0.84 μm, >50% for 0.74 - 0.87 μm [49]), InP (56.7% for 0.87 μm, >50% for 0.75 - 0.925 μm [48]) Si (>42% for 0.93 μm [49]), CIS (about 30% for 1.05 μm [49]) and GaSb (>25% for 1.3 - 1.6 μm [49]). Conversion efficiencies have been measured for Si of 45% at 1.02 μm, [50] and for GaAs of about 52% at 0.84 μm [51] and 68.5% at 0.83μm [52]. However, this is a much lower conversion efficiency than that demonstrated by microwave rectennas.

The efficiency of converting electricity to laser light has been increasing. Recent work on diode lasers has achieved 60% electrical to light efficiency for a laser pumping diode bank [53]. Coupled with the >60% conversion efficiency reported for diode pump power at 1.06 μm laser light conversion in a Yb:YAG laser [54] suggests overall conversion efficiency approaching 40%. However, the useful measure of efficiency for solar power satellites is output laser power per unit of solar energy. In this case, the overall efficiency is close to 9%. An alternate to diode-pumped lasers is solar-pumped lasers, which give direct conversion from sunlight to laser light. The current solar-pumped laser efficiency record is held by Nd:YAG at 4.8% [55].

DEMONSTRATION PROJECTS

SPS 2000

The prize for most ambitious wireless power transmission demonstration proposed since Tesla's Long Island tower experiment before World War I goes to the Japanese SPS 2000 project [6, 56]. The purpose is to demonstrate a functioning solar power satellite system including the wireless transmission link and develop the ground infrastructure in several locations to provide the basis for a space solar power market.

The design calls for a gravity stabilized satellite capable of delivering 10 MW of electricity from a spherical 1100 km east-to-west equatorial orbit. The phased array antenna will be capable of steering $\pm 30^\circ$ along the orbital path (E-W) and $\pm 16.7^\circ$ perpendicular to the orbital path (N-S). This will limit the possible rectenna sites to close to the equator. In addition to being limited to an equatorial band, the receiving sites must be at least 1200 km apart to maximize the length of time for power transmission to each individual site. Because power can only be received intermittently at any ground site (about 4 minutes out of the 108 minute orbit for a beam scan angle of 30°) energy storage is an important component of any ground site. Further limitations are placed on the power available to any site by the diurnal rotation of the Earth, since the satellite is incapable of delivering energy while in eclipse over a site during the night. With an average daily coverage of less than 30 minutes per site, 4 to 4.5 MWh of energy could be available to a site from the SPS 2000 satellite.

The satellite is in the form of a long prism. The base of the satellite is always earth facing and mounts the transmitting array. The "roof" faces of the satellite are paneled with photovoltaic cells. The phased array transmitting array is based on a dense array of low energy solid state antenna elements (the design assumes an efficiency of 60%, which has not yet been achieved, the MILAX/METS antenna solid state elements achieved 42% efficiency [57]). To assure target acquisition and tracking, a retrodirective beam at 245 MHz transmitted from each rectenna site is used. The satellite would be launched in sections and assembled on orbit.

Initial designs studies have been completed and a scale model mock-up of the satellite has been made. Several potential receiving sites, from Pacific Islands to South American Andes locations have been visited by the SPS 2000 team, with a generally enthusiastic reception.

Grand-Bassin Project

This project, planned for La Réunion will supply electricity to the remote village of Grand-Bassin [58]. During its implementation, the French led Grand-Bassin project will accomplish several goals. Most important of these is to provide an actual demonstration of point-to-point power beaming. Grand-Bassin is a small isolated mountain village on La Réunion. Set in the scenic environment of a river valley surrounded by steep cliffs, access is limited to trail or helicopter. Several tourist lodges have been established in Grand-Bassin to accommodate sightseers. Further development of the tourist potential of Grand-Bassin is hampered by the lack of electricity in the village to supply refrigeration for food and laundry for overnight guests. Several options were investigated for providing up to 10 kW of electricity to Grand-Bassin. For primarily aesthetic reasons, a microwave wireless power transmission link from the existing terminus of an electric power line was chosen.

The primary constraint imposed on the system was cost. In order to compete with photovoltaic conversion and keep overall energy costs low, the end-to-end electrical conversion and transmission system efficiency had to be at least 20%. Although the aesthetic desire was to use as small a transmitter and rectenna as possible, concern for the perceived safety of the human inhabitants and other biota argues for low energy density (maximum of 5 mW/cm^2) in the beam, with an attendant loss of efficiency. An "H" dipole design is used for the rectenna. The transmitter will consist of injection locked phase and amplitude controlled magnetrons (see above, [33]) feeding a multi-focus parabolic reflector. This design consists of several parabolic reflector sectors with a common focus, a microwave analogue to the Fresnel lens. The distance of the wireless link is 700 m. The design system will utilize a rectenna aperture diameter of 17 m, with a 6 m transmitter diameter to give 95% collection efficiency. Overall ac-to-ac conversion efficiency is calculated to be 57%.

A prototype system demonstration will consist of four multi-focus parabolic reflectors fed by 1 kW magnetrons transmitting over a distance of 150 m to a 180 m^2 H dipole rectenna to deliver 2 kW output power.

Retrodirective Phased Array Antenna/Rectenna Demonstration

Recent and continuing work at Kobe University has led to the development of a 5.8 GHz retrodirective phased array transmission system demonstrator. The antenna uses solid state amplifiers directly connected to the transmitting antenna elements to reduce cable losses and reduce weight and was derived from the antenna design used for MILAX/METS. A half frequency pilot beam (2.9 GHz) is broadcast from the rectenna. Receiving antennae for the pilot beam are integral with the transmitting antenna. The phase of the pilot beam is determined by comparison with the 5.8 GHz master oscillator. The conjugate phase is fed to phase shifters to accurately steer the beam onto the rectenna. Advantages of this system include smaller size and less mass when compared to 2.45 GHz, simple and accurate pointing control and improved efficiency of the power amplifiers. The system was first demonstrated at SPS '97 in Montreal.

SPS End-to-End Terrestrial Demonstration

A test project to demonstrate all the major elements of a solar power satellite on the ground has been proposed [59]. In this demonstration concept, the DC output of a photovoltaic array is used to power a transmitting array at the hundreds of kW power level. The receiving rectenna, located at a distance of 1 to 5 km from the transmitter, would convert the RF power to DC for a utility grid. The objective is to verify practical wireless power transmission and to establish the reliability of components operated over time. In addition to operation data, environmental studies could be performed to ensure the safety of the beam. Finally, it would be possible to test the concept of beam splitting (targeting multiple receivers) from the transmitting antenna.

Microwave Garden

Limited studies have been undertaken to understand the effects of non-ionizing radiation on biota. Regulatory agencies have established widely varying standards and limits for human exposure to microwave radiation dependent both on the wavelength and intensity of the radiation. The most widely cited non-human studies were performed with birds [60] and bees [61]. Japanese researchers have embarked on a long-term project to determine the effect of microwave radiation on the biota [62].

A long-duration microwave exposure facility was built in 1994 in Japan. A horn antenna is mounted at a height of 2 m on a pole in the middle of an 8 m by 8 m test field. The plot is surrounded by a 4 m high shield fence. The radiation field has been mapped to determine local intensities. Several experiments have been conducted with plants on the effect of 2.45 GHz radiation at beam intensities up to 23 mW/cm^2 (the maximum proposed beam intensity for the DOE/NASA Reference Study). Seeds sown in the plot are allowed to germinate and grow while under constant radiation.

The studies have been carried out under natural conditions, leading to the conclusion that whereas the radiation test equipment and facility had been validated, any effect from microwave radiation has been overwhelmed by the local weather conditions.

ISPER

A Japanese led space experiment [12] is being planned to demonstrate a new concept for a solar power satellite. The heart of the concept is a sandwich structure with the retrodirective solid state phased array transmitting antenna integrated with solar cells directly connected to the power amplifiers, eliminating long conducting lines. Light inflatable concentrators would track the sun and reflect light to the solar cells. The experiment consists of a transmitting antenna-photovoltaic array sandwich array deployed from the Japanese Space Flyer Unit (SFU) in low earth orbit beaming to daughter satellites and ground stations. The primary objective of the ISPER experiment is to verify the space operation of the antenna-photovoltaic array sandwich. Secondary objectives are to examine the nonlinear interaction between the ionospheric plasma and the microwave beam demonstrate the solar collector and demonstrate microwave wireless power transmission from low earth orbit. The ground station will receive enough power to light a small lightbulb.

Lunar Rover

A demonstration of a microwave powered rover was completed by the Boeing Company under the SERT program [63]. The demonstration was based on improvements to a 5.8 GHz powered buggy built in the early 1990s [64]. The control electronics were upgraded and the vehicle was operated remotely *via* a wireless internet connection.

New Initiatives

NASDA

The National Space development Agency of Japan (NASDA) invited two teams of Japanese companies to submit proposals for a space solar power demonstration satellite [65]. The satellite would be capable of generating between 10 kilowatts and 1 megawatt of power. The program is aiming for a launch on the H-2A in 2005 to 2007. One of the teams developing design proposals consists of Mitsubishi Heavy Industries Ltd. and NEC Toshiba Space Systems Ltd. The other includes Mitsubishi Electric Corp., Ishikawajima-Harima Industries Co., IHI Aerospace Engineering Co., Kawasaki Heavy Industries Ltd. and Shimizu Corp.

NASA

NASA has developed a series of flight demonstration model systems leading to development of a functioning solar power satellite [13]. They progress in the level of satellite power from Model System Category (MSC) 1 at 100 kilowatts to MSC 4 at 1 gigawatt, which is essentially a full-scale system. Intermediate steps include MSC 1.5 at 1 megawatt and MSC 3 at 10 megawatts. MSC 2 is a lunar rover. Planning is currently underway to define appropriate technology demonstration experiments for MSC 1. It is currently scheduled to carry both laser and microwave power beaming experiments, space-to-space as well as space-to-ground.

Industry

Recent work at Off Earth WPT addressed system studies for ground-to-air wireless power supply systems, including a scaled airship demonstration [66]. This demonstration would use a 12 meter phased array antenna, beaming at 300 meter altitude to a 3m diameter rectenna to provide adequate power to drive the airship at 30 mph. The airship would be some 30 m long and the system would be visible and useful for public relations. Estimated cost for the demonstration would be on the order of \$5 million. A full-scale operational system at an altitude of 20 km would cost \$40 - 50 million.

REFERENCES

- [1] Criswell, D. R. and Waldron, R. D., "Results of analysis of a lunar-based power system to supply Earth with 20,000 GW of electric power", *SPS 91 Power from Space* Paris/Gif-sur-Yvette 27 to 30 August 1991, pp. 186-193
- [2] US Department of Energy Energy Information Administration, "International Energy Outlook 2002" Report No. DOE/EIA 0484 (2001) March 2002
- [3] Glaser, P.E. 1968 "Power from the Sun: Its future", *Science*, 162, 857 (1968)
- [4] DOE 1978 "Satellite power system (SPS) concept development and evaluation program (CDEP) Reference System Report", DOE/ER-0023, October 1978
- [5] *Electric Power from Orbit: A Critique of a Satellite Power System*, National Research Council, National Academy Press, Washington, D.C., 1981
- [6] M. Nagatomo, S. Sasaki, Y. Naruo and V.A. Vanke, "Solar Power Systems (SPS)—investigations at the Institute of Space and Astronautical Science of Japan" *Physics – Uspekhi* **37** (6) 589-599 (1994) Translated by V.L. Savvin, revised by S.P. Harrop from *Uspekhi Fizicheskikh Nauk* **164** (6) 631-641 (1994), http://ufn.ioc.ac.ru/ufn94/ufn94_6/ufn46d.pdf
- [7] M. Nagatomo, *Space Power* **6** 299 (1986) cited in [6]
- [8] R. Akiba and H. Yukota in *Proceedings of the Pacific ISY Conference—A planning Meeting for the International Space Year*, (Kona, Hawaii, 1987) cited in [6]
- [9] David R. Criswell "Overview of the Proposed Lunar-Solar power System", in *WPT-93: First Annual Wireless Power Transmission Conference*, Center for Space Power, Texas A&M University, College Station, Texas PP. 223-231 (1993)
- [10] Harvey Feingold, *et al*, "Space Solar Power—A fresh Look at the Feasibility of Generating Solar Power in Space for Use on Earth": Science Applications International Corporation Report SAIC-97/1005, Science Applications International Corporation, Schaumburg, Illinois, 1997
- [11] Harvey Feingold, *et al*, (1999) "SPACE SOLAR POWER 1998 CONCEPT DEFINITION STUDY", Report Number SAIC-99/1016 Science Applications International Corporation, Schaumburg, Illinois, 1999
- [12] Nobuyuki Kaya, "A New Concept of SPS With a Power Generator/Transmitter of a Sandwich Structure and a Large Solar Collector", *Space Energy and Transportation*, Vol. 1, No. 3, 1996, pp. 205-213
- [13] *Laying the Foundation for Space Solar Power: An Assessment of NASA's Space Solar Power Investment Strategy (2001)*, National Research Council, National Academy Press, Washington, D.C., 2001 <http://books.nap.edu/books/0309075971/html>
- [14] Matthew H. Smith, Richard L. Fork and Spencer T. Cole "Safe delivery of optical power from space" *Optics Express*, **8** (10) 537-546 (2001)

- [15] Henry Harris, personal communication, see also reference 6 in [14]
- [16] Masahiro Mori, "Freeing Gases for Cheap Fuel Cells With Orbiting Laser Cannons" in *SPACE.com* article by Erik Baard http://www.space.com/business/technology/technology/laser_hydrogen_020109 January 9, 2002,
- [17] Richard Dickinson, Unpublished results, 2000
- [18] NASDA Online Space Notes, "Solar-power generation in space: Airship to relay power from space to ground", http://spaceboy.nasda.go.jp/note/Kouso/E/kou106_solar_e.html
- [19] Press Release, ENTECH, Inc. available at <http://www.entechsolar.com>
- [20] R.E. Freeland, G.D. Bilyeu, G.R. Veal and M.M. Mikulas, "Inflatable Deployable Space Structures Technology Summary" IAF-98-1.5.01, 49th International Astronautical Congress, September 28-October 2, 1998, Melbourne, Australia
- [21] D. Cadogan, M.Grahne and M. Mikulas, "Inflatable space Structures: A New Paradigm for Space Structure Design", IAF-98-1.1.02, 49th International Astronautical Congress, September 28-October 2, 1998, Melbourne, Australia
- [22] John C. Mankins, Statement of John C. Mankins, Manager, Advanced Concepts Studies, Office of Space Flight, Before the Subcommittee on Space and Aeronautics, Committee on Science, U.S. House of Representatives, September 7, 2000, http://www.house.gov/science/mankins_090700.htm
- [23] William Whittaker, Peter Staritz, Chris Urmson, "Skyworker: Assembly, Inspection, and Maintenance of SSP Facilities" Presentation to Technical Interchange Meeting 2 December 8, 1999, <http://216.239.51.100/search?q=cache:VbK6CIBbdUgC:www.frc.ri.cmu.edu/projects/skyworker/data/TIM2-Final.ppt+%22space+solar+power%22+robots&hl=en>
- [24] SPACE.com article "NASA's 'Snakebots' Slither to Life", SPACE.com, May 4, 2000, http://www.space.com/news/snakebots_000504.html
- [25] William C. Brown, "The History of Power Transmission by Radio Waves", *IEEE Transactions on Microwave Theory and Techniques*, **32** (9) 1230-1242 (1984)
- [26] Margaret Cheney, *Tesla: Man Out of Time*, Prentice-Hall, Englewood Cliffs, New Jersey, 1981, pp. 164-174
- [27] Hiroshi Matsumoto, "Microwave Power Transmission from Space and Related Nonlinear Plasma Effects" *Space and Radio Science Symposium: 75th Anniversary of URSI*, 26-27 April 1995, Brussels, Belgium, pp. 155-190
- [28] W.C. Brown, "Experimental Airborne Microwave Supported Platform" Tech Rep. RADC-TR-65-188, Contract AF30 (602) 3481, Cec. 1965
- [29] W.C. Brown, "Experiments Involving a Microwave Beam to Power and Position a Helicopter", *IEEE Transactions on Aerospace Electronic Systems*. Vol. AES-5, no. 5, pp 692-702, Sept. 1969
- [30] W.C. Brown, "Electronic and Mechanical Improvement of the Receiving Terminal of a Free-Space Microwave Power Transmission System," NASA Contractor Report CR-135194, Contract No. NAS 3-19722, pp. 51-52, 1977
- [31] Jeff Hecht, *Beam Weapons: The Next Arms Race*, Plenum Press, New York, 1984, pp. 23-25
- [32] Jeff Hecht, *ibid* pp. 3-4
- [33] William C. Brown, "The Electronically Steerable Phased Array Module (ESPAM)" *WPT'95: Second Wireless Power Transmission Conference*, October 16-19, 1995, Kobe, Japan, Abstract 4-1
- [34] Richard Dickinson, Personal communication, 2002
- [35] N. Kaya, Y. Fujino, M. Fujitani and G. Maryniak, "Space Experiments on Microwave Power Transmission", *Proceedings, SPS '97 Conference*, Montréal, Canada, August 24-28, 1997, pg. 249
- [36] H. Matsumoto, *et al* "Microwave Power Transmission Experiment on JEM-EF of International Space Station", *Proceedings, SPS '97 Conference*, Montréal, Canada, August 24-28, 1997, pp. 231-236
- [37] P. Koert and J.T. Cha, (1992) "Millimeter Wave Technology for Space Power Beaming", *IEEE Trans. Microwave Theory Techn.*, Vol. 40, No. 6, pp. 1251-1258, June 1992.
- [38] P. Koert and J.T. Cha, (1993) "35 GHz Rectenna Development", in *WPT-93: First Annual Wireless Power Transmission Conference*, Center for Space Power, Texas A&M University, College Station, Texas PP. 457-466, 1993
- [39] J.O. McSpadden, L. Fan. and K. Chang, (1997) "A High Conversion Efficiency 5.8 GHz Rectenna", in *1997 IEEE MTT-S International Microwave Symposium Digest*, pp. 547-550, 1997
- [40] G. Youn, Y.H. Park, K.H. Kim and Y.C. Rhee, "A Study on the Properties of RF-DC Conversion Efficiency for the Dual-Polarization Rectenna", *Journal of the Iorean Institute of Communication sciences (JKICS)* **25** (3A) 435-442, 2000
- [41] T. Miura, K. Hirayama, N. Shinohara and H. Matsumoto, "Study of High Power Rectennas for Microwave Power Transmission", *IEICE Transactions on communications, Japan*, vol J83-B, 525-533, 2000
- [42] B. Strassner and K. Chang, "5.8 GHz Circular Polarized Rectifying Antenna for Microwave Power Transmission", in *2001 IEEE MTT-S International Microwave Symposium Digest*, pp.1859-1862, 2001
- [43] V. Savvin, "New Possibilities of Cyclotron-wave Converter Improvement", *Proceedings, SPS '97 Conference*, Montréal, Canada, August 24-28, 1997, pp. 187-188

- [44] Yuri A. Budzinski and Serguei V. Bykovski "Cyclotron Wave Converter Development: Experiments, Features and Perspectives", Presented at WPT 2001. La Réunion, France, 2001
- [45] Carlos Algora and Vicente Diaz, "Design and Optimization of Very High Power density Monochromatic GaAs Photovoltaic Cells", *IEEE Transactions of Electron Devices*, **45**, (9), 101, 1998
- [46] Geoffrey A. Landis, and Raj K. Jain, "Approaches to Solar Cell Design for Pulsed Laser Power Receivers" in *WPT-93: First Annual Wireless Power Transmission Conference*, Center for Space Power, Texas A&M University, College Station, Texas PP. 551-564 (1993)
- [47] Raj K. Jain, and Geoffrey A. Landis, "Modeling of High Efficiency Concentrator Solar Cells Under Laser Pulse" in *Laser Power Beaming*, Jack V. Walker, Edward E. Montgomery IV, Editors, Proc. SPIE 2121 pp. 264-268 (1994)
- [48] Raj K. Jain, "Calculated Performance of Indium Phosphide Solar Cells Under Monochromatic Illumination" *IEEE Trans. Electron Dev.*, **40**, pp. 1893-1895 (1993)
- [49] P.A. Iles, "Non-solar photovoltaic Cells" in *Conf. Rec. 21st IEEE Photovoltaic Specialists Conf.*, Kissimmee, FL, May 1990 pp. 420-425
- [50] M.A. Green, J. Zhao, A. Wang, and S.R. Wenham, "45% Efficient Silicon Photovoltaic Cell Under Monochromatic Light", *IEEE Electron Device Lett.*, vol. 13, pp. 317-319 (1992)
- [51] L.C. Olsen, D.A. Huber, G. Dunham, F.W. Addis and N. Anheier, "High Efficiency Monochromatic GaAs Solar Cells" in *Conf. Rec. 22nd IEEE Photovoltaic Specialists Conf.*, Las Vegas, NV, Oct 1991, pp. 419-424
- [52] Mark Henley, Unpublished results, 2001
- [53] Lawrence Livermore National Laboratory, Press Release, 2000
- [54] A. Giesen, cited in Richard L. Fork, Spencer T. Cole, William M. Diffey, Lisa J. Gamble and Andrew S. Keys, "Optical amplifier for space applications", *Optics Express*, **5**, (12) 292-301, 1999
- [55] D. Jenkins, *et al*, "A Solar-Pumped Nd:YAG Laser with a Record efficiency of 4.7 Watt/m² of Primary Mirror Area", *Bulletin of IPS*, **42**, 101, 1996, also see Roland Winston, "Solar-Pumped Lasers" <http://hep.uchicago.edu/solar/laser.html>
- [56] Susumu Sasaki, Yoshihiro Naruo and Makoto Nagatomo, "Engineering Research for Solar Power Satellite SPS 2000", *Proceedings, SPS '97 Conference*, Montréal, Canada, August 24-28, 1997, pp. 73-77
- [57] N. Kaya, H. Matsumoto, H. Kojima, Y. Fujino, and M. Fujita, "Test Projects for Microwave Energy Transmission (MILAX, ISY-METS and Future IPSAT)" in *WPT-93: First Annual Wireless Power Transmission Conference*, Center for Space Power, Texas A&M University, College Station, Texas PP. 245-253 (1993)
- [58] A. Celeste, J.D. Lan Sun Luk, J.P. Chabriat and G. Pignolet, "The Grand-Bassin Case Study: Technical Aspects" *Proceedings, SPS '97 Conference*, Montréal, Canada, August 24-28, 1997, pp. 255-258
- [59] Ralph H. Nansen, "Ground Test Program for Developing Solar Power Satellites", *Space Energy and Transportation*, Vol. 1, No. 3, 1996, pp. 187-194
- [60] Arthur D. Little, Inc., "Responses of Airborne Biota to Microwave Transmission from SPS", *Report to Environmental Protection Agency*, Research Triangle Park, NC 68-02-3278, 1980
- [61] N.E. Gary and B.B. Westerdahl, "Studies of Honey Bees Exposed to 2.45 GHz Continuous-Wave Electromagnetic Energy", University of California, DOE/ER-0095, NTIS, Springfield, VA, 1980
- [62] Hiroshi Murakami, Koji Komiyama, Yoshihiko Kato and Isao Kudo, "Recent Progress in Long-Duration Microwave Exposure Facility", *Proceedings, SPS '97 Conference*, Montréal, Canada, August 24-28, 1997, pp. 279-284
- [63] Mark Henley, Unpublished results, 2001
- [64] S.S. Bharj, *et al* "A Microwave Powered Rover for Space Exploration in the 21st Century", in *WPT-93: First Annual Wireless Power Transmission Conference*, Center for Space Power, Texas A&M University, College Station, Texas PP. 449-455 (1993)
- [65] Brian Erb, *Space Solar Power Newsletter*, vol 4, No. 4, November 2001 http://www.space.gc.ca/csa_sectors/generic_space_tech/expl_prog/whatsnew/2001/nov2001.asp#JAPAN
- [66] Richard Dickinson, Unpublished results, 2001