Developing a First Generation Space Power Technology: An Available Technology, A Needed Power System

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ABSTRACT

We address the potential of delivering electricity to California (or international locations) homes and businesses with energy derived from orbital space power systems. This method of power generation and distribution may be viewed as a precursor to wide-area space power satellites. We consider a small test system, using in-place and readily deployable space assets; and describe the principal and operational capabilities of the proposed project.

(Key Words: space power satellite, electricity generation, space systems, microwave distribution, photovoltaic, energy resources)

INTRODUCTION

Earth-orbiting space power satellite (SPS) platforms can provide expandable and economical options for deregulated electrical power, yet they have not been exploited. Placement of solar conversion facilities in geosynchronous orbits will enable man to start stepping away from the usage of atmospheric-contaminating fossil fuel production of electricity. Moreover, these orbital operations will permit not only the rapid upgrading or augmenting of power production, but also provide impetus to long-term manned orbital complexes and space construction projects.

An experimental SPS prototype can answer three fundamental issues:

(1) *The minimal operational requirements to maintain permanent power reception from space;*

(2) *The required ground effort and orbital support needs for large-scale construction programs; and*

(3) *The ability of man to develop long-term permanent, unmanned structures for civilization enhancement.*

To accomplish its goal, a solar power satellite must not only maintain position in a desired orbital slot, but must also reach an operational level that permits utility reliability on the technology. Until now, failure to meet either condition has held the prospect of solar power satellite systems to the level of a dream.

The challenge of developing a means to deliver space-produced power to ground-based consumers is long-standing. In the book *Solar Power Satellites*, the US Office of Technology

Assessment reviews several proposed methods and conceptual plans, including orbiting mirrors, laser transmission, as well as microwave transfers. More recently, Japan’s Institute of Space and Astronautical Science formulated a planned experiment called SPS 2000. A comprehensive review of current space power ideas was presented during the 1998 Conference on Space Power.

Each concept faces fundamental technological problems. For example, laser beaming of power to Earth is extremely inefficient. While the collection array can deliver 350 watts per square meter (30% efficiency), current laser systems are lucky to convert that energy with more then 21% efficiency. As a secondary problem, the laser energy would provide tropospheric heating, adding to the problematic effects currently seen with rising global temperatures. Reflected sunlight systems generally call for an extremely large tract of land, ranging from 150 to 1000 square miles, for 300 Megawatts as well as the problem of creating an artificial 24-hour day/0-hour night to the affected region.

We are developing a concept, called the First Generation Space Power Satellite, which utilizes readily available technologies. Any system designed for orbital transmission of power to Earth must meet the following criteria:

(1) *Continuous power with near zero maintenance for several years;*

(2) *High efficiency rates for transfer: minimal levels to reach 31% conversion; and*

(3) *High orbital altitude: Geosynchronous orbital levels versus fuel consuming low earth orbits.*

The following sections describe the First Generation SPS concept, its reason for being and expected performance for providing power to Earth.

CURRENT POWER GENERATION IN CALIFORNIA AND ALBERTA, CANADA

California is in a turmoil caused by its dependence on electricity. Consuming an electrical load of 276,000 GW-hours, the state only produces 226,000 GW locally; the remainder is “imported”, from locations throughout the Western US and Canada. Of the locally generated power, only 44% is produced in a manner that doesn’t affect the atmosphere. Table 1 shows the power situation in California, compared to one of the Canadian Provinces. California as a state is the second largest energy market in North America and the fourth largest consumer worldwide. Comparatively speaking, Alberta is a minor player – oddly enough, Alberta is one of the IMPORTERS of energy to California.

Table 1: Electrical Production and Consumption in CA and ALB.

	California, United States		**Alberta, Canada**	
	Current	**Planned/Under Construction**	**Current**	**Planned/Under Construction**
Consumption	(2000) 276,000 GW	(2005) 300,000 GW	(2000) 7,785 MW	(2005) 9,500 MW

Generation	226,000 GW	1,002 GW	9,318 MW	4,408 MW
Deficit (Import)	50,000 GW	72,998 GW	N/A	N/A
Plant Types	**Current Number**	**Current Output**	**Current Number**	**Current Output**
Hydrocarbon/ Vapour Based	459 (45.4%)	126.8 GW	(91%)	8,480 MW
Nuclear	2 (0.2%)	40.5 GW	0 (0%)	0 MW
Environmentally Friendly	550 (54.4%)	59.2 GW	(9%)	839 MW

It should be noted, however, that neither of California's two operating nuclear facilities are operating at more then one-quarter of their rated capability. The current problem of global climate change can be put at the doorstep of the use of solid and hydrocarbons in energy production. The Kyoto agreement mandates the reduction of use of carbon as energy production.

SPS as a technology can reduce the reliance in the long-term on carbon emissions for energy production. The first step is to prove that an SPS can produce energy in geosynchronous orbit and then transmit it to the surface, where it can be converted into electricity. SPS can ameliorate the effects of global climate change by developing an energy source that does not produce gases that produce changes in the earth's atmosphere or produce toxic pollution that can be produced from nuclear reactors. The question is whether large-scale production of energy from orbit can be comparably evaluated versus the cost of new production (both monetary and environmental) on the Earth's surface. When the costs of environmental degradation are factored in and for new production, we believe that this technology is possible when it is ultimately proven capable.

Alberta, like California, has a deregulated utilities industry. However, when Alberta deregulated their utilities they didn't suffer as California did, for several reasons. First, Alberta never required the utilities to sell off their generating systems, whereas California has become increasing aware that forcing the divestiture of power plants was a mistake. Second, California has been importing energy for more then a decade PRIOR to the deregulation; Alberta, with only 10% of California's population, has been exporting energy for as long. Lastly, through judicious use of rate caps, freezes and new construction, Alberta has been much more able to cope with new demands and resource availabilities.

SOLAR/SPACE POWER SATELLITE CONCEPTS

The aerospace community has been using solar collected electricity for nearly half a century (Table 2). Research into increasing the efficiency of this derived power system has been continual, ranging from the types of materials in the cells to how it is manufactured, and even to the physics of how the layers are deposited into place. Using current "state-of-art" solar array materials (triple-junction gallium arsenide), the conversion rate efficiency is rapidly approaching 40%.

Table 2: Solar Power Outputs of Various Space Projects.

Year	Orbital Project	Generated Power
1967	Soyuz Spacecraft	25 watts/m^2
1971	Salyut Space Station	31 watts/m^2
1972	Skylab Orbital Workshop	91 watts/m^2
1984	MIR Space Station	119 watts/m^2
2000	International Space Station	295 watts/m^2
2005*	Space Power Satellite	350 watts/m^2

* Projected

This research has generally attempted to increase the capabilities of solar arrays for small systems, such as the Hughes 600 communications satellites, or the Russian Soyuz spacecraft. When completed, however, the International Space Station will orbit Earth at 200 kilometers with a 110 KW-h energy budget. One hundred ten kilowatt-hours, if beamed to Earth, could power nearly 100 houses or several small businesses and farms.

An orbiting space power system presents serious problems for initial activation:

(1) *The large size and mass of the collection array makes launch system selection difficulties;*

(2) *Requirements need to be met ensuring public safety in the region of the ground collection; and,*

(3) *Adequate means must be made to enable real-time, semi-autonomous guidance and orbital control for the array, so it remains in the sun's line of sight.*

In all, taking all necessary precautions to what is surmountable, to yet another large-scale public works project will add approximately 2.25 tonnes to the SPS mass over a 20-year lifetime.

We propose to develop a small-scale space power system (satellite, control facility and ground receiver system) that may be launched and activated within a five-to-seven year timeframe. The solar panels are each composed of one-meter squares, weighing approximately 1.321 kilograms per panel. These flat sections of gallium arsenide receive 1370 Watts of energy from the sun, and through photochemical action, develop up to 400

Watts of usable energy. Series-parallel cell interconnections will provide a voltage level of 26 VDC across the all array elements.

The key subsystem for array operations is the guidance module. This complex includes solar positioning sensors, a Magneto-Optical telescope and on-board GPS equipment. In order to maintain an alignment with the sun during all phases of orbit, the fine and coarse pointing sun position sensors feed data to a series of attitude rate gyroscopes, which limit the moment of axial drift to the array. The Global Positioning System (GPS) works to control alignment of the SPS in its geosynchronous slot. In all cases, the use of rate control gyroscopes is maximized to reduce reliance and expenditure of cold-gas RCS propellants.

We note that the initial array configuration is adaptable, in that it is capable of having additional elements attached to it for expandability. In this manner, the effective limitation on the Space Power Satellite is the transmitting system.

The conversion of electricity to microwave energy occurs within the Travelling Wave Tube (TWT) section, and is directed to Earth via a reflective dish antenna. Cyclotrons may also be used in this section, given their power handling capabilities.

Ground station activities, monitoring, and control will be performed from a complex attached to the receiving array. This facility, a cross between a “mission control” and a switching station, doesn’t need to be large (roughly 250 square meters would work fine), due to computers and on-board spacecraft systems.

BRINGING ELECTRICITY TO EARTH

In order to deliver solar energy to Earth in a high density and with conversion efficiencies sufficient to be effective, we apply a nested receiving antenna system at ground level. This system receives the multi-megawatt microwave signal (although we are viewing 2.4 GHz as a baseline, we will coordinate the frequency requirements with the FCC and international counterparts), which is down-converted within the receiving elements themselves, and using TWT and/or cyclotron units similar to those aboard the SPS, placed in-phase. This phased energy is stepped down, through transformer activity to a DC voltage level for placement on the Independent System Operator or utility Interties.

Due to safety concerns and Intertie distributions, it is desirable to locate the ground antenna system in a desert location, or other unpopulated area. This comes from the fact that the center point of the receiving array will be subject to power levels of approximately 25 mW/cm^2, which is three times the US standard for continued microwave exposure. Offshore locations are not in a preliminary recommendation for the test satellite and facility, due in part to environmental conditions and a lack of readily available Interties. It is feasible, however, that the test system could be located in any state or country with adequate interest.

SPECIAL CHALLENGES

The technique described above is required to establish conditions for controlled transference of solar energy to ground receiving facilities. They present two identifiable challenges in technology. First, the requisite mass for developing 300 Kilowatts of power, shown in Table 3, exceeds the launch capacity of many current general-purpose launch vehicles. This can be dealt with in two different manners. The first method involves launching the system in multiple segments, and joining the elements together in orbit. The second means of solving this problem is to work with either expendable or reusable heavy lift launch vehicles (such as the Russian Zenit-3SL or the US HLLV).

Table 3: Current Heavy Lift Launch Vehicles.

	Space Transport System-Shuttle (US) ***Reusable***	**Saturn V Rocket (US)** ***Expendable***	**Zenit-3SL Rocket (Russia)** ***Expendable***
Launch Mass	2,029,633 kg	2,916,080 kg	478,390 kg
Mass to LEO	24,400 kg	115,900 kg	13,740 kg
Mass to GEO	5,900 kg	Not developed	5,180 kg
First Stage Thrust	4,440,141 kg-f	3,440,310 kg-f	834,234 kg-f
Second Stage Thrust	2,090,715 kg-f	526,764 kg-f	93,000 kg-f
Propellants	LOH/LOX + solid rocket boosters	Kerosene/LOX + LOH/LOX	Kerosene/LOX
Status	In Operation	Discontinued	In Operation

Second, transmission of 3MW of microwave energy to a predetermined ground site presents special problems associated with the transmitting antenna aperture, beam width, dispersion or footprint, and aiming stability. However, the combined problems are not far beyond reach, as each has been solved as singular issues with other space systems currently in use. This work will consist of finding a commonality in systems design, preferably without sacrificing nominal performance capabilities.

SYSTEM DESIGN

A preliminary design for the First Generation Space Power Satellite has been defined for proposal purposes. The solar collection array, pointing/guidance sensors, and expansion interfaces are located on the “canopy” of the satellite. At the time of deployment, the solar array extends, as well as the antenna, creating an artificial star.

The general locations of the various subsystems are primarily dictated by their necessary function, as well as the secondary systems used for nominal operations. The docking interface, centrally located on the structure, is used to re-supply the attitude control system that maintains the SPS. A Magneto-Optical telescope is used to examine and monitor solar activity, providing warnings of approaching solar flare cycles and sunspot levels. The telescope package serves a dual use function, by also enabling solar physics research without atmospheric interference.

Assuming full function, the SPS internal power grid will average approximately 75 watts of power load, with a potential maximum of 92 watts during re-supply periods. This is a negligible amount versus the overall conversion rate of the satellite.

PROJECT ANALYSIS

We are researching a small-scale prototype unit for deployment to geosynchronous orbit. The First Generation Space Power Satellite will have an orbital lifetime of 20 years, estimating two basic upgrades every 8 years. Under the initial test configuration, the SPS will be brought on-line with 300,000 watts of generating potential; this may be expanded during the first upgrade (or sooner) to 500,000 watts. All internal electronics will be designed to support a 650 KW generating load. The numbers in Table 4 assume nominal re-supply/upgrading activities.

Table 4: SPS Operational Performance Data.

Year	Year Five	Year Seventeen
Orbital Altitude	35,786 kg	35,786 kg
Mass	380,000 kg	680,000 kg
Power	300,000 watts	550,000 watts
Solar Array Size	900 meters^2	1,500 meters^2
Conversion Efficiency	≈ 31%	≈ 40%

We see that the parameters and need stated above more than meet the minimum expectations for initiating a space power complex as outlined above. Therefore, we believe that further work and defining research should be carried out on this very promising technology.

A long-range projection of space-generated power is that eventually after building up sufficient infrastructure in geosynchronous Orbit, it would inevitably be more cost-effective to manufacture the SPS out of material coming from the Moon or from asteroidal material. This is because the amount of energy expended as fuel is less to get a kilogram of material from the asteroid belt to geosynchronous orbit then it is to get the same kilogram of material from the Earth's surface to geosynchronous orbit. This is because of a gravity well existing around planets. After initial investment, in terms of orbital manufacturing capability for the production of the SPS, only a small investment would need to be made on a continued basis, as future space power satellites (SPS) could be manufactured in space. This is comparable to the initial investment that was made by Europe to colonize the Americas. Once the investment was made, the economic system in the Americas was able to manufacture and develop without substantial external investment. Our concept is currently to prove the technology is viable on a pilot level and then development can be made when the technology is proven viable.

PROPOSED RESEARCH AND DEVELOPMENT PLAN

StarGate Research Laboratory (SRL) is developing a proposal for funding to develop a First Generation Space Power Satellite System. We can foresee that the SPS has potentially important near-term applications in local area space-to-ground electrical systems, and in a scaled up version as long-term power source for lunar or interplanetary outpost complex. The technical objectives of this activity are to design and confirm computationally the specifications and applicability of the SPS to current component availability, and especially solar conversion equipment for long-term orbital applications.

As discussed earlier in this paper, the SPS would utilize simultaneous conversion and transmission of electrical energy from solar power. The efficiency of the solar cells is crucial, which is a demonstration as to the factor that this technology is only now maturing. Original concepts, as proposed by P. Glaser in 1968, that would have required collector arrays in the measure of square miles, can now be designed measuring in square meters. Energy from the sun, which radiates an energetic 1.371 KW per square meter at 1 Astronomical Unit, can be partially captured and transferred (via microwave rectification), to locations on Earth for delivery to homes and business as a commercial utility. Questions to be addressed in this research include: Can this conversion efficiency, rated at over 30% on the ground, be a provable and sustainable ratio in orbit? What are the minimal mass requirements to emplace and sustain a geosynchronous SPS system?

Long-term operations would be provided by a maintenance capability derived from current operations in space, such as the STS and International Space Station. Can these orbital assets provide functional operations to the SPS in their current modes? If not, what would be the cost to adapt them, and could this cost be borne fully or partially through other programs in the large-scale space construction realm of activity? The energy derived from the solar conversion will be transmitted to Earth via microwave radio signals. What frequencies, beside 2.4 GHz are available and relatively unaffected by terrestrial interference such as rain, atmospheric water vapor, or other man-made carrier activities? Would the usage of Travelling Wave Tube amplifiers provide better operational performance than Klystron or Cyclotron systems? What is the most stable configuration for transmission?

The prior research into Space Power Systems denotes development of one Megawatt capacity orbital arrays with areas of square miles and ground receiving facilities measuring in the square mile range. Initially, the SRL program seeks to develop a 300 Kilowatt unit with area dimension of approximately one-quarter the Glaser design scale. This can be upgraded to one-half Megawatt while remaining at approximately only one-third the Glaser size. Can a system be designed and put into place that meets all of the original 1968 criteria, at both one-half the 1968 power potential and 1/4 the size?

As indicated above, a small SPS system would be developed for trials. What structural and dynamic interactions are required for the stable placement and operation in orbit?

The high levels of microwave energy at ground level form a functional barrier to daily operations within the perimeter and field of the receiving antenna. In order to achieve the highest level of functionality and performance, these systems must be able to be maintained (repaired, upgraded, and normal system diagnostics, etc.) without shutting the receiver assembly down. What are the functional design requirements for the ground rectenna, to include methods for dynamic manipulation of receiving elements, systems and component configurations, while working inside Federal OSHA regulations regarding hazardous microwave environments? What types of simple protection schemes can be put in-place, as opposed to costly preventative measures? Can underground switching and rectifying equipment be used more efficiently then aboveground installations?

The process of conversion of solar energy is repeatable, by a network of satellites, accompanied by a similar network of ground facilities, or by satellites multiplexing to a limited number of ground stations. Systems designed with capacities of less then 500 kilowatts generational capability can be readily employed with current technology levels. Allowing for production lead times, systems could be orbited and brought on-line within a decade. Because the need for electricity is rapidly outstripping the current and planned production capabilities for electrical facilities, the SRL First Generation Space Power Satellite System can be both economical and achievable, making it an ideal near-term or long-term power system. Unlike other current ground-based power plant concepts used for terrestrial energy production, the SPS system doesn’t emit atmospheric pollutants, require cost-variable fuel sources or depleting resources, nor does it risk groundwater contamination from core breaches. The SPS open architecture and configuration could make the system widely available to global power networks as well as provide impetus to the possibility of large-scale space construction projects and lunar resource utilization.

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