Space Solar Power Proposal

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Introduction

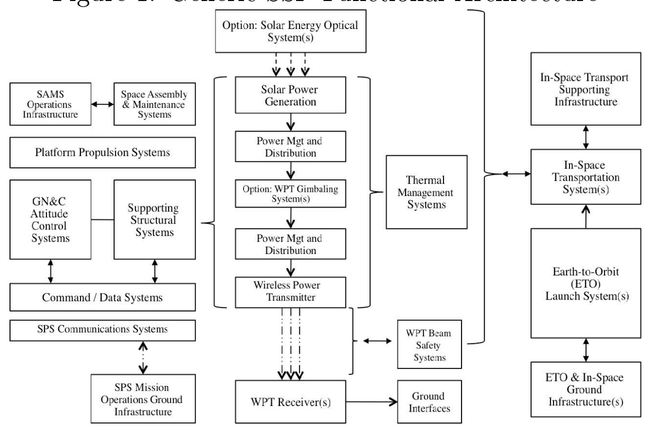
In one of the most ambitious energy projects to date, ARE Enterprises proposes a novel space solar power system to supplement existing terrestrial power with the reliable and clean energy from the sun. The initial system of eight downlink sites is expected to deliver power to the electric power grids of SolarMax Energy Consortium by July 2025 with four of those sites located in the United States and an additional four sites in other host nations. By July 2028, an additional eight sites worldwide, for a total of 16 downlink sites, shall deliver power to customers from our proposed space solar power system.

Overview

A space solar power system is one of the most complex and ambitious systems ever attempted. To consider such a system, it is useful to describe it by the functional architecture given by Figure1 proposed by the International Academy of Astronautics (IAA) Study of Space Solar Power (SSP)[8]. Each of these major functional blocks is presented in turn in this proposal.

The system proposed is based upon transmitting 5 MW of power to the grid from each orbiting satellite with a system of 1000 satellites for each downlink site. The idea is to use large numbers of cheaper satellites to minimize problems given that some satellites will fail. The health and environmental concerns drive the maximum power that can safely delivered to the grid from each satellite. Analysis performed in a previous 1979 SSP Reference System, with a similar system target power capacity of 5 GW, estimated exposure to be 250 W/m^2 above the rectenna center and less than 0.1 W/m^2 15 km from that center. The ANSI/IEEE standard for maximum permissible human exposure is 81.6 W/m^2averaged over six minutes and 16.3 W/m^2 averaged over 30 minutes. Clearly the space above rectenna center would have to be an exclusion zone for all but necessary maintenance workers to meet the standard. Studies have also shown that migratory birds, flying above the rectenna, might suffer disruption in their flying paths and also may suffer heat stress, so there may need to be additional measures such as noise makers in place to discourage wildlife from crossing the main beam area[7].

Figure 1: Generic SSP Functional Architecture



Earth to Orbit

ARE Enterprises proposes a SSP system in geostationary orbit where the distance from transmitter to the receiver is 35,786,000 meters not counting an additional distance that is dependent on the latitude of the receiver as compared to the equator. Other orbits were considered, but recent technological advances in propulsion technology, and the disadvantages of the other orbits favor the geostationary orbit. A recent trade study whose results were delivered at the International Space Development Conference in 2008 from the Boeing Company and NASA highlights the options for various SSP orbital configurations[4].

Low Earth orbit (LEO) is attractive since it requires a smaller rectenna and it would be easier to maintain and assemble, but the satellite is only in view for minutes each orbit. The receiver and/or the transmitter would have to be designed so that beam would be steered continuously, resulting in power losses in a practical system due to that steering. Although smaller in size than in other orbits, additional rectennas would be needed to receive the beam as it swept across the Earth's surface. Despite those additional rectennas, the satellite would still have a relatively low duty cycle in terms of the time it is actively contributing to the electrical grid. Furthermore, health and environmental concerns would likely cause large exclusion zones due to the need to minimize exposure to the main lobe of the beam. LEO also has more atmospheric drag as compared to other orbits, and that effect would increase station keeping costs. The additional debris in LEO also poses an hazard that could interfere with system reliability.

Middle Earth orbit (MEO) has some of the advantages of LEO, but also has some complications that limit its usefulness. MEO orbit still requires beam steering, but it can cause visibility problems to the receiver depending on the inclination of the orbit. Highly inclined orbits have higher launch costs, but they can better serve the high latitude locations.

In contrast geostationary orbit provides relative simplicity since it does not require beam steering and thus the fixed location of the beam is more amenable to public acceptance given health and environmental considerations. This consistency outweighs the additional diameter of the rectennas as compared to other orbits. Furthermore, some of the advantages of LEO can be realized in the geostationary case given recent advances in propulsion technology. GEO orbit is expected to allow

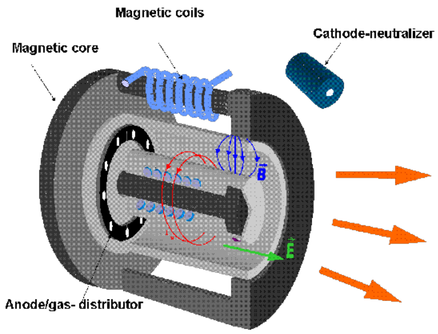


Figure 2: Hall thruster concept for transporting SSP from LEO to GEO

the SSP satellites to deliver power to the grid over 99% of the time with only about an hour of service interruption on the spring and fall equinoxes when the satellites fall in the path of the Earth's shadow.

The Falcon Heavy Launch System by SpaceX would launch all payloads into a geosynchronous transfer orbit using two-stage-to-orbit vehicles that are powered by liquid oxygen and kerosene (RP-1) propellants. In this way 19,000 kilograms (42,000 lb) can be delivered to geostationary transfer orbit, where Hall thrusters can deliver the satellite into geostationary orbit. This launch system is expected to be available no later than 2014 with a cost between $80 and $125 million USD[3]. Falcon Heavy was selected since "Falcon Heavy will carry more payload to orbit or escape velocity than any vehicle in history, apart from the Saturn V moon rocket, which was decommissioned after the Apollo program. This opens a new world of capability for both government and commercial space missions," according to Elon Musk CEO and chief rocket designer at SpaceX.

In Space Transportation System

The SSP satellite would be delivered to LEO by a conventional rocket, but ion thrusters would deliver the payload to GEO. According to Steve Olsen of Glenn Research Center, advanced electric propulsion devices like Hall thrusters can deliver a factor of five times the payload to GEO as compared to biprop and cryogenic biprop thrusters by reducing the need to launch and carry heavy propellant. Unlike traditional chemical rockets, Hall thrusters eject plasma exhaust, and that plasma can obtain higher speeds than traditional fuels. Further advances in drive technology could allow Hall thrusters to have an even greater advantage. Direct-power drive from solar arrays may allow for 13-15 metric tons of payload for a 20 ton launch as compared with a mere 2 ton payload for conventional chemical propulsion. Xenon fuel is the default choice currently, but additional research for lighter fuels such as krypton and noble gas mixtures is ongoing and may reduce the propellant mass even more during the proposed contract period. Figure 2 shows an illustration of the proposed Hall thruster[1]. The Hall thruster is expected to take 120-230 days from LEO to reach GEO, and it provides 50 kW power from an attached 200 kW solar array. The thrusters would be then be used for station keeping to maintain proper satellite orbit.

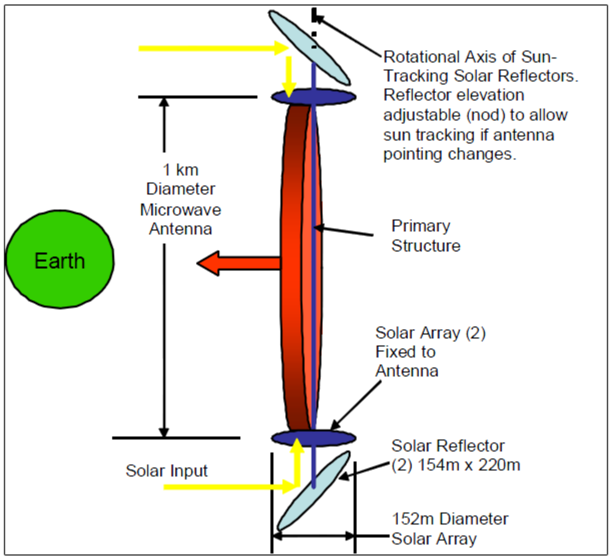


Figure 3: SSP satellite system for 5 MW power generation

Solar Power Generation

The overall satellite design is based upon a concept originally proposed by Naval Research Laboratory and expanded upon by ARE Enterprises. This basic design is a 5 MW satellite that features a 1 km diameter antenna with sun-tracking reflectors that have adjustable elevation angles. This configuration, with the solar arrays directly atop a primary truss structure, minimizes the electrical cabling and helps reduce the mass that needs to reach orbit. Each satellite is equipped with two solar arrays and each are 18,300 m^2 or 152 m in diameter. Figure 3 shows a sketch of the proposed system. The satellite is oriented in orbit so that the truss runs in a north-south direction.

Besides minimizing needed cabling, this design also allows the solar array to radiate heat on both sides of the array, just as in conventionally solar powered satellites. This approach to thermal management is key to the success of the SSP, despite the added mass as compared with alternative designs. Another competing proposal, referred to as the SPS Type III: Sandwich-Type SSP Concept has received attention, but the thermal management problem is not solved for this configuration[5]. The "sandwich" module design places a layer of photovoltaic cells on top of a DC-RF conversion layer which itself sits on top of an antenna resulting in a severe concentration of unwanted heat.

In this proposed system, the solar array includes triple junction (3J) concentrating solar cells. The cells can aggregate sunlight up to several hundred times its standard concentration to provide for increased efficiency. The triple junction cells are optimized to maximize the electrical energy output by matching different band gap materials to a certain band of incoming radiation. Currently available triple junction cells (typically GaInP/GaAs/Ge) have efficiencies of nearly 30%, and triple junction cells under development (GaInP/GaAs/InGaAs) are believed to have efficiencies of 33%.[6]. For a concentrating system the limiting factor for efficiency may be the optical concentration factor and the ability to dissipate excess thermal radiation under these conditions. Alternative cell technologies like thin film or organic cells show promise, but their low nominal efficiencies of about 10% would require much larger arrays and reflectors, so the triple junction cells are preferred.

Power Management and Distribution

The power distribution system would be 60 times the capacity of the largest system deployed to date, the International Space Station (ISS) which currently delivers 84 kW. The plan would be to increase the voltage of the solar arrays to between 500-1000 V. Currently Entech has 600 V solar concentrator systems, but more testing is needed to determine the optimal settings since these large voltage introduce proportionally large currents that waste energy in the form of heat. During the equinox eclipse periods, the satellite may also need large batteries to supply power to the electronics, although the batteries are considered optional in this proposal pending cost and weight constraints[6].

Wireless Power Transmitter

To convert the electrical energy from DC to radio frequency, the system would use a phased array with lower power magnetron transmitters operating at the 5.8 GHz ISM band. The magnetrons are phase-locked with 5 kW output power and efficiencies of 85.5%. The magnetrons operate at 6 kV and dissipates the waste heat at 350 °C with a pyrolytic graphite thermal radiator. Magnetrons are favored over competing technology like klystron transmitters due to several factors including lower cost, lower voltage operation, small form factor, and longer projected lifetime[6]. The 5.8 GHz band is chosen to minimize the required size of the receiving rectenna while at the same time adopting the relative mature 5.8 GHz RF technology where research and development is abundant. The 5.8 GHz band represents the most reasonable choice given the more severe atmospheric attenuation at higher frequencies as shown in Figure 4.

Th phased array would be approximately 10-dB Gaussian tapered by having ten distinct power levels, where each of the center elements radiate 59 W, and the edge elements radiate 5.9 W. The Gaussian distribution is chosen since it has the highest beam coupling efficiency from transmitter to receiver [8].

Wireless Power Receiver

The wireless power receiver, referred to as a rectenna, to capture energy at 5.8 GHz is based on the past fifty years of research with rectennas. W.C. Brown launched the field of wireless power transfer with his work at Raytheon in the 1960's on aluminum bar-type antennas at 2.45 GHz that were over 90% efficient, and modern practical rectenna designs for SSP at 5.8 GHz have projected efficiencies over about 80%.

The diode is the most critical component for high efficiency and the diode is also the main source of loss in the rectenna system. The rectenna would contain GaAs Schottky barrier diodes that have demonstrated efficiencies of over 80%. The breakdown voltage of the diode is typically

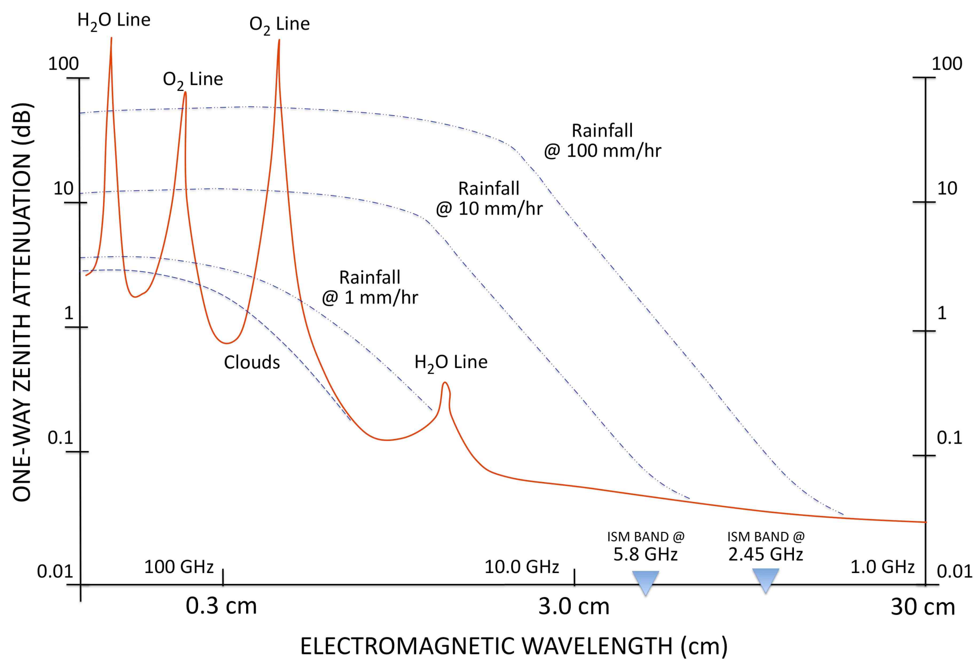


Figure 4: Atmospheric attenuation at various frequencies

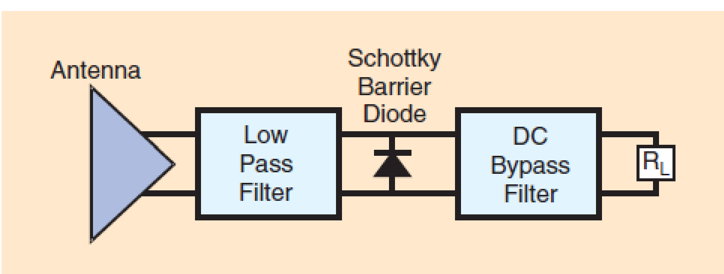


Figure 5: Basic rectenna components

a limiting factor in its ability to handle power. Since the diode also has the potential to radiate harmonics of the received frequency, a frequency selective surface acts as a filter between antenna and the diode. Each antenna element in the array could then be a rectangular patch antenna to maximize efficiency as compared to circular patch antennas[9].

The size of the rectenna is generally governed by the following relationship.

$D_R \approx 2.44\frac{R}{D_t}\lambda$

where $D_R$is the diameter of the receiver, R is the separation distance of the receiver and transmitter, $\lambda$is the wavelength, and $D_t$is the diameter of the transmitting antenna. The factor of 2.44 in the relationship is also referred to as τ and corresponds to a beam coupling efficiency of greater than 96-97%. This is equivalent to the physics of diffraction limited optics in imaging, where planar light is focused into an Airy disk with a diameter to the first null. For this proposal the minimum diameter of the rectenna if it were at the equator, is

$$\begin{aligned} D_R &= 2.44\frac{35,786,000}{1000}0.051688 \\ &= 4.513 \quad \text{kilometers} \end{aligned}$$

The system should use circularly polarized waves for maximum flexibility to avoid losses due to Faraday rotation and to avoid the need to maintain strict polarization from transmitter to receiver.

Beam Safety System

In order to control the beam and ensure it stays pointed at the intended receiver, the rectenna emits a pilot signal that is received at each portion of the transmitter array. This pilot signal is compared to a reference pilot signal on the satellite. Should a phase difference exist when the incoming pilot signal and the reference signal, the signal is then phase conjugated and fed back into the control circuitry for the DC-RF converter. Without the pilot signal, the transmitter will dephase the power beam at that portion of the transmitting phase array and peak power will fall proportionally.

SSP Communication System

For command and control of the SSP satellite, a C-band communications link at should be used. The up-link frequency is 4 GHz and the downlink frequency is at 6 GHz. These frequencies are typical for conventional satellite communications. The bandwidth of the link does not need to be high relative to other digital applications, so higher bands such as Ku-band (12-18 GHz) are not needed. The lower frequency also experiences less attenuation with precipitation.

The data is modulated onto the carrier with $\pi/4$ differential phase-shift keying since this modulation works well to combat phase rotation errors. Error correction is provided by turbo codes. CDMA would be used to provide communications channel access for each satellite.

Onboard the satellite a center fed dish antenna of radius10λor 0.75 meters would serve as the main antenna to receive the commands from the Earth station. A similar antenna would transmit to the ground. High gain transmit and receive antennas would be at each ground station as well. Given that the SSP satellite is relatively large, the large radius 10λ antennas are preferred due to

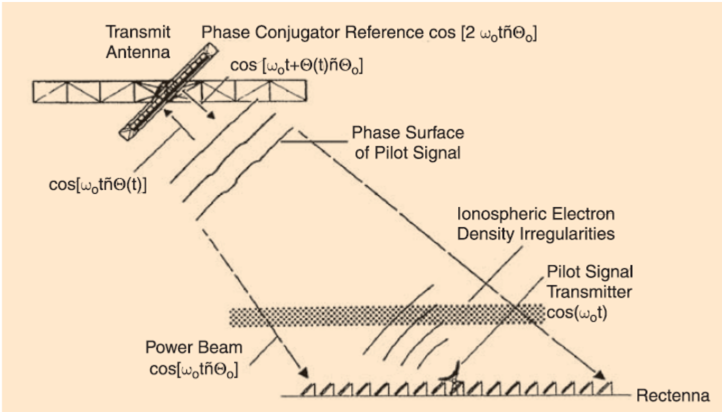


Figure 6: Beam control for proposed rectenna

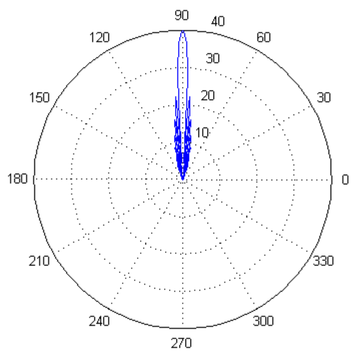


Figure 7: Radiation pattern of radius 10λdish antenna with no tapering

their superior gain as compared with smaller radius5λantennas. With no tapering the radiation pattern of the antenna would resemble Figure 7. The relatively narrow beam width should not pose a problem since the satellite is expected to maintain correction orientation for power transfer. A backup lower gain omnidirectional antenna would serve as a communications link in the event the satellite boresight is pointed elsewhere.

Cost and Schedule

As a basis for system cost, ARE Enterprises is using estimates originally released by Spaceworks Enterprises Inc, a commercial company, in a presentation entitled “First Revenue Satellite Financial Analysis”. The estimates provide a break down of mass for each component of the satellite and total cost estimate for the satellite itself given the LEO to GEO transfer approach previously discussed[2].

Table 8 – Mass Allocations, 5-MW SBSP System, LEO to GEO Transfer

Allocation	Total Mass (kg)	Comments/Basis
Attitude Control	50	Based on Upper Stage
Command & Data Handling	50	Based on Upper Stage
Communications	100	Based on Upper Stage
Mechanisms	500	
Energy Collection	20,000	250 W/Kg
Transmission Payload	10,000	TBD
Power Distribution & Wire Harness	704	Al Wire 1.4 kg/100m2 for 36000 m2
Thermal	300	3 large pump loop systems
Misc. Mass/ Margin	100	Estimate
Total Minus Propulsion and Structure	31804	Total of Non-Scaleable Subsystems
Propellant	20,000	LEO to GEO Transfer Plus 10 Yrs NS-EW GEO Station Keeping, 6000 m/s
Propulsion	2,200	Propulsion Dry Mass
Structure	5,400	Assume 10% structure
Total Space Vehicle	59404	

Figure 8: Mass for each component of 5 MW SSP satellite

Naval Research Lab (NRL) Space Solar Power (SSP) 5 MW system

Item	DDT&E Cost (in $M, FY2010)	Acquisition Cost (in $M, FY2010)	Notes
Technology Development (to TRL 6)	**$0.0**	**$0.0**	Assumed to be 0
Phase A/B	**$60.1**	**$18.4**	3% of total main hardware
TOTAL MAIN HARDWARE	**$2002.8**	**$612.3**	
Spacecraft Bus	$982.6	$285.4	
Transmission	$518.9	$192.9	
Systems Integration	$501.3	$134.0	
TOTAL WRAPS	**$936.2**	**$288.5**	
Fee	$207.2	$63.8	
Program Support	$228.0	$70.2	
Contingency	$501.6	$154.5	
GROUND SYSTEM	**$20.0**	**$15.0**	Estimate
TOTAL	**$3,109.1**	**$1,546.2**	

Figure 9: Budget for each development phase and component

Figure 8 shows the mass of each component.

In Figure 9 the budget for the development and acquisition is shown for each part of the SSP system. Using these estimates, the total system costs are shown in Figure 10. The break even price per kW-hr is $0.157 over a SSP satellite lifetime of 30 years. Launches would start in 2015 and occur over the next 10 years with about 2500 launches every year. It is assumed that economies of scale are in place with a large number of satellites and launches. First the launch cost is based upon $100/lb since we are near the 3162 flights per year if were are willing to compress the launches slightly closer in time or if we are willing to build the second 8 downlink sites and their supporting constellation of satellites concurrently. Secondly, the remaining satellites DDT&E and Acquisition cost is assumed to be a combined $200 million per satellite which is based upon the fact that the cost to mass produce and acquire the remaining satellites includes only the cost of the physical hardware, fuel, assembly, and transport to a launch location. The next 8 downlink sites would follow the same price curve as the first 8 and the locations would be determined by market conditions.

Costs and Figures for SSP System	Explanation
59,400	kg per satellite
8,000	satellites
19,000	kg per launch in Falcon Heavy
25,263	launches for initial 8000 5 MW satellites
$44,555,555,556	launch cost for all satellites at $100/lb
$803,009,000,000	DDT&E cost for 8000 satellites
$801,446,200,000	Acquistion cost for 8000 satellites
$1,649,010,755,556	Total cost to build and launch 8000 satellites
40	MW power for 8000 5 MW satellites
350,400,000,000	kW-hr power from 8000 satellites each year
$0.157	per kW-hr assuming an operational life of 30 years for each satellite

Figure 10: Total system cost breakdown with cost per kW hr

References

[1] What is a hall thruster?, December 2011.

[2] John R. Olds A. C. Charania and Dominic Depasquale. Operational demonstration of space solar power (ssp): Economic analysis of a first revenue satellite (frs), 2011.

[3] Kirstin Brost. Spacex announces launch date for the world's most powerful rocket, April 2011.

[4] M. Henley, S. Potter, J. Howell, and J. Mankins. Wireless power transmission options for space solar power. In *International Astronautical Congress*, 2002.

[5] P. Jaffe, J. Pasour, M. Gonzalez, S. Spencer, M. Nurnberger, J. Dunay, M. Scherr, and P. Jenkins. Sandwich module development for space solar power.

[6] W. Neil et al. Johnson. Space-based solar power: Possible defense applications and opportunities for nrl contributions. Technical report, Naval Research Laboratory, 4555 Overlook Ave., SW, Washington, DC 20375-5320, October 2009.

[7] J.C. Lin. Space solar-power stations, wireless power transmissions, and biological implications. *Microwave Magazine, IEEE*, 3(1):36 –42, mar 2002.

[8] John C. Mankins. The first international assessment of space solar power: Opportunities, issues and potential pathways forward, 2011.

[9] L.M. Tan. Efficient rectenna design for wireless power transmission for mav applications. Technical report, DTIC Document, 2005.