Space Solar Power by

SOLAR VISion

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Abstract

Space Solar Power (SSP) is the design of providing power to the earth via solar energy collected in space. The main way this differs from terrestrial solar power systems is the Photovoltaic (PV) collectors are positioned in space as opposed to the surface of the earth. Once the energy of the sun is collected in space, it is converted to Radio Frequency (RF) energy and transmitted down to rectifying antennas, also known as Rectennas, positioned strategically on earth for distribution to the electric grid. This proposal comes with a vast set of advantages as well as a new set of challenges for the energy and space industry, many of which will be discussed in this technical report.

Introduction

This International Statement of Work (ISOW) describes the design and implementation of the SOLAR VISion program which will fully integrate a Space Based Solar Power System in compliance with the SolarMax Request For Proposal (RFP). One would need a photovoltaic panel 43 m^2 on earth to produce the same amount of electricity of a 1 m^2 PV panel that is placed in space strengthening the case for space solar power. This is due to the fact that the power received at the outer edge of the atmosphere is 1360 W/m^2. (Komerath, 2011). In space, where clouds and night don't exist, power generation is constant with the exception of short periods of eclipse.

Advantages to using the SOLAR VISion innovative design are:

- Limitless, clean, safe solar power to the world.
- Independence from foreign energy
- Efficient utilization of Satellite assembly time and travel to orbit.
- Compatible with various launch & power distribution methods.

Initially eight SOLAR VISion Satellites will supply eight downlinks to provide power to the eight rectenna sites defined by the Solar Max Energy Consortium. By July 2028, three years after the first 8 have been activated, an additional 8 satellites will be launched and connected to the network. The eight rectenna sites are listed below.

1. West Virginia Mountaintop site for PJM Interconnection - 19¢ per kWh. 39 degrees North Latitude.
2. South Texas site for ERCOT Interconnect - 11¢ per kWh. 27 degrees North Latitude.
3. South Eastern Power Administration (SEPA) Interconnect in South Georgia - 12¢ per kWh. 31 degrees North Latitude.
4. Northern Mexico (Baja California Norte) site for CAISO Interconnect - 20¢ per kWh. 31 degrees North Latitude.
5. Colombia, Ecuador, Peru Interconnect - 11¢ per kWh. 2 degrees South Latitude.
6. Japan - 22¢ per kWh. 31 degrees North Latitude.
7. Central European feed. - 26¢ per kWh. 40 degrees North Latitude.
8. Myanmar (Burma) site for China (Southern Power Grid) and India - 11¢ per kWh. 25 degrees North Latitude.

Launch Systems

The primary means of SOLAR VISions satellites transportation into orbit will be reusable launch vehicles currently under design by Space Exploration Technologies Company, also known as SpaceX. It is estimated that Generation 2 launch vehicles will be able to deliver freight to a Geostationary Earth Orbit (GEO) at $220/kg. This is predicted to be achievable once launch rates exceed 3,162 flights per year. The Falcon 9 launch vehicle can deliver 10,450 kg to Low Earth Orbit (LEO) and around 4,500 kg to Geosynchronous Transfer Orbit (GTO) (Falcon 9 Overview: Performance). With the total weight of each satellite at 430,000kg, 42 launches would be required to put a satellite into LEO and 96 for GTO. The continual development in this technology area by SpaceX is a critical performance parameter as launch cost is one of the primary inhibitors of any space solar power system.

Through a joint venture with SolEvator, SOLAR VISion is also under development of a solar powered space elevator concept being designed to lift payloads into space without the use of rockets. Using boron nitride nanotube based materials, chosen for their high strength to weight ratio, radiation shielding properties, thermal and chemical stability, to form an orbital tether between earth and Geostationary Earth Orbit. The design calls for the initial space solar satellite to be launched by conventional means to form the counterweight of the tether in space. Post deployment and initial assembly, the solar satellite will begin to provide power for the lifting mechanism. The remaining satellites and support equipment will be transported to the GEO transfer orbit by these means. The space solar power satellite variant under consideration for development using this method can be designed using larger arrays and photovoltaics since weight would no longer be the limiting factor to reaching orbit. This program is early in the design phase and is being considered as an alternative method to the Falcon 9 launch vehicles.

Since weight of the payload being launched into space is proportional to the cost it is imperative the satellite subsystems be discussed to understand where the weight comes from and why SOLAR VISion is exceeding in providing low weight solutions

Subsystem Design

The main subsystems aboard SOLAR VISion satellites are Power, Attitude and Orbit Control, Thermal Control, Transmission Antenna and the Photovoltaic Array subsystems.

<u>Photovoltaic Array</u> – Thin film photovoltaics will be used to generate the solar power on board the satellite. Thin film technology is one hundredth as thick as regular crystalline PV resulting in a total weight reduction for the design. SOLAR VISion has contracted out Suntech Power to produce the solar cells for this program. The photovoltaic arrays produced by Suntech can provide a total of 10 GW power output from two PV arrays each 3 km across. Space qualified thin-film cells provide 16.8 kw/kg which puts the total weight of a satellite PV at $5.95 * 10^5$ kg.

Power Subsystem – System power necessary for the main satellites functions will be derived from the solar cells. This is considered to be the most efficient way of providing the power needed to accomplish the tasks of the satellite. Radioisotope Thermal Generators (RTGs) will be used to generate energy and provide power to the subsystems during launch, initial installation and for the short periods of time when the satellite is not in direct sunlight (due to the nature of the orbit chosen, this will only occur twice a year for a very brief period of time - Details of the orbit are discussed below).

Attitude & Orbit Control – Over time natural phenomenon such as orbital forcing and perturbations will pull the satellites out of the desired orbit. This forcing results in Eccentricity, Precession and Obliquity variations. In order to overcome these forces our design implements Momentum Wheels which provides reliable and high power station keeping for all of SOLAR VISion's satellites.

Thermal Control – The temperature range for a satellite in GEO is -171 C to 108 C (New Process for Space Qualified Electronic Components , 2011). Cooling fins, heatsinks and radiators will be employed as thermal control for the electronic devices.

Transmission Antenna – Active Electronically Scanned Arrays (AESA) have been chosen as the antennae for this program. The advantages of using AESA include high jamming resistance, the ability to operate at various frequencies and the increased reliability as single failures will not fail the operation of the system as a whole. The space transmitting antenna diameter is 1.5 km. From the equation below, the half power beam width is calculated to be .002 radians.

$$\theta_{HPBW} = \frac{\lambda}{D_1 \pi}\sqrt{33{,}000}$$

Orbital Parameters

The final orbit chosen for the satellites of the SOLAR VISion program is the Geostationary Earth Orbit at 36,000km above the earth's equator. To the Rectennas on the ground, the satellites will appear to be motionless at a fixed position in the sky at all times. This eliminates the need for steering mechanisms on the antennas, dynamic and intermittent beam pointing. The satellites solar cells will maintain in direct sunlight throughout the year with the exception of two brief periods of eclipse. The period that a given satellite will be in the earth's shadow is 75 minutes per night during the spring and fall equinox, which equates to less than 1% of the year. These benefits of a GEO satellite orbit outweigh the design challenges which include increased receiver size on the ground of up to 18 times (Komerath, 2011), increased transmit power requirements and increased energy to orbit.

Launching a satellite into GEO orbit is a costly expenditure for current and future launch systems. SOLAR VISion satellites will be launched into a Low Earth Orbit (LEO) significantly reducing launch costs. From the Launch Systems section we see that this would reduce launch costs by 50%. Once in LEO, the satellite will perform a Hohmann Geostationary Transfer Orbit to reach GEO. For a satellite orbiting the earth, the total energy of the body is half the potential energy at the semi-major axis, a. Since the total energy of a body is equal to the sum of its kinetic and potential energies we get the relationship shown below.

$$E = \frac{-GMm}{2a} = \frac{1}{2}mv^2$$

From the equation above the change in velocity required for the satellite to transfer from the circular LEO to an elliptical orbit and then change from the elliptical orbit back to a circular one at the higher altitude is calculated as follows:

$$\Delta v_1 = \sqrt{\frac{\mu}{r_1}}\left(\sqrt{\frac{2r_2}{r_1+r_2}} - 1\right) = 5.32\frac{km}{s}$$

$$\Delta v_2 = \sqrt{\frac{\mu}{r_2}}\left(1 - \sqrt{\frac{2r_1}{r_1 + r_2}}\right) = 7.11\frac{km}{s}$$

$$\Delta v_T = \Delta v_1 + \Delta v_2 = 12.43\frac{km}{s}$$

The time required to complete the Hohmann transfer and move each satellite from LEO to GEO is given by:

$$t_H = \pi\sqrt{\frac{(r_1 + r_2)^3}{8\mu}} = 13032s$$

Figure 1 below illustrates the geometry of this Hohmann transfer maneuver (Minimum Energy Transfer Orbits).

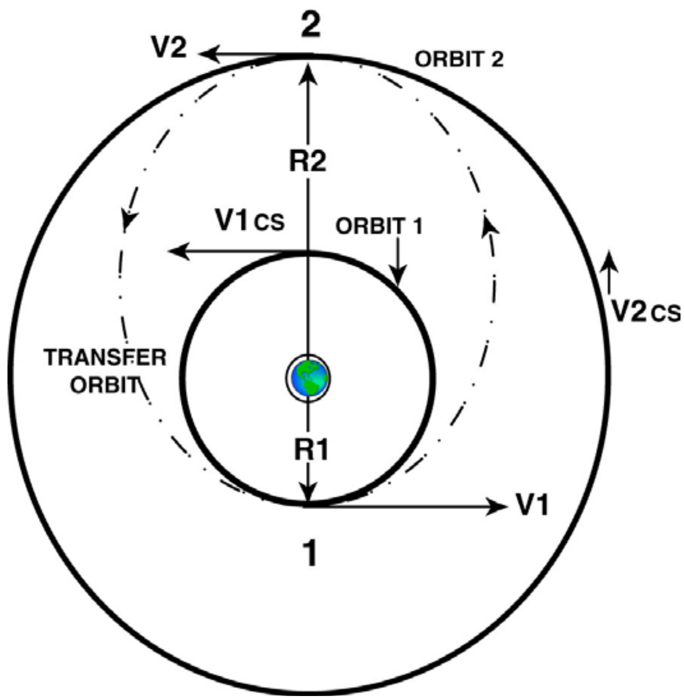

Figure 1 Geometry of a Minimum Energy Transfer Orbit

Microwave Power & Communications Systems

As we have discussed earlier in the report, the energy must go though a few technically challenging transformations before it can be delivered to the grid and used by the end user. One of the most important parameters to a successful Space Solar Power system is the beaming distance and frequency. Several beam frequencies were considered in our design. First, lasers were considered. The benefits to using a laser would be the ability to manufacture realistic sized transmit and receive antennas which is a function of wavelength. Increased immunity from atmospheric effects is another benefit of using lasers. Some of the disadvantages of laser use for SSP are it is dangerous, it is forbid by international space treaties and it is inefficient. Second, millimeter waves were analyzed. While they show great potential in receiving up to 80% of the beam power at our distances and aiding in reducing antenna size – millimeter waves show heavy losses through atmospheric effects such as rain and fog. From the figure below we could infer heavy dropouts during periods of extended rain or fog (Komerath, 2011).

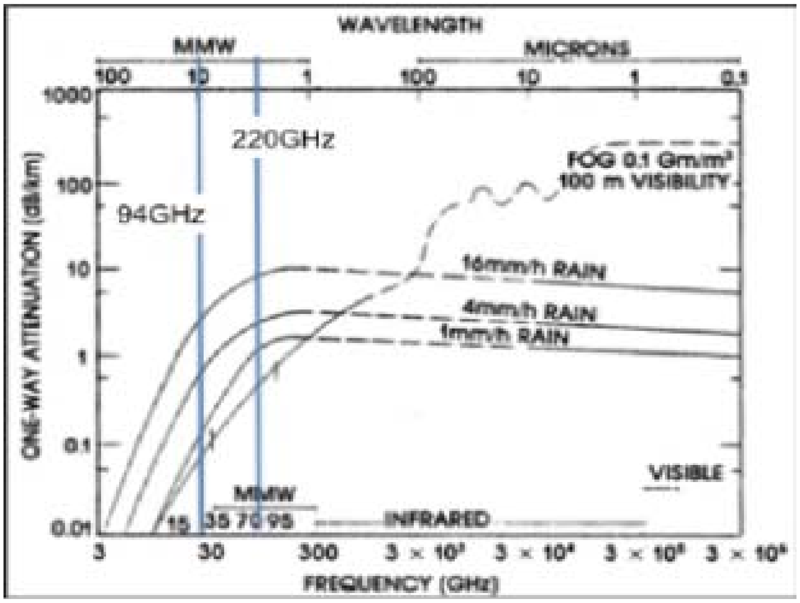

Figure 2 Impact of Rain & Fog on Millimeter Wave Regime

In order to achieve a relatively tight beam and small antennas while maintaining the ability to transmit in all weather, SOLAR VISion determined the optimal operating frequency to be 5.8 GHz. This frequency should produce minimal effects on atmospheric heating, existing satellites & aircraft that may pass through the beam of personnel who happen to be near the beam as it is well within the exposure limits. Recall from the Orbital Parameters section the beaming distance will be near 36,000 km (depending on exact position in orbit and which rectenna site it is beaming to).

System Noise – To calculate the Additive White Gaussian Noise (AWGN) of our communications link we make the following assumptions: the physical noise temperature of the system is 200k.

$$P_N = BKT_{phy} = 2.76 * 10^{-13}\ W$$

Transmitted Power – To guarantee a received power of 1 GW at the rectenna the transmit power can be derived from the linear power budget equation below to be:

$$P_T = P_R \frac{(4\pi r)^2}{G_T G_R \lambda^2} = 51\ \text{GW}$$

Carrier-to-Noise Ration (CNR) – The carrier to noise ration of the system is defined by:

$$CNR = \frac{P_T G_T G_R \lambda^2}{(4\pi r)^2 k T_{sys} B} = .24$$

Rain Attenuation – Rain attenuation is calculated for the rectenna located in the city with the worst anticipated rain rate. Both the South Texas site at ERCOT and the South Georgia site at SEPA have rain rate intensities in the k region. We wish to calculate worst case rain attenuation and will use R=100$^{mm}/_{hr}$, α = 1.2 (horizontally polarized), and k=.00175. (Pratt, 2003)

$$A = \gamma_R L_{eff} = .1104$$

Where $\gamma_R = kR^{\alpha} = 0.0011$ & $L_{eff} = \frac{h_R - h_S}{sin\theta_{el}} = 1000km$

Earth Station Collector Design

The rectenna design will divide the power received into five blocks for distribution to the power grid. Since the transmitting antenna is 1.5 km in diameter, the earth station antenna is calculated from the equation below to be 1.24 km.

$$D_2 = \frac{\lambda\, \mathrm{r}}{D_{\,1}} = 1241\, m$$

The earth station antenna will have a cassegrain reflector to focus the power beam. The Rayleigh Criterion defines the standard deviation of the surface roughness to be $\sigma_n > 6.4 * 10^{-3}\, m$.

$$\sigma_n > {}^{\lambda}/_{8}$$

Resiliency of Electronics

To aid in maintenance and increase lifetime, the satellites will be built with robotic servicing in mind. For the points of failure and routine maintenance identified, SOLAR VISion will contract the Satellite Servicing Capabilities Office (SSCO) of the National Aeronautics and Space Administration (NASA). NASA will use the International Space Station's (ISS) unmatched capabilities to repair, refuel, and aid in assembly of the satellite in LEO. Since our satellites will eventually make orbit and spend most of their time in GEO, we will take advantage of NASA's future plans to implement satellite servicing in this orbit as well.

(PREBLE) Table 1 DC power distribution

	WEIGHT(Kg) on	WEIGHT(Kg) on	COSTS($)

DEVICES	"SolarDisc"	Antennae Disc	
Relays, Circuit Breakers, Converters	2000	285,000	126,530,000
High Temperature Superconductors (HTSC)	2,474,000	340,000	20,000,000**
Slip Ring Assemblies	5255	5255	(Not calculated)
Cable & Wire	(Not calculated)	175,000	8,950,000
30 KW Magnetrons		825,800 (235,000 units)	141,000,000
Copper Cable or Aluminum Bus Bar instead of HTSC	12,349,000 13,500,000 (Not included in totals)	1,234,000 1,350,000 (Not included in totals)	65,607,000 40,952,000 (Not included in totals)
TOTALS	2,481,255	1,631,055	296,480,000

Budget and Timeline

Photovoltaics follow the typical 80% technology learning curve where the module price decreases by 20% for every doubling of cumulative production as shown below (NREL Photovoltaics Research, 2011). From this we infer our PV module price.

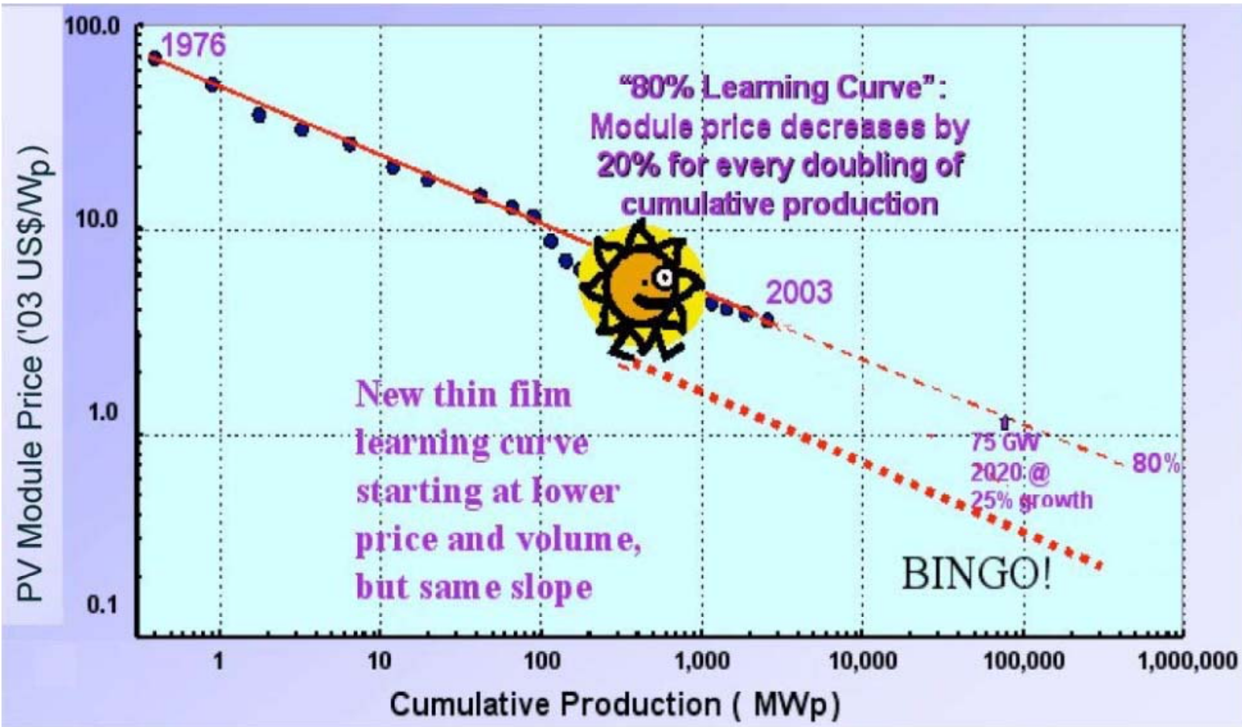

Figure 3 PV Learning curve

The figure below illustrates the timeline of critical events for the SOLAR VISion program. While it is an aggressive schedule the key to success would be the knowledge and experience gained from the rapid repeatability of launches. A more detailed schedule can be found in the Work Breakdown Structure (WBS).

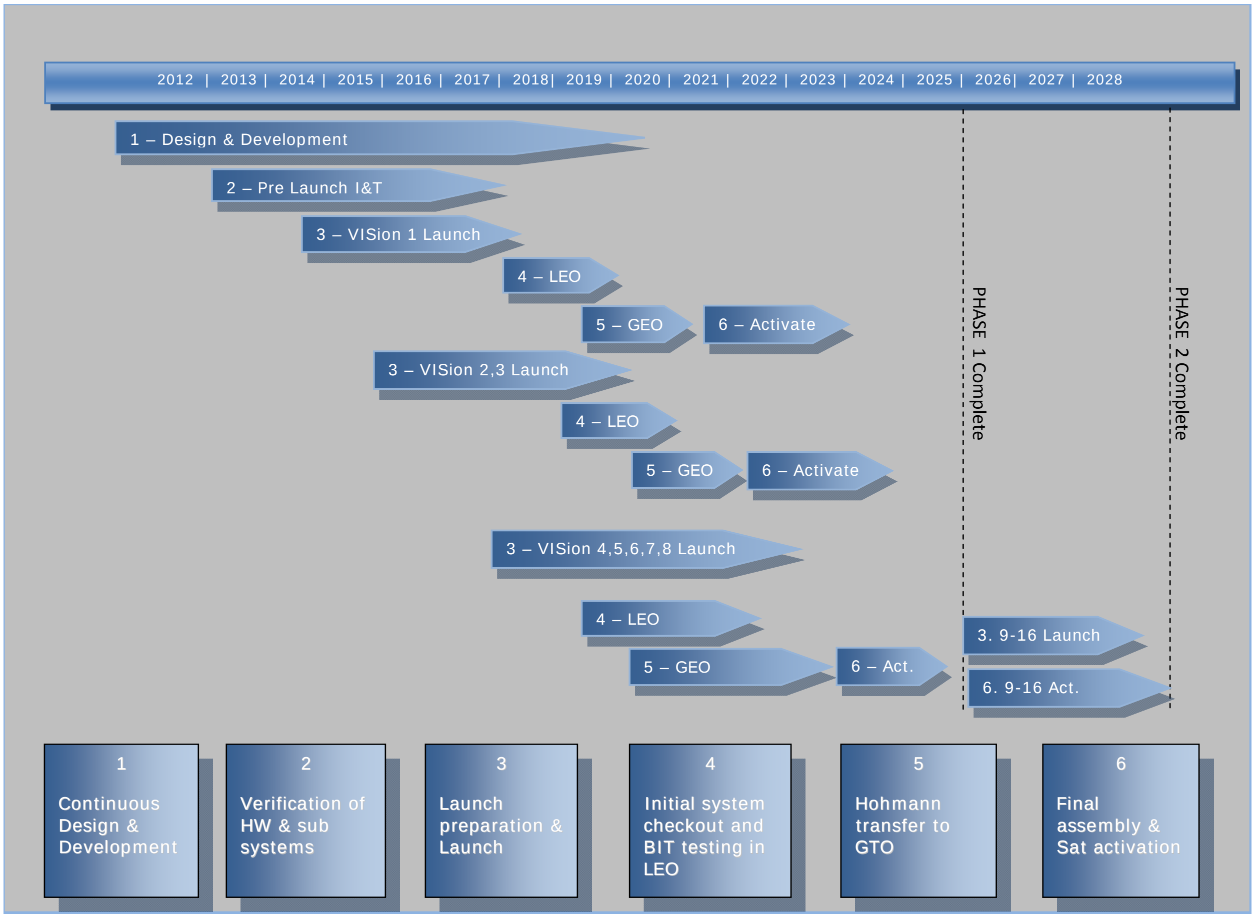

Figure 4 SOLAR VISion Project Timeline

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