Space-Based Solar Power System

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Table of Contents

1 Introduction

With the world's population continuing to grow and global warming on the brink of causing a dramatic shift in the Earth's climate, development of a clean and reliable power source has never been more urgent. Although numerous alternative energy sources have been pursued, none of the technologies have taken off. However, technological developments of the last twenty years have given new life to the idea of space-based solar power as a means for meeting these demands.

Space-based solar power would bring numerous benefits over its terrestrial counterparts. One of the major benefits is that the power generation will be clean. Unlike, coal, oil, or natural gas based power plants; space-based solar power will only release greenhouse gasses once, during launch. Furthermore, space-based solar power would provide constant, sunlight at levels eight times greater than what can be harvested by solar cells on Earth [1]. Given its clean production and constant free power source, space-based solar power has the opportunity to redefine power production as we know it.

2 Project Description and Goals

The goal of this design is to design an economically feasible, end-to-end system for harvesting solar energy from space and beaming it down to earth. Similar studies have been done in the past by reputable organizations such as NASA and the Department of Energy. Although those organizations found space-based solar power to be uneconomical, new technological developments and multi-corporate cooperation have changed the playing field.

The space-based portion of the system consists of a constellation of solar energy harvesting satellites (referred to as SunSats) that collect solar power and transmit the energy via a 5.8 GHz beam back to earth. An artist's rendering of a SunSat can be seen in **Figure 1**. Initially there will be eight of these satellites located in various geostationary orbits (GEO) corresponding to their matching ground station. This will later expand to include eight more during the second phase and will be modularly expandable afterwards.

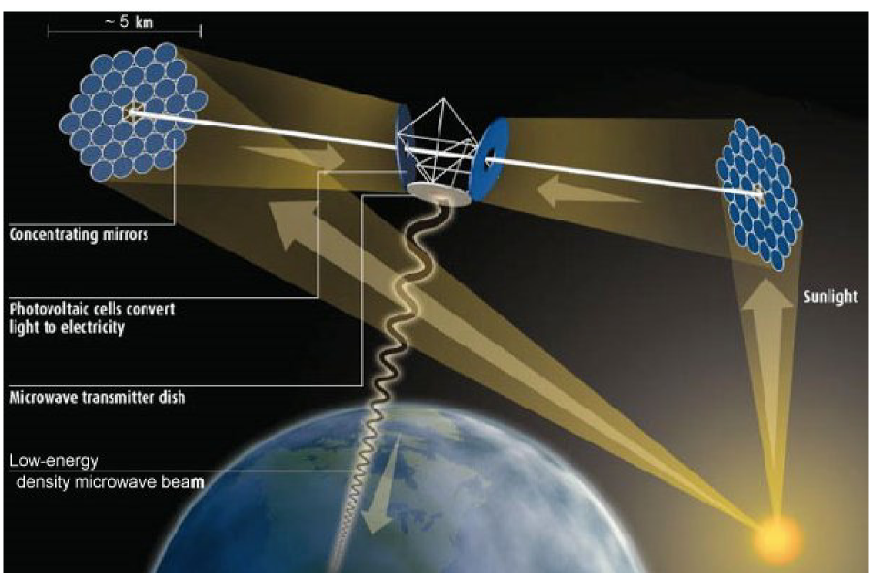

Figure 1. A graphic representation of a SunSat in action

On earth, ground stations featuring large rectennas will be capable of converting the broadcasted microwave frequency back into DC power. Once converted DC, the power will then be transformed into AC and pumped into the electrical grid, at which point its use becomes transparent to the end-user.

3 Technical Specifications

3.1 SunSat

The SunSats are required to produce radio frequency power at a constant rate with minimum interruptions. The three key parts for doing so are: the solar cell arrays, the power conversion hardware, and the battery backup system.

3.1.1 Solar Cell Arrays

Each solar cell array will consist of a thin film photovoltaic that can produce 16.8 kilowatts/kilogram. This material will be laid out in a circular pattern similar to the one shown in **Figure 1**. The circle will be three kilometers in diameter and will provide five gigawatts of power. A simple power density calculation shows that in order to produce 10 gigawatts of total power, approximately 595,238 kg of the thin film photovoltaic will be required.

The solar arrays will be paired with a reflector array to help concentrate solar energy onto the photovoltaic cells. The reflector array will also be laid out in a circular pattern but will be five kilometers in diameter. The reflector array will consist of a support structure layered in the equivalent of extremely reflective aluminum foil. Given an assumed thickness approximately equal to a sheet of aluminum foil (0.02 mm), each reflector array will have a mass equal to 1000 kg, not including support structure.

3.1.2 Power Conversion Hardware

The DC power produced by the SunSats will be beamed back to Earth at 5.8 GHz. This frequency was chosen not only because of its minimal attenuation by rain (a system constraint that cannot be controlled or avoided), but also due to the fact that many of the most advanced and efficient hardware designs employ this frequency. Furthermore, the higher frequency (i.e. using 5.8 GHz instead of 2.4 GHz) increases the gain of the antennas used in the design and thereby the efficiency of the system.

When it comes to converting DC to RF energy, there are many options with varying strengths and weaknesses. However, after filtering for products that can operate in the gigawatt range and proposed 5.8GHz frequency, only two remain: klystrons and magnetrons.

Klystrons are a mainstay for particle accelerators. A klystron works by accelerating a beam of electrons in bunches through a cavity. RF energy is passed into the cavity and the electron bunches that move through during an opposing magnetic field are accelerated. The amplified signal then is directed toward a second cavity where it is guided out of the device [13]. A diagram of the process is shown in **Figure 2** below. They are capable of producing high powers at efficiencies approaching 65% [14].

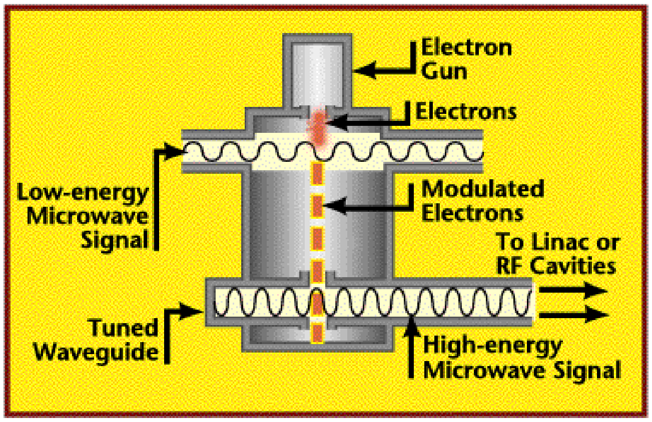

Figure 2. Diagram of a Klystron

The magnetron is known as a "cross-field" device due to its use of both electric and magnetic fields. A cross section of the device is shown in **Figure 3**. Heat is applied to the inner, circular cathode in the presence of a constant magnetic field. This causes the ejection of energetic electrons which, upon contacting the negatively charged cavities in the anode, are propelled circularly into the main cavity. This cycle causes the amplification that occurs at the resonance frequency of the main cavity [12]. According to a study by NASA and JPL published in 2000, they were able to develop a magnetron with an efficiency of 85.5% [11]

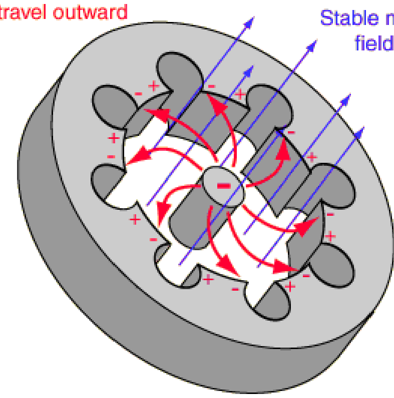

Figure 3. Inner workings of a magnetron [12]

Given the higher efficiency of the magnetron, it was the only logical decision. Despite any potential weight differences, the goal of the project is to provide as much energy as possible to the ground stations. This can only be accomplished by transmitting energy with the highest possible efficiency.

3.1.3 Battery Backup System

In order to maintain satellite connectivity during eclipses, each SunSat will be equipped with a battery. NASA has previously performed a study on the various rechargeable battery types that are being used in space applications [6]. **Figure 4** and **Figure 5** were taken from the study. From these figures it is easy to conclude that Ag/Zn batteries should be used due to their high power/weight density as well as their high power/volume density.

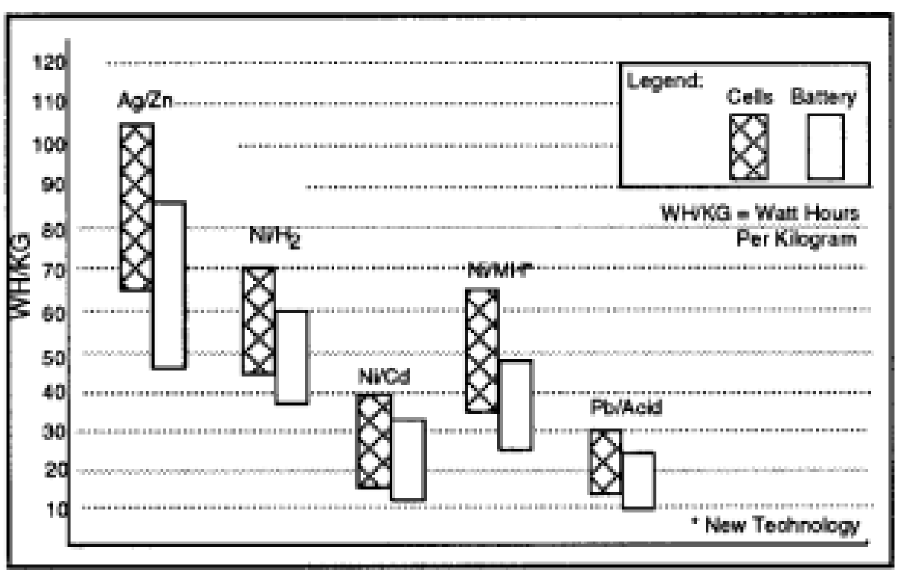

Figure 4. Power/Weight density of rechargeable batteries used in space applications [6]

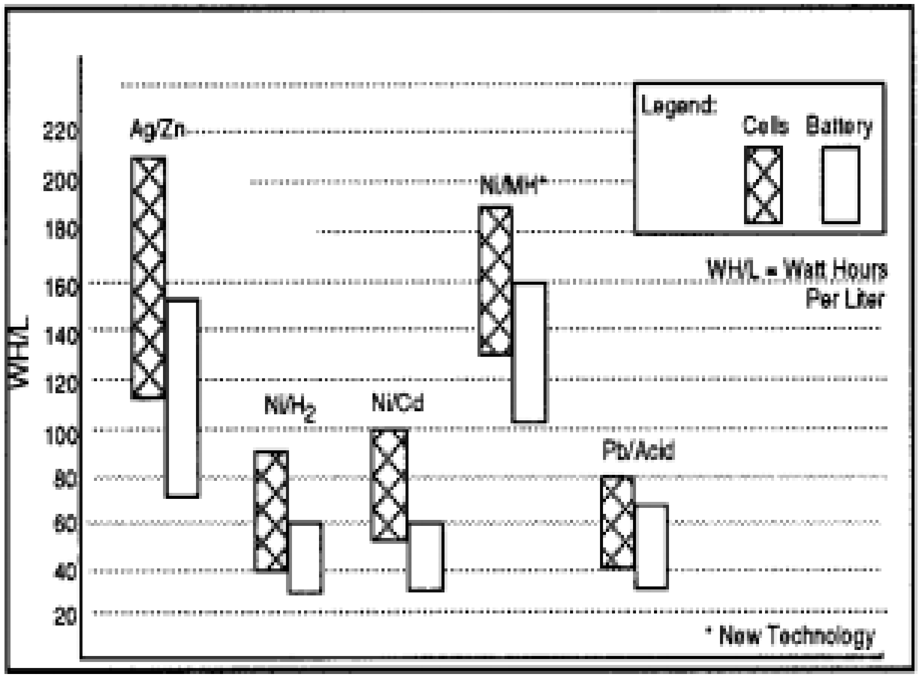

Figure 5. Power/Volume density of rechargeable batteries used in space applications [6]

Since the battery will only need to be used for a maximum of 70 minutes during peak eclipse season [5] and will only power the minimum necessary hardware to maintain connectivity to the satellite, it will not need to be very powerful. The minimum hardware will include heaters for the electronics, the communication TWTA and antenna, as well as various onboard computers and diagnostics.

3.2 Orbit

3.2.1 Parameters

Each SunSat will be located in a geostationary orbit. The benefits of geostationary orbits are as follows:

- The SunSats will never go out of view
- The satellites' transmitter dishes will not be required to move extensively
- The SunSats will avoid the large amount of debris located in lower orbits
- The rectennas will not be required to actively track the SunSats

The exact orbits of the initial eight satellites will be within the GEO belt at latitudes matching those of the ground stations described in **Table 1** below.

Table 1. Locations of Initial Eight Ground Sites

SunSat	Ground Station
1	West Virginia
2	South Texas
3	South Georgia
4	North Mexico
5	Columbia, Ecuador, Peru
6	Japan
7	Europe
8	Myanmar

3.2.2 Orbital Insertion and Station Keeping

In order to minimize costs, the launch vehicles will only be used to place the SunSats into a Hohmann GEO transfer orbit as seen in **Figure 6** below. Once in the transfer orbit, an ion drive will be fired to slowly elongate each satellite's orbit until it reaches the desired parameters.

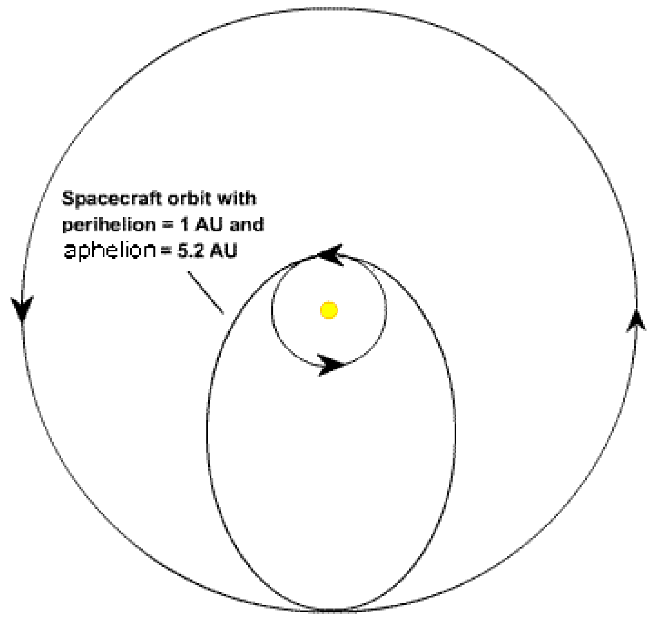

Figure 6. Hohmann transfer orbit [15]

In order to maintain the correct orbit of the SunSats, a certain amount of adjusting will be required. Orbital adjustments will be accomplished through the use of three pairs of low power thrusters (one pair for each axis).

There will also be four momentum wheels that will assist in attitude control of the craft. Three of the momentum wheels will correspond to the x, y, and z axes while the fourth will act redundantly by being inclined across all axes.

3.3 Telemetry and Control Link

In order to successfully inject the SunSats into their proper orbits and to ensure their health, a telemetry and control link will need to be established that is separate of the power transfer assembly. This link will be used for the following:

- Performing station keeping maneuvers

- Deploying the solar arrays and reflectors
- Monitoring the health of the spacecraft
- Commanding of the various on board systems and backups

Given the importance of this link, it will need to be capable of communicating with the earth station no matter what orientation the satellite is in. Furthermore, to deter dangerous cyber attacks and unapproved use, the link will need to be secure and difficult to jam.

3.3.1 Encoding and Encryption

The telemetry and commanding link does not require a large amount of bandwidth, but needs to be persistent throughout all weather conditions. To this end, S-band frequencies of 3.4/3.5 GHz have been chosen as the carrier frequencies for the link. These frequencies are set aside by the FCC for fixed service satellites such as the SunSats and will therefore not require special permission to be acquired [7]. A total of 100MHz of bandwidth on each link will provide ample room for telemetry and commanding. As an added benefit these S-band frequencies are little affected by inclement weather. This will allow the ground station to maintain link with the satellite even during severe weather.

A newly developed 1/2 rate, 2D 16-state forward error correcting code will be used to provide redundancy in the communication link and help to bring the signal closer to the Shannon channel capacity limit. This code has recently been implemented by iDirect [8], and as such iDirect has been asked to assist in the codes implementation. The resultant signal will then be encrypted using an Advanced Encryption Standard (AES) with a 256-bit key, Elliptic Curve Public Key Cryptography, an NSA approved encryption standard for sending data classified up to the Top Secret level [9].

Once encrypted, a simple QPSK modulation scheme will be used to minimize the required bandwidth. The signal will then be spread using CDMA. Spreading the signal will have the negative effect of requiring more bandwidth, but will have the benefit of creating jam resistant signal.

3.3.2 SunSat Antenna

To accomplish persistent communication, an omnidirectional antenna similar to the one seen in **Figure 7** below will be used on the SunSats.

Figure 7. Omnidirectional Antenna [10]

The omnidirectional antenna will provide a relatively low gain around 15 dBi [10], but will enable communication with the SunSat from any angle or orientation, an especially important feature during orbital insertion.

The omnidirectional antenna will be attached to a 10 watt traveling wave tube amplifier. This power source will allow for the signal to power through any weather conditions, but will not drain the battery unnecessarily during eclipses. The antenna will add a modest 1 kilogram to the weight of the satellite [10].

3.3.3 Ground Antenna

For the ground station, a simple offset parabolic antenna with the ability to track the satellite will be used. This antenna will be 10 meters in diameter providing a gain of approximately:

$$G = 4\pi A/ \lambda^2 = 51 \text{ dBi} \quad (1)$$

This antenna will also have the ability to transmit power at up to 10 watts using a traveling wave tube amplifier.

3.3.4 Link Budget

The parameters previously defined, have been reiterated in **Table 2** below.

Table 2. Telemetry and Control Link Parameters

Parameter	Value
Omnidirectional Antenna Gain (G_t)	15 dBi
OmnidirectionalAntenna Power (P_t)	10 W
Parabolic Antenna Gain (G_r)	51 dBi
Altitude of SunSat (r)	35786 km
Frequency	3.4 GHz

The logarithmic link equation is given as follows:

$$P_r = P_t + G_r + G_t + 20\log(4\pi /\lambda) - 20\log(r) \quad (2)$$

The last two values represent the losses due to atmospheric attenuation and distance, respectively. Substituting in the values from **Table 2,** results in a received power of -117 dBi. This is a best case scenario and does not reflect many of the additional losses that the signal may incur (i.e. antenna efficiency, amplifier efficiency, or inclement weather). However, the signal is strong enough such that the link will still be maintained even with a 50% decrease in signal strength.

3.4 Power Transmission Link

The success of a space-based solar power design is mainly dependant on the ability to transmit power from space back to Earth. Specifically this transmission link is expected to be as efficient as possible so that a large percentage of the energy harvested can be recovered on Earth. With this in mind, it was determined that the rectenna would attempt to harvest approximately 84% of the transmitted power.

3.4.1 Transmitter Dish Array

One of the key features of the transmitter dish needed to be its ability to minimize side lobe levels so as to prevent any unwanted radiating on the ground. In order to do this, it was necessary to create a transmitter dish that is made up of an array of smaller dishes. The aperture illumination across these dishes can then be tapered in such a way that minimizes side lobes. This can be done by using a 10dB Gaussian taper across the array as discussed in a directional magnetron study conducted by NASA and JPL. This means that the power density on the edges of the array would be 1/10 that of the center of the array [11].

In order to balance the goals of maximizing antenna gain and minimizing rectenna size, the transmitter dish array was designed to be 500 meters in diameter. Although this seems large, the array will be folded up for transport and will not be deployed until the satellite has been properly injected into its final orbit. This will allow the transmitter dish to easily fan out in space, where it will be less affected by gravity and thereby require less support. Nonetheless, this large amount of metal will add a significant 1,600,000 kg to the total weight.

3.4.2 Rectenna

Once the energy is transmitted to the Earth, it is the job of the rectenna to convert the RF energy back into DC power. When determining the type of rectenna to use, efficiency was given the highest priority.

The technique chosen for the rectenna is one developed by Suh and Chang [16]. Suh and Chang developed a method for converting RF to DC at 5.8 GHz with 82.7% efficiency (as well as 84.4% for 2.45GHz). The design is based off the use of a printed dipole antenna that is attached to a series of filters that block the re-radiation of higher order harmonics. After passing through the filters, the signal is then directed through a Schotky diode, capacitor and load-matched resistor where it is rectified into DC power [16]. A diagram of the rectenna design can be seen in **Figure 8** below.

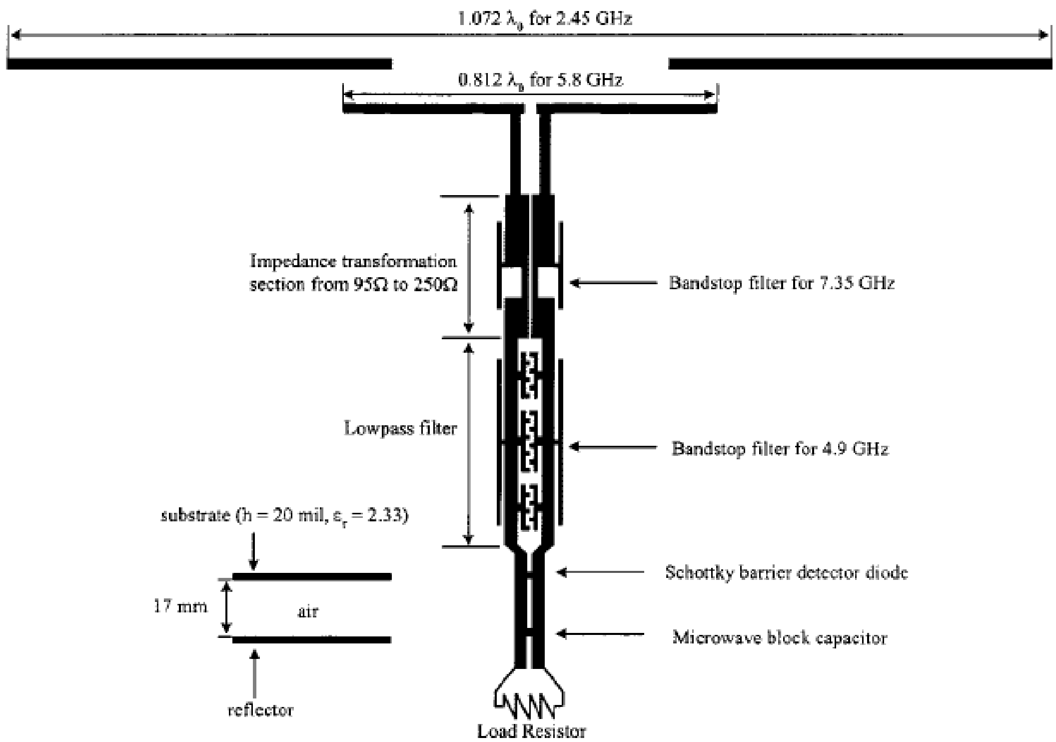

Figure 8. Rectenna design by Suh and Chang [16]

In order to maximize the amount of energy harvested from the rectenna site, these smaller rectennas will be placed in a large circular array. The most efficient size for the larger array to harvest approximately the entire main lobe of energy is governed by the equation:

$$D_r*D_t = 2.44*\lambda*r \quad (3)$$

Solving this equation for D_r, results in a value of approximately 9 kilometers.

3.4.3 Link Budget

The previously discussed parameters regarding the Power transmission link have been reiterated in **Table 3** below.

Table 3. Parameters For Power Transmission Link

Parameter	**Value**
Transmitter Antenna Efficiency (η_t)	90%
Main Lobe Efficiency (η_L)	84%
Transmitter Antenna Power (P_t)	10 GW
Magnetron Efficiency (η_m)	86%
Rectenna Harvest Efficiency (η_h)	50%
Rectenna Efficiency (η_r)	82.7%
Frequency	5.8 GHz

Using these values in the equation below one can determine that the approximate end-to-end efficiency:

$$P_r = 10\log(P_t * \eta_m * \eta_L * \eta_t * \eta_h * \eta_r) \quad (4)$$

For this equation the path loss is already included in the main lobe efficiency. Therefore, the end-to-end efficiency calculates to be approximately 47%. This means that on a clear day a total of 4.7 GW of power will be delivered to each ground station.

4 Design Approach and Details

4.1 Space Hardening

There will be many steps in the process to space hardening the satellites before sending them into space. These steps will help discover any areas of the satellite that need to be redesigned or tweaked in order to ensure a successful launch.

The first step in space hardening will be to protect any sensitive areas of the satellite. This includes reflectors and solar panels that will be exposed to debris that is flying around in orbit. Protection will include extra layers of clear glass for the solar panels and possibly a clear film covering for the sun reflectors. The satellite will also need to be protected from radiation, of which it is likely to be exposed to in space. Radiation testing will determine where and to what extent shielding will need to be applied to the satellite.

The hardening process will also include extensive lifespan testing in order to determine the expected lifetime of each part. From the outcome of these tests, the number of spares and level of redundancy for each part will be determined. The amount of redundancy will be based on a 20 year lifetime of the SunSats. Although this seems long, it is well within reach given the minimum station keeping required and the low amount of debris encountered in GEO orbit.

In addition, vibration testing will be carried out. This testing will take place on an extra satellite that will be built for the sole purpose of testing. The satellite will be exposed to high levels of vibrations simulating those felt during launch. The outcome of this test will shed light on the areas that need to be reinforced or to which vibration dampening material needs to be applied.

Lastly, the satellite will need to be subjected to the same large temperature fluctuations that will be experienced in orbit. This will help to determine where heaters will need to be added throughout the body of the spacecraft as well as which parts will need to be shielded or possibly passively or actively cooled.

4.2 Potential Impacts

Although there are a large number of benefits to space-based solar power, there are also some unknowns. These unknowns include the potential impact of transmitting large amounts of energy on the atmosphere and animal/plant life. Furthermore, using microwave frequencies similar to those already used by electronics may cause unwanted interference.

4.2.1 Environmental

Much research has been done on the environmental impact of wireless transmissions. Transmitting power wirelessly could potentially have negative effects on both the atmosphere and animal/plant life.

Atmospheric effects of high power radio transmissions have been poorly studied in the past. However, it is generally agreed that some amount of ionosphere level heating will occur [4]. Nonetheless, the radiation from the beam will be of low enough energy that it will be non-ionizing. In other words, the beam will be incapable of stripping an electron from a molecule, the main cause of mutations [2].

In regards to humans, the Occupational Safety and Health Administration (OSHA) has deemed that the acceptable level of consistent radio frequency exposure in the 10 MHz to 100 GHz range is $10 mW/cm^2$ [3]. The power density at the center of the array will greatly exceed this limit. However, the power density will taper off exponentially when moving away from the center. To mitigate any possible side effects of the high radiation levels, workers on the rectenna will be required to wear protective suits and a monitored security fence that is well labeled will be constructed a minimum of 500 meters from the perimeter of the rectenna.

This power density would exceed the OSHA standard for aircraft as well. Therefore, a no-fly zone would need to be established around the beam in order to avoid any incident exposure. Since satellites are already well protected from radiation given their environmental conditions, the addition of space solar power should not have any effect on them. However, it may interfere with communication if the satellite is flying through the power transmission beam and as such will need to be taken into consideration.

4.2.2 Existing Electronics

A major concern of broadcasting at microwave frequencies is interference with wireless devices currently using the same spectrum. According to NASA studies conducted in relation to the 1980 space-based solar power design, electronics may be affected up to 100 km from the rectenna. However, strategic use of terrain and sparsely populated areas for rectenna locations can help to diminish these issues [17].

4.3 Outages

Although all attempts will be made to ensure minimal down time, some outages will unavoidable. These outages will be both natural and unnatural in nature.

The most common and uncontrollable outages will be due to eclipses. Between February 28 and April 11, and between September 2 and October 14, roughly 21 days either side of the equinoxes, the satellites will go into a solar eclipse every day. The eclipses will gradually get longer until a maximum of approximately 70 minutes. The eclipses will then gradually get shorter until they are gone [28]. Routine maintenance will be scheduled within these windows to minimize downtime.

Another major outage concern and unknown is inclement weather. Although it is highly unlikely that the weather will stop all incoming power, it is likely that the weather will attenuate the signal strength. The location of the earth station will be the sole factor in determining how often the power supply will be degraded or potentially interrupted.

Given these possible outages it is still expected that the satellites will operate at full capacity for 99% of the time.

4.4 Assembly

Due to the sheer size of the satellites multiple launches will be needed to get all of the parts into orbit. Once these parts are on orbit they will need to be assembled. This is more cost efficient and easily done in low earth orbit (LEO). Therefore, before the vehicles are moved into GEO orbit they will be assembled in LEO.

5 Timeline

The timeline for the project has been determined as described in **Table 4** below.

Table 4. Timeline for Space-Based Solar Power Design

	'12	'13	'14	'15	'16	'17	'18	'19	'20	'21	'22	'23	'24	'25	'26	'27	'28
Phase 1																	
R&D																	
Space Hardening																	
Launch #1																	
Assembly in LEO																	
Transfer to GEO																	
On-orbit Testing																	
Launch #2&3																	
Assembly in LEO																	
Transfer to GEO																	
Launch #4&5																	
Assembly in LEO																	
Transfer to GEO																	
Launch #6-8																	
Assembly in LEO																	
Transfer to GEO																	
Phase 2																	
Launch #9-16																	
Assembly in LEO																	
Transfer to GEO																	

6 Budget and Cost Analysis

6.1 SunSat

Final development and manufacturing of the SunSat still needs to be accomplished. However, assumptions have been developed regarding the costs of each satellite. This assumption works out to approximately $8 billion per satellite including parts, labor, materials, and assembly on orbit. Multiplying this by the eight satellites needed plus an extra satellite for testing, results in a total phase 1 SunSat cost of $72 billion.

6.2 Launch

The going market price for launches has slowly come down over the years and will likely continue to drop in the future as more launches are required. As such, the launch price per kilogram of payload has been calculated with regards to **Figure 9**. The dark curve corresponds to first generation launch vehicles. The other lines correspond to the second and third generation launch vehicles as noted.

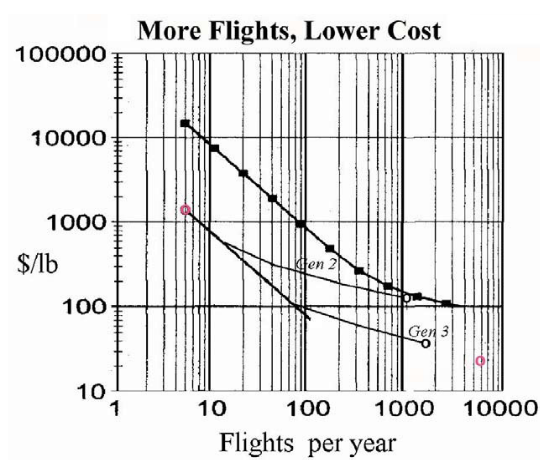

Figure 9. Launch costs per pound of payload given in RFP

It has been assumed that the second generation launch vehicle will come online in 2016, five years after the initial program launch. At this point the cost will be approximately 222$/kg to a Hohmann GEO transfer orbit. **Table 5** below summarizes the mass of the satellite.

Table 5. Breakdown of SunSat Mass by Subsystem

Subsystem	**Mass (Kg)**
Solar Array	595,238
Reflector Array	2,000
Transmitter Dish	1,600,000
Additional Amount	100%
Total	**4,394,476**

Given the total mass of each satellite, the launch cost for one calculates to be \$975,573,672. This value increases to \$7,804,589,376 when the eight satellites launched in phase one are taken into account. It should again be noted here that the sheer size of these satellites will require multiple launches per satellite.

6.3 Ground Command and Monitoring

As with all power production facilities, people will need to monitor the system and make corrections when need be. For the first phase, it was assumed that five teams of eight employees would be needed, including eight extra specialists and managers. Four teams would work on a rotating shift schedule and one team would act as backup for the others, but would carry on typical daily work schedules when not needed. The total costs for this are broken down in **Table 6** below.

Table 6. Employee Costs

SubLevel	**Value**
Number of Operators	40
Pay	35$/hr
Yearly Cost	$2,912,000
Total Costs for Phase 1 Life (20 yrs)	$58,240,000

6.4 Cost Summary

The total cost of the project as well as each major part of the system can be seen in **Table 7** below.

Table 7. Total Costs of Space-Based Solar Power System

SubSystem	**Cost ($)**
SunSats	27,000,000,000
Launches	7,804,589,376
Employees	58,240,000
Total	**25,921,069,376**

Given the total cost and the 20 year expected lifetime of the satellites, the 99% working time, and the expected delivery of 4.7 GW, the cost per kWh for phase one satellites over their lifetime will be $0.013. This figure is quite low but assumes no significant failures or interruptions are encountered. However, if the initial funds can be accrued, the design has been justified over the long term.

7 References

1. Price, Steve. "Beam It Down, Scotty!" *NASA Science*. NASA, 23 Mar. 2001. 15 Nov. 2011. <http://science1.nasa.gov/science-news/science-at-nasa/2001/ast23mar_1/>.
2. Logan, James. Safety of Space-Based Solar Power. Tech. Space Energy, Feb. 2009. Dec. 2011. <http://spaceenergy.com/i/pdf/safety_paper.pdf>.
3. Occupational Safety and Health Standards, Occupational Safety and Health Administration § 1910.97 (1996).
4. Robinson, T., T. Yeoman, and R. Dhillon. *Environmental Impact of High Power Density Microwave Beams on Different Atmospheric Layers*. Tech. no. 18156/04/NL/MV. Leicester, UK: Radio and Space Plasma Physics Group, 2004.
5. "Satellites, Geo-stationary Orbits and Solar Eclipses." *IPS Radio and Space Services*. Australian Government. 10 Nov. 2011. <http://www.ips.gov.au/Category/Educational/SatelliteEclipse.pdf>.
6. United States of America. NASA. *Battery Selection Practice for Aerospace Power Systems*. NASA. <http://engineer.jpl.nasa.gov/practices/1221.pdf>.
7. "Spectrum Dashboard." *FCC.gov*. FCC. 5 Dec. 2011. <http://reboot.fcc.gov/spectrumdashboard/resultSpectrumBands.seam?conversationId=17844>.
8. "2D 16-State Error Correction Coding." *IDirect.net*. IDirect. 2 Dec. 2011. <http://idirect.net/~/media/Files/Tech%20Briefs/2D%2016State_final.ashx>.
9. "NSA Suite B Cryptography." *NSA.gov*. NSA. 5 Nov. 2011. <http://www.nsa.gov/ia/programs/suiteb_cryptography/>.

10. "WiFi Antenna | High Gain 802.11 Omni Wireless Antenna." *RadioLabs - Radio, Wireless and Beyond -*. RadioLabs. 2 Dec. 2011. <http://www.radiolabs.com/products/antennas/2.4gig/high-gain-wifi-antenna.php>. "50ST1G18." *Amplifiers.com*. 15 Nov. 2011. <http://www.amplifiers.com/post/50ST1G18.pdf>.

11. Dickinson, R. "Magnetron Directional Amplifier Space Solar Power Beamer Concept Design."*JPL.NASA.gov*. NASA, 4 May 2000. 13 Dec. 2011. <http://trs-new.jpl.nasa.gov/dspace/bitstream/2014/15070/1/00-1077.pdf>.

12. "Magnetron Operation." *The Magnetron*. GSU. 5 Dec. 2011. <http://hyperphysics.phy-astr.gsu.edu/hbase/waves/magnetron.html>.

13. "Accelerator : Klystron Is a Microwave Generator (SLAC VVC)." *SLAC Public Website Server*. Stanford. 10 Dec. 2011. <http://www2.slac.stanford.edu/vvc/accelerators/klystron.html>.

14. Buenas, A., and G. Faillon. "A High Power Long Pulse High Efficiency Multi Beam Klystron."*Cern.ch*. CERN. 26 Nov. 2011. <http://mdk2001.web.cern.ch/mdk2001/Proceedings/Session12/beunas.pdf>.

15. "Hohmann Transfer Orbit & Total Travel Time." *Polaris Project*. Iowa State University. 2 Dec. 2011. <http://www.polaris.iastate.edu/EveningStar/Unit6/unit6_sub2.htm>.

16. Suh, Y., and K. Chang. "A High-efficiency Dual-frequency Rectenna for 2.45- and 5.8-GHz Wireless Power Transmission." *IEEE Transactions on Microwave Theory and Techniques* 50.7 (2002): 1784-789. Web.

17. "Some Questions and Answers About the Satellite Power Systems." *NSS.gov*. NASA/DOE, Jan. 1980. Web. 2 Dec. 2011. <http://www.nss.org/settlement/ssp/library/1980DOESPS-QuestionsAndAnswersAboutSPS.pdf>.