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SunSat Design Competition 2013-2014 Second Place Winner – Team Solar Maximum LLC: Sun-Synchronous Orbits

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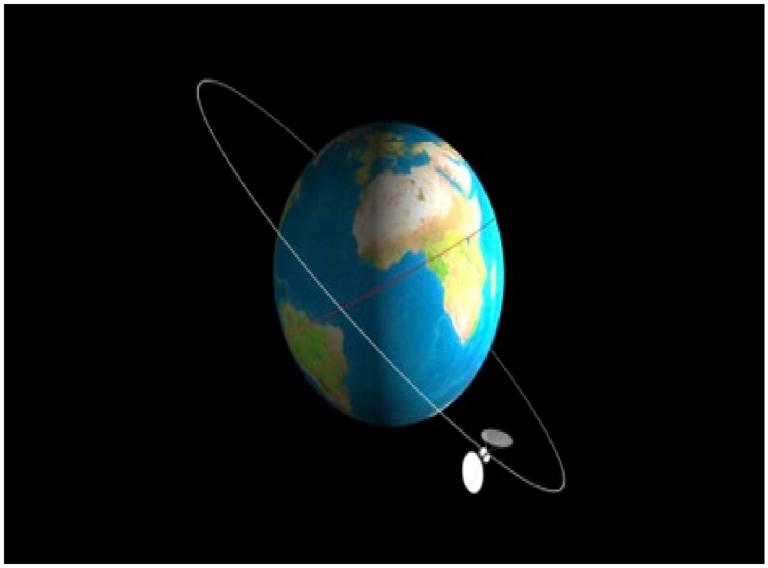

Space Solar Power Technical Plan
Concentrated Solar in Sun-synchronous Orbit

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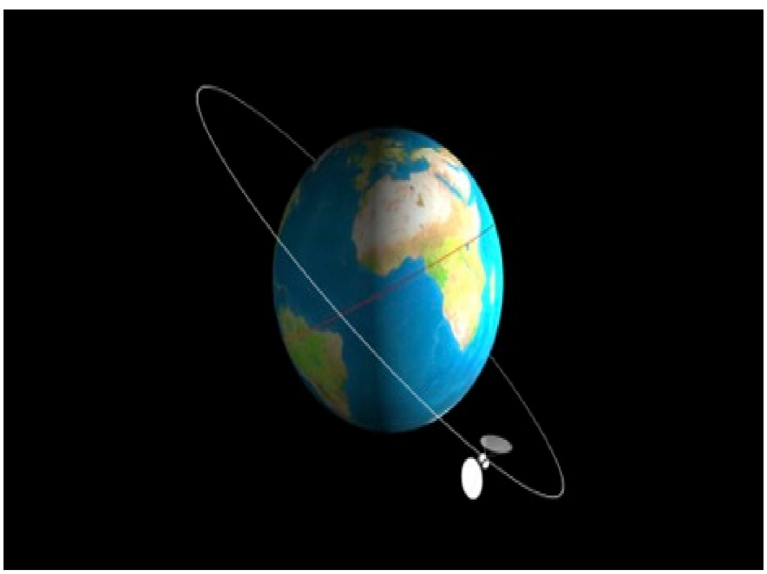
ABSTRACT

The orbital location of PowerSats plays a critical role in determining the mass of the solar power satellite (PowerSat) transmitter and the size of the rectenna on the Earth's surface. These in turn play an important role in the cost of deploying the PowerSat, especially the cost of launching the PowerSat into orbit as the transmitter makes up a large part of the PowerSats mass. We will consider a new approach to PowerSat orbital positioning by considering a circular sun-synchronous orbit at 5,185.3 kilometers with an inclination of 142.1 degrees. Locating the PowerSat at this location offers several benefits and only one major drawback. The benefits include small transmitter, small ground rectenna, small minimum power levels, constant energy production and constant energy delivery.

The one drawback in that this location is in the inner Van Allen radiation belt, which is a high radiation environment. Locating the PowerSat in the radiation belt is problematic as the radiation can damage the solar cells. However, the use of highly concentrated solar energy can potentially be used to heal the damaged solar cells, thereby providing a reasonable solution to the problem of radiation damage.

Ideally the use of highly concentrated solar energy would be used in the design of the PowerSat anyway to reduce the mass to orbit requirements.

By placing the PowerSat constellation in a medium Earth orbit (MEO) that is sun-synchronous the constellation can provide continuous power to specific sites on the ground. However, SPS in this orbit, which is the most intense region of the Earth's Van Allen radiation belt, would require dramatic advances in radiation hardening for all systems. Solar arrays, in particular have been found to be susceptible to degradation due to exposure to radiation. Self-regeneration of solar cells using heat has already been demonstrated at the experimental stage and the high heat level available at 2,000 suns solar concentration should be sufficient to heal the cells. Concentrated solar energy can potentially reduce PowerSat energy production system mass by an order of magnitude (90%). This combined with a close orbit which can reduce transmitter mass by an order of magnitude (90%), will allow for the development and deployment of much smaller, more mass efficient PowerSats. In addition to these advantages the PowerSats will also have a much lower minimum power level which means that much smaller systems can be deployed incrementally rather than building massive PowerSats as has been proposed in the past. This paper and accompanying visualization will discuss the benefits of combining concentrated solar energy at 2,000 suns concentration with an MEO sun-synchronous orbit at 5,185.3 kilometers with an inclination of 142.1 degrees to achieve a low mass PowerSat and how to overcome the problem of a high radiation environment by taking advantage of the solar energy available to periodically heal the solar cells.



PowerSat in Sun-synchronous orbit

Click here to see the video: Concentrated Solar in Sun-Synchronous Orbit - 2014 SunSat Design Competition

TECHNICAL BRIEF

INTRODUCTION

Increasing energy consumption, shrinking resources and rising energy costs will have significant impact on our standard of living for future generations. In this situation, the development of alternative, cost effective sources of energy has to be a priority. As conventional energy sources grow more expensive there is a need for abundant and low cost power across the Earth. Space Solar Power (SSP) can provide this energy. This paper will show that it is possible to design, engineer and deploy the proposed SBSP systems within just a few years. The basic technology already exists and this technology when combined with the innovation offered by the authors makes SSP an economically attractive technology for near future energy production. In the past SSP was considered to be uneconomical but this has changed with new low Earth orbit (LEO) SBSP concepts which demonstrate the ability to produce cost effective SBSP.

The orbital location of PowerSats plays a critical role in determining the mass of the solar power satellite (PowerSat) transmitter and the size of the rectenna on the Earth's surface. These in turn play an important role in the cost of deploying the PowerSat, especially the cost of launching the PowerSat into orbit as the transmitter makes up a large part of the PowerSats mass. We will consider a new approach to PowerSat orbital positioning by considering a circular sun-synchronous orbit at 5,185.3 kilometers with an inclination of 142.1 degrees.

Locating the PowerSat at this location offers several benefits and only one major drawback. The benefits include small transmitter, small rectenna, small minimum power levels, constant energy production and constant energy delivery. The one drawback in that this location is in the inner Van Allen radiation belt, which is a high radiation environment. Locating the PowerSat in the radiation belt is problematic as the radiation can damage the solar cells. However, the use of highly concentrated solar energy can potentially be used to heal the damaged solar cells, thereby providing a reasonable solution to the problem of radiation damage. Ideally the use of highly concentrated solar energy would be used in the design of the PowerSat anyway to reduce the mass to orbit requirements.

Concentrated solar energy can potentially reduce PowerSat energy production system mass by an order of magnitude (90%). This combined with a close orbit which can reduce transmitter mass by an order of magnitude (90%), will allow for the development and deployment of much smaller, more mass efficient PowerSats. In addition to these advantages the PowerSats will also have a much lower minimum power level which means that much smaller systems can be deployed incrementally rather than building massive PowerSats as has been proposed in the past. This research paper will detail the orbit mechanics and benefits of PowerSats located in a circular sun-synchronous orbit at 5,185.3 kilometers with an inclination of 142.1 degrees and utilizing concentrated solar energy at 2,000 suns concentration for low mass and radiation healing.

By placing the PowerSat constellation in a medium Earth orbit (MEO) that is sun-synchronous the constellation can provide continuous power to specific sites on the ground. However, SPS in this orbit, which is the most intense region of the Earth's inner Van Allen radiation belt, would require dramatic advances in radiation hardening for all systems. Solar arrays, in particular have been found to be susceptible to degradation due to exposure to radiation. Self regeneration of solar cells using heat has already been demonstrated at the experimental stage and the high heat level available at 2,000 suns solar concentration should be sufficient to heal the cells. This paper will discuss the benefits of combining concentrated solar energy with an MEO sun-synchronous orbit to achieve a low mass PowerSat and how to overcome the problem of a high radiation environment by taking advantage of the solar energy available to periodically heal the solar cells.

Sun-synchronous Orbit

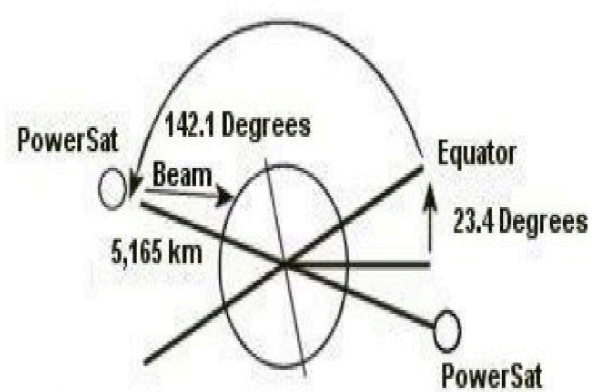
Altitude Km	Inclination	Orbits/day	Angle off sun
5165.3 _	142.1	7	56.5

Orbital data

Orbital height km	5,165.3
Orbital speed km/h	21,160.9
Orbital period hours	3.4254
Orbits/day	7
Radius	1.80 Earth radius
Orbit Circumference km	72054.31

Each PowerSat will pass over seven times per day delivery a steady stream of energy to four Earth based rectenna. That is 28 times per day that each PowerSat can beam energy to each rectenna. A Constellation of 100 PowerSats, each beaming 250 megawatts of energy can deliver 25 gigawatts of energy to the Earth.

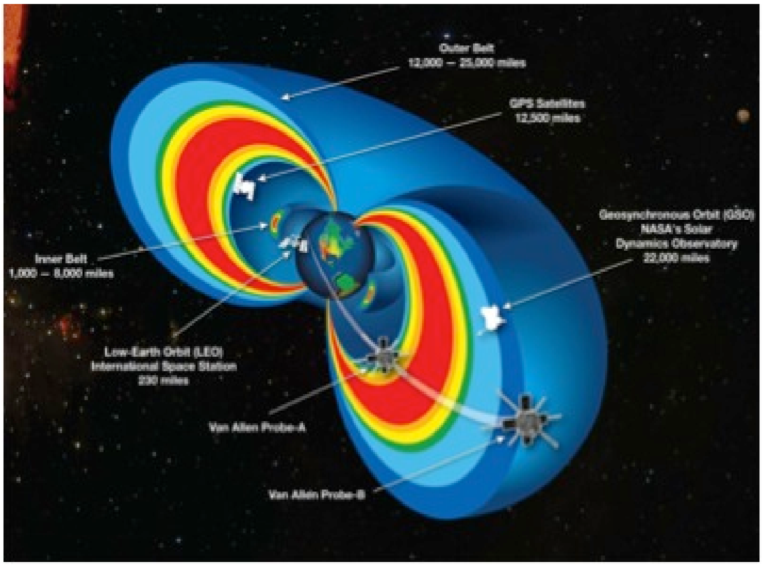
max sep	5165	km	beam half			Tx diameter	
Freq	Rx Diameter		angle	Radians		km	metres
2.5 GHz	5.11	km	a/2 =	0.000989351	d =	0.147976	147.97 57
5.8 GHz	3.35	km	a/2 =	0.000648596	d =	0.097292	97.292 33
15GHz	2	km	a/2 =	0.000387222	d =	0.024874	24.873 55
38 GHz	1.5	km	a/2 =	0.000290416	d =	0.033165	33.164 74
1.5 mcron	1.00E-02	km	a/2 =	1.94E-06	d =	9.45E-04	0.9451 95



Sun-sychronous orbiting PowerSats at 5,165 km/142.1 degrees

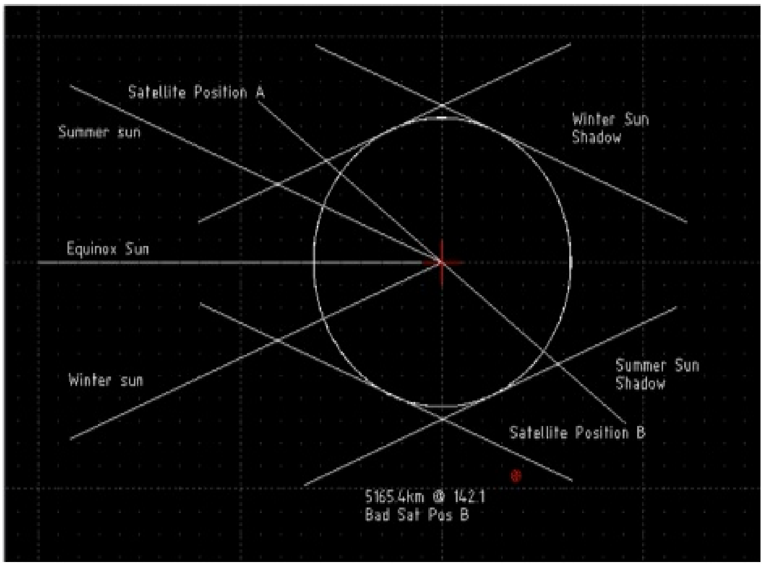
Van Allen belts represent considerable risk to today's orbiting satellite technology. The belts consist of highly penetrating radiation, which eventually inflict damage to delicate internal circuitry. Van Allen radiation belts consist of highly charged, energetic particles, fixed around Earth by the planet's magnetic field. While protons form one radiation belt, trapped electrons present two distinct structures, the inner and outer belt. The inner electron Van Allen Belt extends typically from an altitude of 0.2 to 2 Earth radii (L values of 1 to 3) or 600 miles (1,000 km) to 3,700 miles (6,000 km) above the Earth. In certain cases when solar activity is stronger or in geographical areas such as the South Atlantic

Anomaly (SAA), the inner boundary may go down to roughly 200 kilometer above the Earth's surface. The inner belt contains high concentrations of electrons in the range of hundreds of keV and energetic protons with energies exceeding 100 MeV, trapped by the strong (relative to the outer belts) magnetic fields in the region.



Solar cells, integrated circuits, and sensors can be damaged by radiation. Geomagnetic storms occasionally damage electronic components on spacecraft. Miniaturization and digitization electronics and logic circuits have mae satellites more vulnerable to radiation, as the total electric charge in these circuits is now small enough so as to be comparable with the charge of incoming ions. Electronics on satellites must be hardened against radiation to operate reliably. The Hubble Space Telescope, among other satellites, often has its sensors turned off when passing through regions of intense radiation . A satellite shielded by 3 mm of aluminium in an elliptic orbit (200 by 20,000 miles (320 by 32,000 km)) passing the radiation belts will receive about 2,500 rem (25 Sv) per year. Almost all radiation will be received while passing the inner belt.

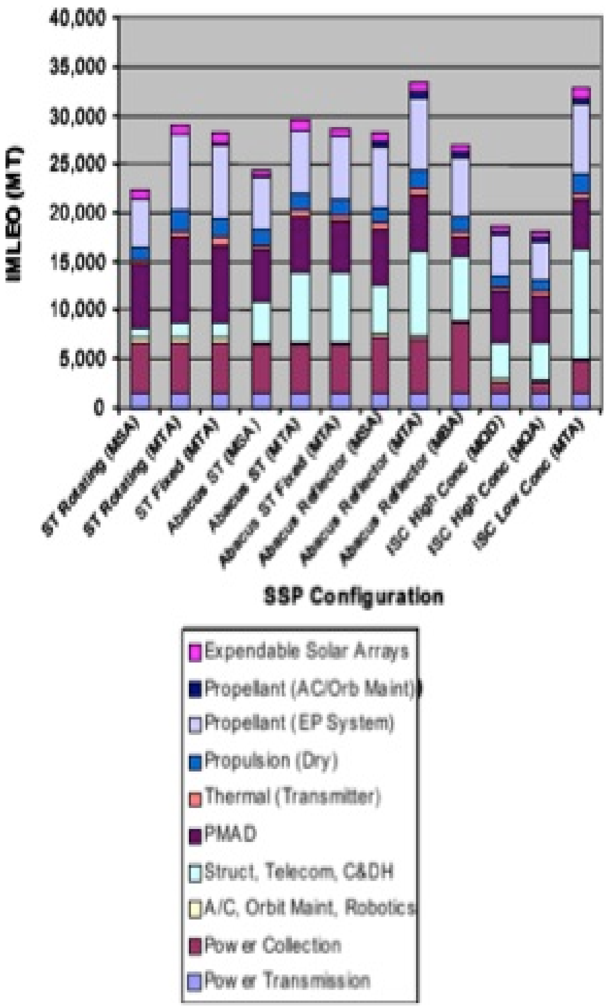
Concern about solar cell radiation damage goes back to the very beginning of discussion on the feasibility of SSP. Tests of Annealing of radiation damage in silicon and gallium arsenide solar cells goes back as far as 1979 (1).



Massive Solar Concentration

Solar arrays have been and continue to be the mainstay in providing power to nearly all commercial and government spacecraft. Light from the Sun is directly converted into electrical energy using solar cells. One way to reduce the cost of future space power systems is by minimizing the size and number of expensive solar cells by focusing the sunlight onto smaller cells using concentrator optics.

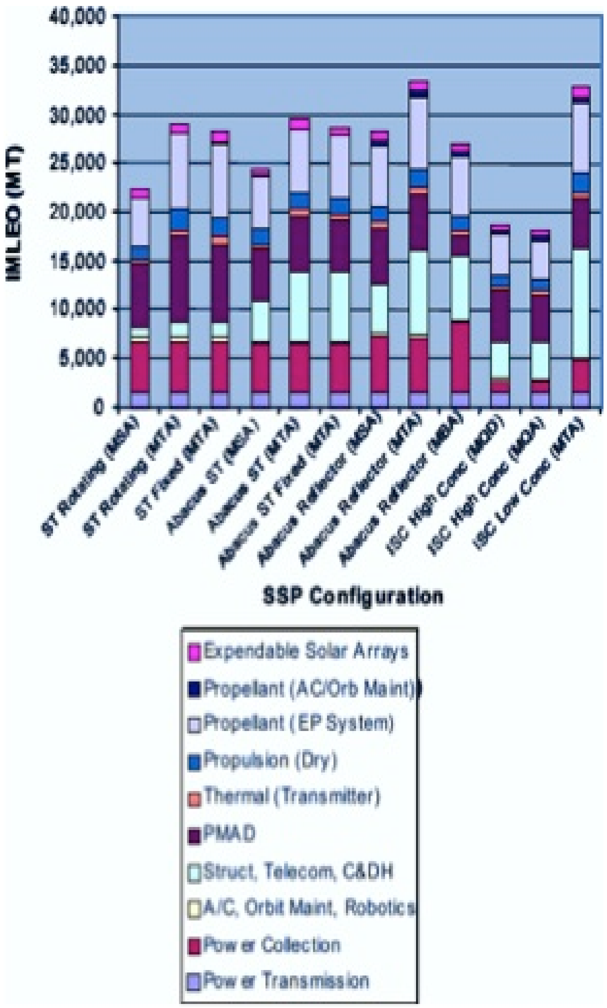
Using solar concentrator PV systems in space would potentially offer huge reductions in mass (5). At 2,000 suns concentration the solar cell mass could be reduced by some 90%. However, this mass savings would be offset by light reflector mass, which could be low mass inflatable reflectors, and radiator mass for an active cooling system. For solar electric Space Tugs there is the possibility of using the tugs ion propellant a solar cell coolant. Since ion drives are fuel efficient the propellant would be consumed slowly, thus the propellant would generally be available for use as a cooling fluid. As the space tug moves out into the solar system, such as a mission to Mars, the light from the sun would gradually diminish as the propellant is also diminished. Using concentrated solar on a PowerSat is a better solution as the PowerSat would remain in orbit and beam the energy to the space tug.



Looking at the NASA/DOE 1980s 5GW SSP reference models, there are actually two, the first model used silicon photovoltaic cells at 16.5 percent efficiency and had a mass of 51,000,000kg (112,200,000lbs) and the second model used higher efficiency gallium aluminium arsenide photovoltaic cells at 20 percent efficiency and 2 x solar concentrations and had a mass of 34,000,000kg (74,800,000lbs). The basic infrastructure in space or on the ground to build such massive structures in space does not exist. The cost of just the supporting infrastructure would be massive and a huge technical challenge.

The second 1980 NASA/DOE model using 2x solar concentration had only 66.6 percent the mass of the first model. Both models provide five gigawatt of power and the transmitter is the same size on both models because the amount of power being transmitted is the same and the proposed satellite location in GEO is the same. The second model is clearly more efficient in power production and has less mass to orbit which means lower launch costs.

In the 1990s there were some new concepts such as the integrated symmetrical concentrator (ISC) that moved to somewhat higher frequencies (from 2.4 to 5.8 gigahertz) and higher solar concentration at 4X. This reduced the mass to 20 million kg. This was a 58.82 percent reduction is PowerSat mass. Even greater mass savings are possible if we update the technology to what is possible today. These mass savings will allow us to consider SSP as an attractive option to replace carbon based fuels. It would allow for the first time for Earth to become an Electric Planet.



We can see that the ISC design achieved its mass reduction in large part by moving to a higher solar concentration level. We also saw this approach work well in the in 1980s models with the 2x solar concentration model. This trend is important to note because in 2008 IBM demonstrated 2300 suns solar concentration.

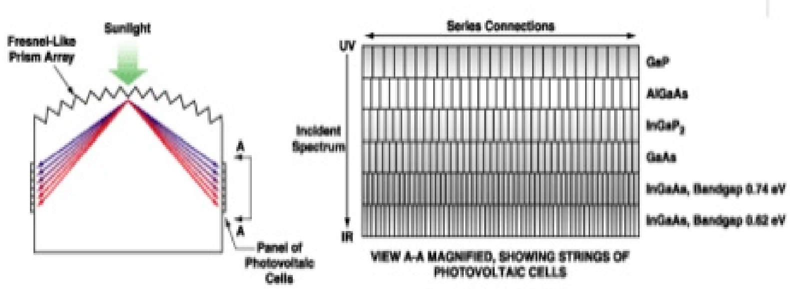
If you are going to do SBSP you need to start by asking a few basic questions. For example, what is the trend in Photovoltaic efficiency and system design? Comparing the NASA/DOE 1980 2x solar concentration model to the flat panel model shows a substantial reduction in satellite mass (a net mass savings of 66%). The Integrated Symmetrical Concentrator (ISC) at 4x solar concentration again substantially reduces satellite mass (another 58%). When considering the potential for concentrated solar power - What is the upper limit in solar concentration? Is it 4x, 10x, 100x, 1000x or higher? Looking at terrestrial solar power we are now seeing hardware coming to market at 500-1000x solar concentration. This technology can also be used in space. One of the great benefits of space is that there is no gravity and this allows for the deployment of very large and very low mass structures, such as large solar reflectors.

Since the ISC design concept is now very old a good place to start would be to update the model at the highest possible solar concentration levels. Once you have done that then you can look at other options such as increasing the power level, alternative orbits, deployable microwave antennas, etc., etc. The goal is to reduce the system mass to the point that it can become economically viable. How you get to that point is the challenge.

Rainbow Concentrators

Photovoltaic arrays of the rainbow type, equipped with light-concentrator and spectral-beam-splitter optics, have been investigated in a continuing effort to develop lightweight, high-efficiency solar electric power sources. This investigation has contributed to a revival of the concept of the rainbow photovoltaic array, which originated in the 1950s but proved unrealistic at that time because the selection of solar photovoltaic cells was too limited. Advances in the art of photovoltaic cells since that time have rendered the concept more realistic.

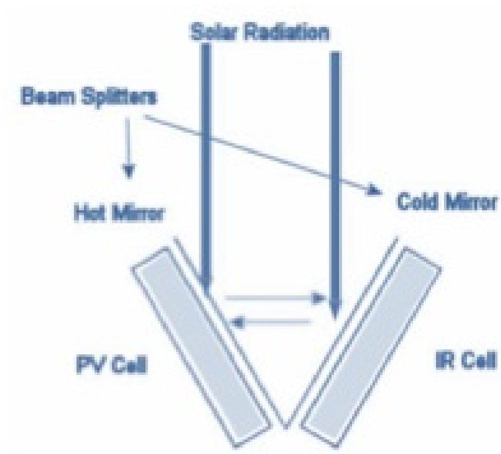
A spectral beam splitting architecture does provide an excellent basis for a multi-junction photovoltaic system with virtually ideal band gap combination, thus having the potential to reach very high conversion efficiency. In comparison to monolithically grown multi-junction solar cells, the spectrum splitting is provided by an additional optical element added into the course of the solar beam.



Early Rainbow Concentrator concept

The development of a "solid state" SSP system will allow deployment of high efficiency, low mass solar power satellites. To achieve this, solar radiation is first concentrated and then this concentrated beam is split into two beams using beam splitters. A beam splitter plate type is an optical window with semi-transparent mirrored coating to break a beam into two or more separate beams. One beam will contain the Infrared radiation and the other beam will contain the balance. To do this we will use an innovative system of two beam splitters, a Cold Beam Splitter and a Hot Beam Splitter. A Hot Beam splitter reflects infrared (IR) light and lets the rest pass though and the Cold Beam splitter lets the IR though and reflects the rest. This allows the use of photovoltaic solar cells that are tuned to these two groups, which can mean higher efficiency. This design was discussed in a paper written by the author and presented by Thomas Taylor at the International Space Development Conference in 2012.

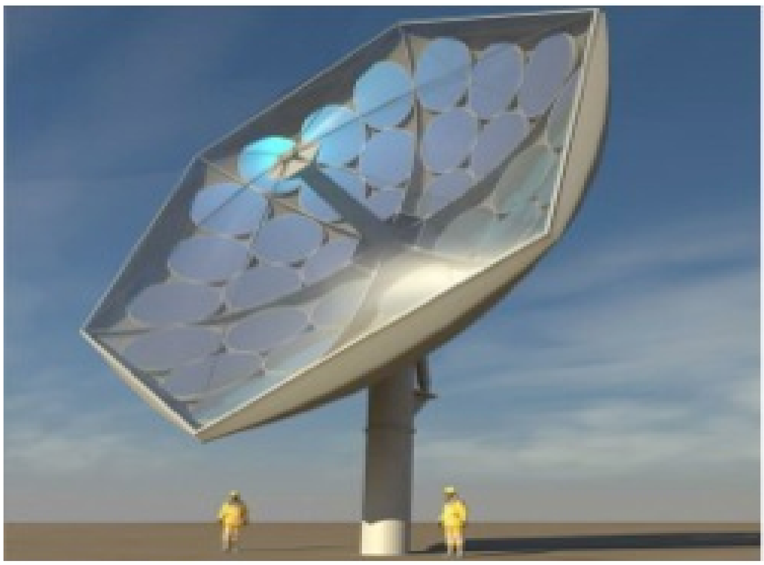
Depicts the conceptual configuration currently moving into ground testing. It consists of two different solar cells, sunlight splitting mirrors and active cooling both on the ground and in orbit. A spectral beam splitting architecture does provide an excellent basis for a multi-junction photovoltaic system with virtually ideal band gap combination, thus having the potential to reach very high conversion efficiency. In comparison to monolithically grown multi-junction solar cells, the spectrum splitting is provided by an additional optical element added into the course of the solar beam.



Using higher levels of solar concentration is very beneficial to SSP satellites due to the large potential mass reductions. The trade-off between reflector mass and solar cell mass is an easy trade as reflectors can be very low mass in space.

Using 2,000 suns solar concentration would reduce SSP satellite solar cell mass by approximately 90% verse a flat panel system with no solar concentration. This would be off-set somewhat by the increased mass of the reflectors and any required active cooling system. In the IBM demonstration in 2008 they used a liquid metal behind the solar cell to absorb the waste heat generated by the cell. They then used water to cool the liquid metal. This technology is now finding its way into high performance personal computers as a way to cool high output microprocessors which can generate a lot of waste heat.

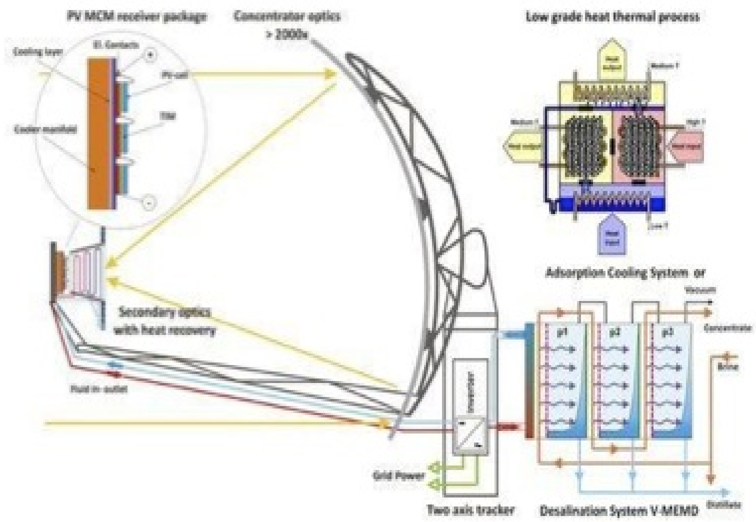
"IBM researchers have achieved a breakthrough in photovoltaics technology that could significantly reduce the cost of harnessing the Sun's power for electricity. If it can overcome additional challenges to move this project from the lab to the fab, IBM believes it can significantly reduce the cost of a typical CPV based system. By using a much lower number of photovoltaic cells in a solar farm and concentrating more light onto each cell using larger lenses, IBM's system enables a significant cost advantage in terms of a lesser number of total components".



IBM solar collector will concentrate the power of 2,000 suns, keep its cool

Modern solar collectors can concentrate only so much energy for safety's sake: too much in one place and they risk cooking themselves. An IBM-led group is working on a new collector dish that could avoid that damage while taking a big step forward in solar power efficiency. The hundreds of photovoltaic chips gathering energy at the center will be cooled by the same sort of microchannel water cooling that kept Aquasar from frying, letting each chip safely concentrate 2,000 times the solar energy it would normally face.

There are advantages and disadvantages both in the use of mirrors and lenses for concentrating sunlight. Lenses are associated with a relatively high optical loss, typically about 30%, due to reflection and absorption. The heat load is not a problem in lens systems because the cells are spread out on a plate, with plenty of space for each cell to dissipate the waste heat. With mirrors the typical losses are only 10-15%. However, because mirrors focus all of the light onto one highly illuminated area, the cells must be placed closely together in an array. All of the heat load must therefore be dissipated through the back of the cells, which makes cooling in these systems a challenge. In fact, the efficient removal of this heat load is one of the major obstacles for creating viable mirror-based high concentration systems. There is a need for a cooling device that uses a liquid coolant, cools efficiently across the entire surface, while not shading the concentrator, and operates at a low pumping power. There is no particular reason why you can’t use this or similar technology with an SSP satellite.

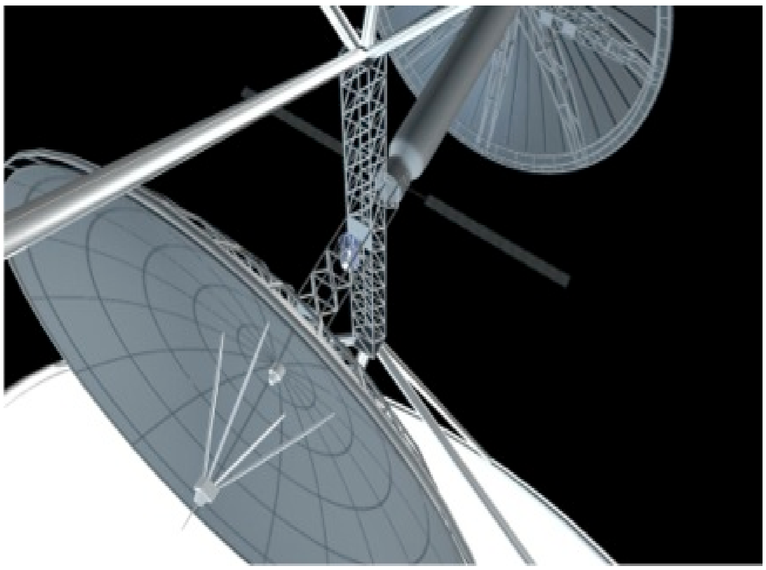


The main difference would be that in space you would probably use a different coolant fluid to cool the cells. This coolant could be ammonia for example. Another possibility would be to use the electric propulsion system propellant, such as Xenon or Argon, as the coolant. This would allow dual use of the propellant. Since the propellant is consumed slowly over a period of years this might work out really well. In space it is easier to get rid of high temperature heat than low temperature heat. An effective means for transferring thermal energy is with a pumped fluid loop. A pump provides the driving force necessary to create fluid flow over a hot surface of the solar cells transferring heat to the fluid and subsequently over another, colder surface that accepts heat from the fluid. A variable speed pump can be included to throttle flow based on temperature requirements of the system.

In space it can get terribly cold, especially when shadowed from the sun’s rays. Even so, it can be difficult to get rid of heat in space since there is no air or other mechanism to promote convection of the waste heat away from the cells. Low mass passive and active cooling system solutions will be needed. One possible passive solution would be to get rid of the Ultraviolet (UV) rays before they reach the solar cells. This might be done by absorbing the UV radiation at the large light reflectors and then radiating it out into space. UV is only 3% of the solar spectrum but is almost 100% waste heat at the solar cells, so getting rid of it before it strikes the cells can reduce the amount of waste heat.

Photovoltaic Mass Reduction

In 2008 IBM demonstrated concentrated solar at 2,300 suns, receiving 230 watts/sq/cm solar input an generating 70 watts electrical output for an efficiency of 30%. Using a cascading PV system it would be possible to obtain an efficiency of 40% or 92 watts/sq/cm electrical output. At 92 watts/sq/cm we could obtain 92,000 watts per square meter. 100 square meters of cells would generate 92,000,000 watts or 92 megawatts of electricity. Using advanced triple-junction cells at 84mg/cm the mass of the 100 sq/m of PV cells would be approximately 84kg.



Space deployable PowerSat

Solar concentrators for use in space have received growing attention in the past few years in view of their many potential applications. Among those, perhaps the most important ones are space power generation and solar thermal propulsion. In the former, the concentrator is used to focus solar radiation on a conversion device, e.g., a photovoltaic array or the high temperature end of a dynamic engine. For GEO you will notice that an SSP system using 40% efficient solar cells at 2,000 suns concentration might reduce satellite mass by some 70% and reduce LEO to GEO ion propellant mass by 552,924kg (70%). Note that reflector technology for 10,000:1 concentration has already been proposed for Solar Thermal Rockets by both NASA and DOD.

What is the current state of technology in concentrated solar power? What if the mass of SBSP power system could be substantially reduced using massive solar concentration? If the SBSP Satellite uses solar concentration at 2,300 suns we can also reduce the power system components by an order of magnitude or 90% (IBM, 2008), but this would be offset somewhat be the addition of reflector mass and the mass of an active cooling system.

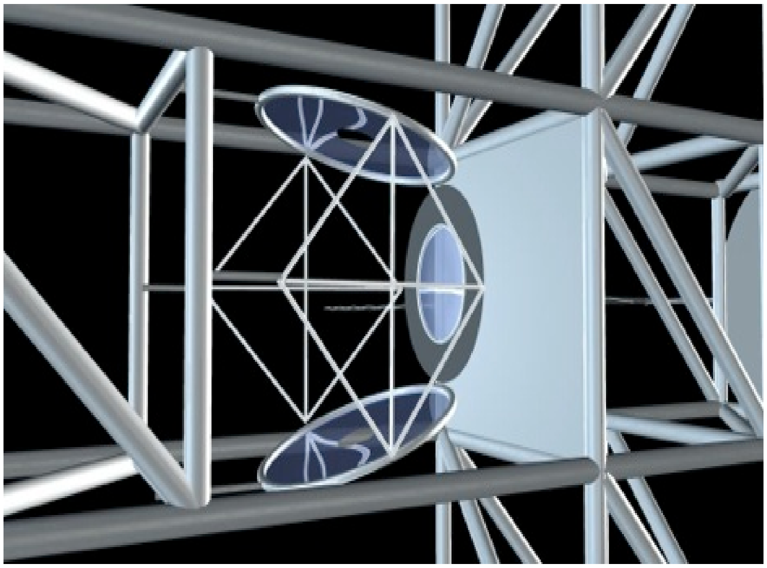
Results of the IBM solar experiment at 2,300 suns concentration
2,300 suns
230 watts onto a centimeter square solar cell
Cell size 1cm/2
Cell mass 1mg/cm
70 watts of usable electrical power,
30.4% efficiency
Waste heat 69.6%, 160.08 watts
Un-cooled temp 1600 degrees Celsius
Cooled temp 85 degrees Celsius
Cooling technology – liquid metal/water

Let’s that a look at how this would affect PowerSat mass. The reduction is solar cell and supporting structural mass could substantially reduce the Mass of the PowerSat.
5.8Ghz 2,300x Concentration, 30.4% efficient PV, 1GW, Mass 7,640,000kg, Transmitter 6,500,000kg, Power 1,140,000kg
Note that the transmitter is now 6 times more massive than the power system.

SBSP Application 2.5GW
2,500,000,000 watts / 70 watts per cell = 35,714,285 cells
35,714,285 cells x 1mg each = 35,714,285 mg = 34.714 kg
A 2.5 Gw PowerSat operating at 2,300 suns concentration would only need 34.7 kg of solar cells.

Photovoltaic Cooling

For cooling the photovoltaic cells a wide variety of systems concepts are possible. One particular setup proposes to use an active cooling system using Ammonia similar to the one used on the International Space Station (ISS). Ammonia freezes at -107 degrees F (-77 C) at standard atmospheric pressure. The heated ammonia circulates through huge radiators located on the exterior of the Space Station, releasing the heat as infrared radiation and cooling as it flows. The heat-bearing ammonia can't lose heat fast enough to reach its freezing point before the liquid circulates back inside the warmer confines of the satellite. The Ammonia will pass between the sets of solar panels and extract the waste heat. The Ammonia is then cooled and recycled back to collect more waste heat. The proposed concept works well for space solar satellites as well.



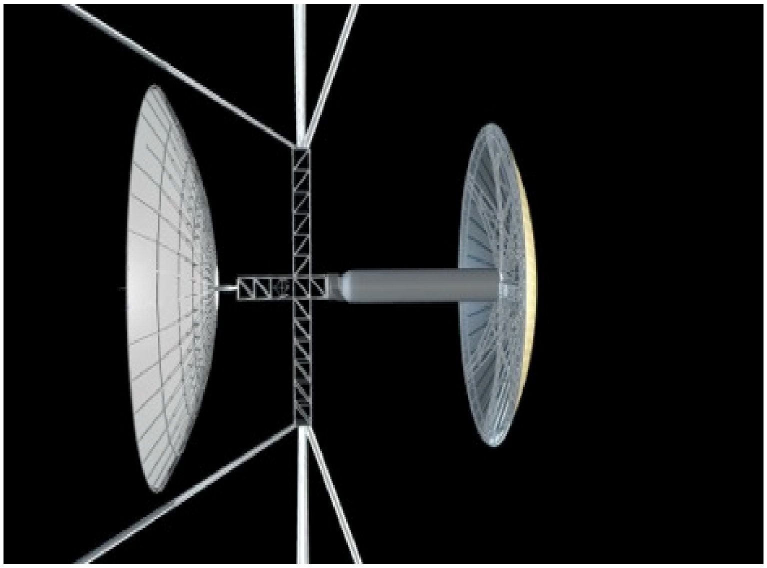
Two reflector solar concentrator

The Holy Grail of SSP

Concentrated Solar Power (CSP) is the Holy Grail of Space Solar Power (SSP). The key to accessing the Holy Grail is Thermal Waste Power Management. When considering for example the Integrated Symmetrical Concentrator (ISC) SSP systems concept as presented the presentation of on H. Feingold, C. Carrington, Evaluation and Comparison of Space Solar Power Concepts, Presented at the 53rd International Astronautical Congress, 2002,IL,USA.

We see two models presented. The first model uses a solar concentration at 2x and the second model uses solar concentration at 4x. When compared to the NASA/DOE 1980 2x model we see that the benefits of the 2x ISC model is just an improvement in packaging as the separation of the solar concentrator from the PV array allows the PV cells to be packaged much closer which reduces wiring and structure. The 4x ISC is however a large improvement over the 1980s model (and the ISC 2x model) because the higher concentration ratio actually reduces PV mass and the wiring and structure that goes with that mass.

The logical question to ask at this point is - What would happen at high solar concentration levels? The answer is of course greater reductions in PV, wiring and structural mass. At 2,000 suns concentration there is an order of magnitude reduction in solar cell mass. The problem that comes into play is that high solar concentration ratios increase the Thermal Waste Power Management problem. Additional mass has to be added to the CSP system to handle this problem. Designing a low mass thermal solution to space CSP is the key to the Holy Grail.



Empty propellant tank being used as a space radiator

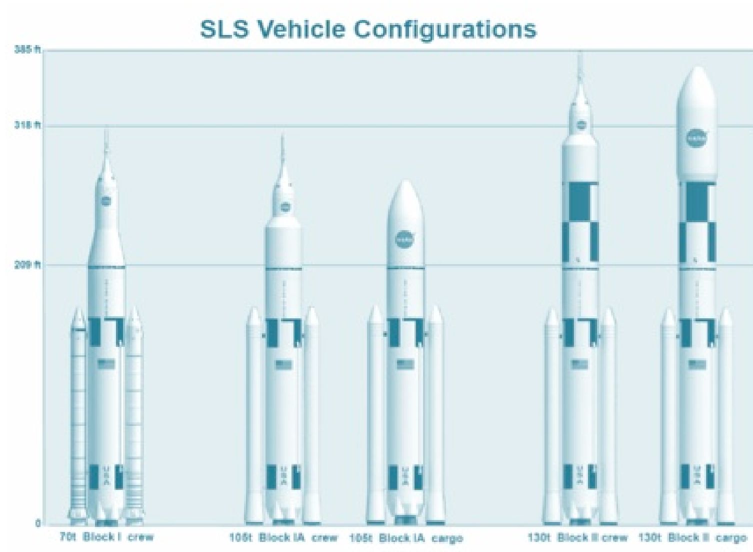
Carbon/Carbon radiator

The carbon-carbon radiator panel conducts thermal energy more efficiently than other materials currently being used to dissipate thermal energy on satellites. The use of high conductivity fibers in C-C fabrication yields materials that have high stiffness and high thermal conductivity, and since the density of C-C panels is considerably lower than aluminum panels typically used on satellites, significant weight savings can be realized by replacing Aluminum radiators with C-C radiators. C-C also has an advantage over other high conductivity composites materials in that the thermal conductivity through the thickness of the material is significantly higher. C-C also has markedly higher specific thermal efficiency than aluminum and offers improved performance for lower volume and mass.

The advantages of carbon-carbon composite are:

1. it has high strength
2. it has low weight (density less than aluminum)
3. it has high thermal conductivity
4. it can be used at high temperatures (currently used in aircraft brakes and the Space Shuttle wing leading edge).

Another possible solution to waste heat management would be to use the empty rocket stage propellant tanks as space radiators. Once launched into space the chemical propellant tanks would be vented and then used as radiators. Since the mass would be essentially free on orbit this appears to be a good approach to reducing radiator mass. Since heat rejection at high temperature works better in space you might want to run the coolant through the space radiators first and then dump it into the launch vehicle tanks and use them as medium to low temperature radiators. Here the coolant would come into contact with the tank walls and radiate the heat out into space. For the space radiators a Carbon/Carbon radiator could be used.



Space Launch System (SL): Note the huge size of the vehicles tanks. SLS can lift approximately 80,000 kilograms into orbit.

NASA's Space Launch System could deliver multi-megawatt PowerSats into low Earth Orbit. Such PowerSats could beam energy to several space tugs traveling back and forth between the Earth and the Moon. This would provide a low cost in-space transportation to support Lunar or free space colony settlement. Such a system could also be used as a booster system for crew and cargo transport to Mars.

Increasing energy consumption, shrinking resources and rising energy costs will have significant impact on our standard of living for future generations. In this situation, the development of alternative, cost effective sources of energy has to be a priority. It is possible to design, engineer and deploy the proposed PowerSats within just a few years. The basic technology already exists and this technology when combined with the innovation offered by the authors makes SSP an economically attractive technology for near future energy production. In the future new heavy lift launch vehicles, such as SLS could deploy ever larger versions of these PowerSats, possibly of gigawatt scale as technology reduces the mass of the PowerSats.

BUSINESS PLAN

Executive Summary

As the World's need for energy continues to grow driven by population growth and increased industrialization, new options for energy will be needed. This is especially true given that reserves of convention energy sources such as oil, gas and uranium are rapidly being depleted and that green house gases being released into the atmosphere are causing large scale damage to the Earth. We find that alternatives energy sources such as wind, ground solar and biomass have physical site limitations and while they are certainly desirable from an ecologically prospective are often high cost and cannot meet the Earth's future energy need even if fully developed. Is there a source of energy that is abundant and cost effective? Actually, yes, there is such a resource and it is called the Sun.

US yearly usage approx 3.783 trllion kilowatts-hrs (4.32 EE11 watts on average - 2008) Estimated world usage approx 1.9 terawatts (1.92 EE12 watts) on average - 2007

Space Solar Energy has the potential to cost effectively meet all of the Earth's current and future energy needs. Space solar power also has the potential to reverse America's half a trillion dollar a year balance of payments deficit and to generate a new generation of American jobs. Energy is a huge market and only Space Solar Power can provide the amount of clean energy demanded by the seven billion people living on the Earth.

Business Concept

University of Utah physicist Tim Garrett published a 2009 paper that gives strong indirect support to SSP. In an article based more on physics than economics, Garrett suggests that energy conservation will have little effect in the long run, and that the globe currently needs to replace and/or add about 300 Gigawatt-equivalents of new non-carbon energy sources each year in order to stabilize current greenhouse gas levels. This rate of construction would not, however, reduce the current rate of greenhouse gas production. With current global demand at 16.4 Terawatts, and about 14 Terawatts of this energy coming from carbon fuel, he estimates it would take 46 years to eliminate all the existing carbon energy production, that is, if we could build an additional 300 equivalent Gigawatts (0.3 Terawatts per year) of carbon-free energy plants to cover new energy demands for both fuel and power.

Basic Concept - SolarSat

SolarSat Corporation is built on the assumption that the management of space solar satellite technology and the development of in-space transportation services will be the most important stepping stone in development of space solar power for terrestrial use. This is to be achieved by partnering up with local telecommunication satellite manufacturing companies, be they private or government run. The terrestrial energy market is worth an estimated $1 trillion and there is a projected growth of 20% per year. SolarSat Corporation aims to tap into this market, and expects to be able to capture a 10-20% market share within twenty years.

Unlike traditional sources of energy such as oil, gas and coal (the fossil fuels), SBSP doesn't involve the burning of fossil fuels, which have been shown to cause severe environmental problems and global warming. SBSP is also more efficient than traditional solar power, as sunlight is almost five and a half times as strong in space as it is on the surface of the earth, as it does not have to interact with the atmosphere, weather, and day/night cycles. Space based solar power would be able to run continuously, when placed in Sun-synchronous orbit.

Past concepts for space based solar power depended on huge launch vehicle cost reductions to be viable, the frequency of rocket launches needed to increase and the cost per kilogram needed to substantially decrease. They also required methods of assembly in space, human system architecture, etc. to be developed. We will take an approach based on satellite mass reduction.

Utilizing a standard global commercial business model would minimize the spending of initial risk money, and then expand early space power demonstrations and later revenue operations using foreign sales and extensive foreign subcontracting participation in hardware and financing. This is similar to the oil companies in Alaska when they pooled their money and spent $20B carefully to get the oil to flow in 1978, then spent another $200B to develop 18 more nearby oil fields.

Company

The SBSP concept being developed by SolarSat Corporation does not depend on human space system architecture, in-space assembly, or huge reductions in launch vehicle cost (although that would be beneficial). The system described in this business plan uses available technology to reduce the PowerSat mass by an order of magnitude, thereby removing the huge mass to orbit requirements imposed on past concepts. Our SolarSats are small, efficient and powerful.

SolarSat Corporation plans to design, build, deploy and operate Solar Power Satellites (PowerSats) in a unique Sun-synchronous orbit (SS-O) at 5,165 kilometers and 142.1.1 degrees. SolarSat Corporation's Solar Satellites (SolarSats) will operate at 2,000 suns solar concentration (1,600c) and utilize the empty launch vehicle propellants tanks as low temperature space radiators. This innovative design will reduce the mass of the SolarSat solar array by ninety percent compared to past concepts.

The combination of SS-O and Concentrated Photovoltaic power production provides a net reduction in mass to orbit of seventy-five percent compared to past

GEO concepts. It also allows for the incremental deployment of much smaller SolarSats – 49 SolarSats into SS-O, instead of one huge PowerSat in GEO. The reduction in mass and ability to deploy smaller SolarSats creates a business opportunity that is unique in history in that it will generate abundant low cost power from space.

Company Description
Our approach is small enough to launch on existing vehicles and more importantly to be financed by the private sector.

Industry Analysis
SolarSat LLC will be a global energy company. The energy business is the largest industry on Earth and has many participants with large capital investments in sources of energy generation, power infrastructure and existing customer base. Changing their energy world requires innovation, a better, more reasonably priced energy sales cost that actually finds it way down to the end user energy customer, enough private investment to actually start a new solar power industry in orbit and sales into the start of the existing energy delivery cycle used by existing energy providers plus their continued prosperity as Earth changes from fossil fuels created by the sun and stored for long periods on the planet to collected energy from the sun, the ultimate source of all our energy.

Technological Factors
Further changes with SolarSat include the ability to transmit the energy in orbit to specific points of use on Earth and to vary the size of the transmitting satellite to meet the customers need on the ground, which may permit underdeveloped countries to omit the power grid upgrade problems by accepting power from space nearer the point of use. This is somewhat like the use of cell phones in developing countries where stringing copper wire all over the country is changed to cell phone towers near the population centers. America is an industrialized country, where cryogenic power grids are being considered to push more power thru America's power grids. Locating power sources near power use is important, when you remember Hoover Dam loses half its energy in ~275 miles of transmission losses to LA.

There have been a number of studies on the economics of based space solar power; however, these studies have always focused on locating the solar power satellite in GEO. Medium Earth Orbits (MEO) and Low Earth Orbits (LEO) are sometimes mentioned in these studies but the discussion always focuses on GEO. This is interesting because the limitation on successful deployment of SBSP systems has always been limited by the mass to orbit problem, a problem that can be solved by MEO and LEO satellite positioning. It has been known since at least 1980 (J. Drummond, 1980) that positioning the power satellite in a lower orbit would reduce the mass of the satellite transmitter by an "order of magnitude". Since the transmitter makes up a large part of SBSP satellite mass a 90 percent reduction in transmitter mass would seem to be very beneficial.

Previous studies indicate the transmitter in these models is 1 km in diameter and its mass is estimated at 13,382,000kg. If SolarSat reduces this by "an order of magnitude" or 90% by moving the SBSP satellite into LEO, as suggested by Drummond in 1980, the mass savings would be 12,043,800kg. This is 12 million kilograms you don't have to launch into space and a 35.4 percent reduction in Solar Satellite mass. If the satellite where to use 40 percent efficient PV cells, which reduced the mass to 23,691,000kg and we moved the satellite into low Earth orbit (LEO), which would reduce the mass even more to 11,647,200kg, the amount of mass launched into orbit would be reduced by 22,352,800kg or 65.7 percent.

If the SBSP Satellite uses solar concentration at 2,000 suns we can also reduce the power system component by an order of magnitude or 90% (IBM, 2008). The satellite mass is 34,000,000kg less transmitter mass of 13,382,000kg giving a power component mass of 20,618,000kg multiplied by .1 for an order of magnitude reduction gives 2,061,800kg. Adding the power component at 2,061,800kg to the reduced mass transmitter at 1,338,200 gives a total of 3,400,000kg for a 5gw SBSP Satellite verse 34,000,000kg for the NASA GEO model at x2 concentration. We have now reduced the total mass to orbit for an SBSP Satellite by 90%. Note that moving the transmitter closer also reduces the ground receiver (rectenna) by 90%.

The cost to launch these 170 satellites using the lowest cost launch available today, which would be the Proton, is estimated at $100,000,000 each for a total of $17,000,000,000. We can see that SBSP is a major enabling technology for launch vehicles.

The mass of the transmitter is reduced by an order of magnitude as was pointed out by Drummond way back in 1980 and the satellites can be launched on existing launch vehicles and launched incrementally.

Market Size and Growth

Basically, market size and growth potential in the two selected geographic market segments are unlimited, but many business plans probably say that. We believe this one may actually be truly unlimited.

The European Union spends $148 Billion per year on Cap and Trade so the idea that we can't afford SBSP is clearly not a valid argument.

Market Trends

The trend is, of course, up as the rest of the world desires the standard of living enjoyed in the industrialized world. It is not just the desire for increased comfort, communications, heat, cooking, etc., but the population is increasing at an alarming rate in combination with more people wanting a higher standard of living.

Purchasing Decision Process
Before the SolarSat demonstration mission is launched each customer is given the opportunity to participate in a Franchise Power Agreement with a small purchase fee covering marketing costs only. The signed Franchise Power Agreement with the current electrical power supplier firms up a future agreement to purchase power only valid after the demonstration mission, but requiring a substantial Franchise Fee paid after the demonstrated capability of the demonstration mission.

Competition
There are no competitors in space solar so the competition is conventional energy sources.

Distinct Competitive Advantage
Early patent and IP protection are distinct competitive advantages.

Scalability of Deployment
Currently, there are approximately 70 launches per year. Since the PowerSats can be launched in increments of 100 megawatts with a mass of only 80,000 kg they can be incrementally deployed using very near term launch vehicles such as the Space Launch System. Units as small as 50 megawatts can also be deployed using the Space X Falcon Heavy.

The success space based solar power will be determined by the ability to decrease cost,
with much of this depending on the reduction of PowerSat mass.The orbital location of PowerSats plays a critical role in determining the mass of the solar power satellite (PowerSat) transmitter and the size of the rectenna on the Earth's surface. These in turn play an important role in the cost of deploying the PowerSat, especially the cost of launching the PowerSat into orbit as the transmitter makes up a large part of the PowerSats mass. We will consider a new approach to PowerSat orbital positioning by considering a circular sun-synchronous orbit at 5,185.3 kilometers with an inclination of 142.1 degrees. Concentrated solar energy can potentially reduce PowerSat energy production system mass by an order of magnitude (90%). This combined with a close orbit which can reduce transmitter mass by an order of magnitude (90%), will allow for the development and deployment of much smaller, more mass efficient PowerSats. In addition to these advantages the PowerSats will also have a much lower minimum power level which means that much smaller systems can be deployed incrementally rather than building massive PowerSats as has been proposed in the past. This research paper will detail the orbit mechanics and benefits of PowerSats located in a circular sun-synchronous orbit at 5,185.3 kilometers with an inclination of 142.1 degrees and utilizing concentrated solar energy at 2,000 suns concentration for low mass and radiation healing.

Financial Information

Financing involves two types of capital. Equity for product development and lease financing for long term vehicle operations and maintenance. Since our vehicles are fully reusable they will be leased financed in a manner very similar to ComSat financing.

ENDNOTES

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