The Space Grid

Sun-synchronous orbiting SBSP Satellites with Equatorial orbiting Reflector Satellites for Earth and Space Energy

By

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Abstract

The development of an economically viable space-based solar power (SBSP) system is critical to the Earth's future and for future space development. PowerSat technology is also critical to supporting sustainable private and government space ventures, including space lift, space exploration and space infrastructure development. Such a system would greatly expand the need for space lift capability from small reusable launch vehicles for SBSP satellite maintenance to large expendable launch vehicles for deploying GW class SBSP satellites into orbit. The technology needed for SBSP is also needed for in-space solar electric transportation systems needed for space colonization as the technology is the same. The hope has been that gradual improvement in photovoltaic or other technologies such as thermal systems would solve the mass to orbit problem for SBSP systems. However, this in itself does not appear sufficient to make SBSP economically viable. This paper presents a new architectural option for SBSP using a Sun -synchronous orbit (SS-O), wireless power transmission (WPT) and a space power relay (SPR). This new concept is called The Space Grid. The Space Grid relies on the use of two separate satellite constellations. The power satellite (PowerSat) constellation is placed in SS-O dusk to dawn orbit at 800km and has access to constant sunlight and is used to produce the power. The Equatorial reflector satellite (ReflectorSat) constellation is in a 4,000km equatorial orbit and is used to distribute the power to the rectenna on the Earth's surface. The power is produced by the PowerSats in SS-O and beamed to the ReflectorSats in equatorial orbit and then bounced to the rectenna on the ground. This combination allows for the production and distribution of power to the Earth's surface without the problems normally associated with non-Geostationary (GEO) PowerSat concepts and without having to place the PowerSats in GEO. The Space Grid reduces the mass of a PowerSat transmitter by approximately 67% by moving it closer then past GEO concepts and allows for higher power levels and therefore much smaller (60%) and less costly rectenna on the ground and reduces the minimum size from 5GW to only 2GW allowing quicker deployment of space energy to solve the Earth's energy problems. WPT transmission could be microwave or laser but for this paper microwave will be used for easier comparison with past concepts.

Acronyms

Space-based Solar Power (SBSP)
Power Satellites (PowerSats)
Wireless Power Transmission (WPT)
Space Power Relay (SPR)

Space Power Grid (SPG)
Gigawatt (GW)
National Aeronautics and Space Administration (NASA)
Department of Energy (DOE)
Low Earth Orbit (LEO)
Equatorial Medium Earth Orbit (EMEO)
Geostationary Orbit (GEO)Kilograms (kg)
Solar Electric Propulsion (SEP)
Beamed Solar Electric Propulsion (BSEP)
Photovoltaic (PV)

Introduction

The basic technology for SBSP and Solar Electric Propulsion (SEP) have important similarities. This is especially true when considering beamed solar Electric propulsion (BSEP). This paper will look at a new concept for SBSP but will also show how the same concept can be used for space settlement, i.e., space colonization by supplying massive amounts of energy to orbiting spaceships.

Wireless Power Transmission (WPT) and it relation to space may be thought of as extending our two dimensional power transmission networks on the Earth to space and to other planets and space vehicles. Such a system could be used for a wide variety of applications. One such application would be providing large amounts of power for an electric spaceship needed for an in-space transportation system. Electric propulsion has long been recognized for its benefits if there were a suitable energy source for the large amounts of power required by electric thrusters. Conventional prime power sources in space are massive relative to electric thrusters and must be accelerated along with the less massive parts of the vehicle. Further, they are expensive and costly to transport into space. In contrast, beamed microwave power removes the prime power source from the vehicle and therefore has a very low mass relative to other potential prime power sources in space, including chemical, nuclear and solar electric. The combination of WPT and electric thruster technology would make it possible to replace conventional chemical rocket propulsion for missions beyond low Earth orbit (LEO) with enormous economic and safety benefits. It is interesting to note that the technology required for WPT PowerSats is very similar to that required for WPT Solar Electric propulsion (SEP) systems. By pursuing SBSP to supply the Earth with energy we are also developing the technology for large scale colonization of the solar system at the same time.

Space Solar Power

The largest potential application for microwave power transmission is SBPS satellites. In this application, solar power is captured in space and converted into electricity and beamed to the Earth. Several concepts have been proposed in the past for LEO PowerSat beaming to Earth to alleviate the launch cost problem (2, 9). It has been known since at least 1980 that placing PowerSats in LEO would reduce satellite transmitter mass by “an order of magnitude” (Drummond (2)), i.e., about 90%. However, the problems of PowerSat stationing in LEO are the Earth’s rotation under the satellite, Earth shadowing and the Oceans.

A comparison of the NASA/DOE SBSP concepts dating back to the 1980s shows the mass problem related to SBSP satellites in Geostationary orbit (GEO) (12,13,14,15,16). The transmitter mass problem for GEO PowerSats can be seen below.

NASA 1980 Option 1: 1x Concentration, 16% efficient PV, 5GW, Mass 51,000,000kg, Transmitter 13,000,000kg, Power 38,000,000kg

NASA 1980 Option 2: 2x Concentration, 20% efficient PV, 5GW, Mass 34,000,000kg, Transmitter 13,000,000kg, Power 21,000,000kg

ISC 1990: 4x Concentration, 20% efficient PV, 5GW, Mass 23,500,000kg, Transmitter 13,000,000kg Power 10,500,000kg

ISC 2010: 4x Concentration, 40% efficient PV, 5GW, Mass 18,250,000kg, Transmitter 13,000,000kg, Power 5,250,000kg

Notice above that even when you double the efficiency of the power system by doubling the solar concentration or doubling the photovoltaic (PV) efficiency or both that the transmitter mass is still the same at 13 million kilograms for a 5GW transmitter. It becomes very clear that new approaches to mass reduction are needed for SBSP and BSEP to become economically viable. One way to reduce the mass is to move the transmitter closer but there are some problems in doing that. These problems include reduced beam time due to satellite speed around the Earth and the Earth's rotation, Earth shadowing which blocks the satellite for the suns energy and the large size of the oceans that make it difficult to transmit energy when you are very close to the Earth.

Shadowing Problem

For LEO satellites much of the orbit is spent in the Earth's shadow and no solar power can be produced. This means you have to launch even more satellites to make up for the estimated 40% power loss.

The period of an orbit is; T = 2 * pi * SQRT(a^3 / mu)

mu = 398,600.4418 km3/s2

T = 90 minutes = 5,400 seconds

Rearranging the equation a = mu (T/(2 * pi)^2)^(1/3)

Obtains an altitude of 286.36 km - and the utilization is precisely 59.37%

Beam Time Problem

Because the Earth rotates under the satellite the beam time to a ground rectenna would be very short at roughly 200 -300 seconds (Jones R. (3)). Since the SBSP satellites would be very close to the Earth and would be traveling very fast there is little time to beam to power to the rectenna. This can be solved using a space power relay (SPR). By placing approximately ten reflectors in a 4,000km equatorial orbit we can achieve constant power as shown below.

Time over target 18 minutes

4,000 km orbit = 175.32 sec orbit / 18 minutes of beam time = 9.74 reflectors (rounded to 10)

Ocean Problem

Another problem with LEO PowerSats is the Earth's Oceans. For example, the distance from Indonesia to the coast of Colombia and Peru across the Pacific Ocean is 19,800 kilometers. The SPR reflectors can overcome this problem because the PowerSats can choose which reflector to use to beam to the Earth. By having reflectors in space it would be possible to move the power to where it is most needed.

To overcome these problems we use Sun -synchronous orbit (SS-O) PowerSats and a space power relay (SPR). These concepts will be discussed briefly and then merged into a new concept call the Space Power Grid.

Sun-synchronous orbit

Sun-synchronous orbit (SS-O) is a special case of the polar orbit. Like a polar orbit, the satellite travels from the north to the south poles as the Earth turns below it. The orbital plane of a sun-synchronous orbit must also precess (rotate) approximately one degree each day, eastward, to keep pace with the Earth's revolution around the sun. Sun-synchronous orbits are typically low Earth orbits (LEO) ranging from 550 to 850 km and are therefore close to the surface of the Earth. There is a special kind of sun-synchronous orbit called a dawn-to-dusk orbit. In a dawn-to-dusk orbit, the satellite trails the Earth's shadow. When the sun shines on one side of the Earth, it casts a shadow on the opposite side of the Earth. Because the satellite never moves into this shadow, the sun's light is always on it. Since the satellite is close to the shadow, the part of the Earth the satellite is directly above is always at sunset or sunrise. This allows the satellite to always have its solar panels in the sun.

Figure 1: Satellite in Sun-sync dusk to dawn orbit. Note that the satellite never enters the Earth's shadow and the solar panels can always face the sun.

Another advantage of SS-O for PowerSat stationing is that they can always be facing the sun side of the Earth. This means that all of the power transmitters can be located on the day side where power is need most. A GEO PowerSat will follow the ground transmitter day and night and does not have the flexibility of the SS-O PowerSat without adding space reflectors. This would defeat the primary reason for considering GEO. Since the goal is to deliver as much power as possible to where it is needed the most, the Space Grid would transmit all of the power to the day time side of the Earth. Beaming all the power to the day side of the Earth is more productive than Earth based solar power since the solar energy in space is much greater than on the ground. Additionally, the Earth is rotating so the "day side" is always changing but the energy being transmitted by the SBSP satellite is constant.

Space Power Relay

Space Power Relay (SPR) has been proposed in the past. (N. Komerath, N. Boechler, S. Wanis (4) R. Dickinson (5) and J. Mankins (6), D. Criswell D (7) Ehricke, K. (8), N. Komerath, N. Boechler (9) I. Bekey, R. Boudreault (10)) The SPR proposed by Ehricke (8) placed the reflector in GEO so the power beam had to travel 36,000 km to the reflector and then another 36,000km back to Earth. In the proposed system the space-based reflector was estimated at 2,500 tons per million kilowatts. At an estimated 2,500 tons per million kilowatts, the space reflector was considerably lower in mass than the SBSP designs of the day, which were estimated at 8,000 tons per million kilowatts received at the ground rectenna. Ehricke (10) suggested that the reflector could be placed into a lower orbit to reduce transmitter size to 1 million kilowatts and rectenna size from 55 square miles to 15 square miles. There have even been proposals for Moon to Earth SPR systems using space-based reflectors to move the energy around the Earth (Criswell (9)). A similar concept was proposed by the Federal Aviation Administration (FAA) in the 1960s for air traffic control. In that system, the microwave beam generated on the Earth's surface would bounce off a large space reflector in GEO and then back to the Earth to track moving aircraft (Grumman (11)). The FAA concept was not proposed as a power relay; however many of the components were the same as those required by space power relay. The problems with past power relay concepts for a Space Power Grid (SPG) are the large mass requirements. Although the SPG is much lower mass than SBSP the mass requirements for past concepts are still large when the system are located in GEO, or on the Lunar surface.

It has been suggested by N. Komerath (4, 9) that SBSP could be added to a SPG system. They proposed a space power grid (SPG) that beamed energy into space from collection locations on Earth and bouncing it off lightweight reflectors to earth-based microwave collectors for local distribution. In the SPR concept, the satellites act as waveguides, and do not perform conversion to DC, therefore it is very efficient.

The Space Grid

Combining SS-O PowerSats using WPT with SPR for power distribution would reduce the minimum size of the PowerSat by 250% compared to a GEO PowerSat. The minimum power level of an SBSP satellite in GEO is approximately five gigawatt (GW). This is due of the great distance of 31,000 km the microwave beam has to travel to get from GEO to the rectenna on the Earth's surface. As the beam travels this great distance it spreads. In order to have enough power in the beam to activate the rectenna of the ground you have to build a very large PowerSat in GEO. With the Space Grid the distance traveled is much shorter since beam travels from the PowerSat in an 800 km SS-O to the reflector in a 4,000 km equatorial orbit and then to the Earth. The shortest distance would only be 3200km when the two satellites line up at the equator over the rectenna and the maximum distance would be about 12,000 km using a constellation of ten reflectors. This is only 38.7% of the distance from GEO. This reduces the minimum size of the PowerSat from 5 GW to only 1.935 GW (rounded to 2GW). Additionally, we will see a 60% decrease in the aperture of the PowerSat transmitter.

The proposed solution, which is a new invention, is to place low mass Reflector Satellites in an Equatorial Medium Earth Orbit (EMEO) and use the reflector satellite to reflect the power transmitted from the PowerSat to the rectenna on the Earth's surface. Placing just a few reflector satellites in EMEO to reflect the energy to rectenna on the Earth's surface is potentially a low cost solution since the reflectors can be very low mass inflatable structures **(4,9)**.

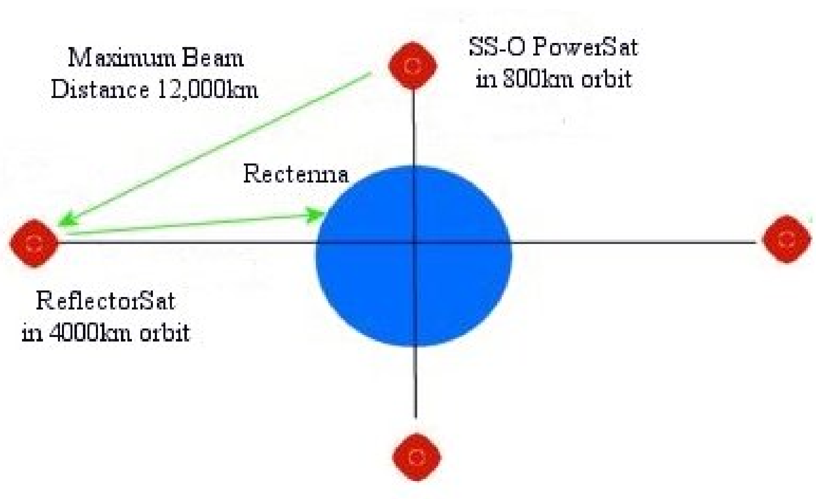

Figure 1: Looking at the equator, showing SSO PowerSats and Equatorial ReflectorSats

Assuming the same technology level as proposed in the 1980 NASA/DOE study with a 5GW PowerSat with 2x solar concentration and 20% efficient solar cells we see that the total mass of was 34 million kg. Of this the transmitter mass was estimated at about 13 million kg or 38.2% of the total mass. A 2GW PowerSat in SS-O is only 40% of the GEO PowerSat mass or 13.6 million kg. The transmitter mass of the 2GW system being estimated at 38.2% of the total mass would be about 5,263,200 kg. However since the beam distance has decrease by 60% the transmitter mass can now be reduced by 60%. This would reduce the transmitter mass to only 3,157,920 kg giving a satellite mass of 11,494,720 kg.

Sun-synchronous orbiting SBSP Satellite with Equatorial orbiting Reflector Satellite for Earth Energy

Assuming a 20% mass penalty for launching into SS-O due to the greater Delta-v required for launching into a near polar SS-O orbit this would be equal to launching 13,793,664 kg into equatorial orbit for a mass penalty of 2,298,944 kg. However, there is more to this because you would have to move the GEO satellite from LEO to an altitude of 31,000 km and the SS-O satellite from LEO to only 800 km. Moving a satellite that distance would consume lots of propellant even when using efficient ion drives. According to the 1980s NASA/DOE study the propellant mass would be 1/10th of payload mass, so to move the satellite to GEO would consume 3.4 million kg of ion propellant. Using today's technology we might get a propellant mass fraction of 20% and this would cut propellant mass in half to 1.7 million kg. Therefore, the total mass to orbit, not counting any space infrastructure, would be 34 million kg plus 1.7 million kg of propellant for a total mass of 35.7 million kg. By comparison the SS-O mass to orbit for a same 5GW of power would be 11,494,720kg times 2.5 or 28,736,800kg plus launch penalty of 20% or 5,747,360kg plus 50,000 kg for the reflectors in EMEO for a total of 34,534,160kg. Therefore, the mass difference is only about 1,165,840kg. However, to obtain power from space you only need to deploy an 11,494,720 kg 2GW system rather than a 34,000,000 kg 5GW system and this is the main benefit of the Space Grid. It reduces first cost to power and allows a much smaller SBSP satellites to be deployed on orbit more quickly.

The Constellations

The proposed SBSP system would use eight SBSP satellites, ten reflector satellites and eight Earth rectenna. The reason for ten reflectors is related to the view time of each reflector over a rectenna below, which is about eighteen minutes. From the SS-Orbit each PowerSat can view most of the reflectors and chose which one to beam to using electronic beam steering. The proposed constellation can provide power to the eight ground stations. With eight SBSP satellites, each producing 2GW of energy the constellation would deliver 16 GW of clean energy to the Earth.

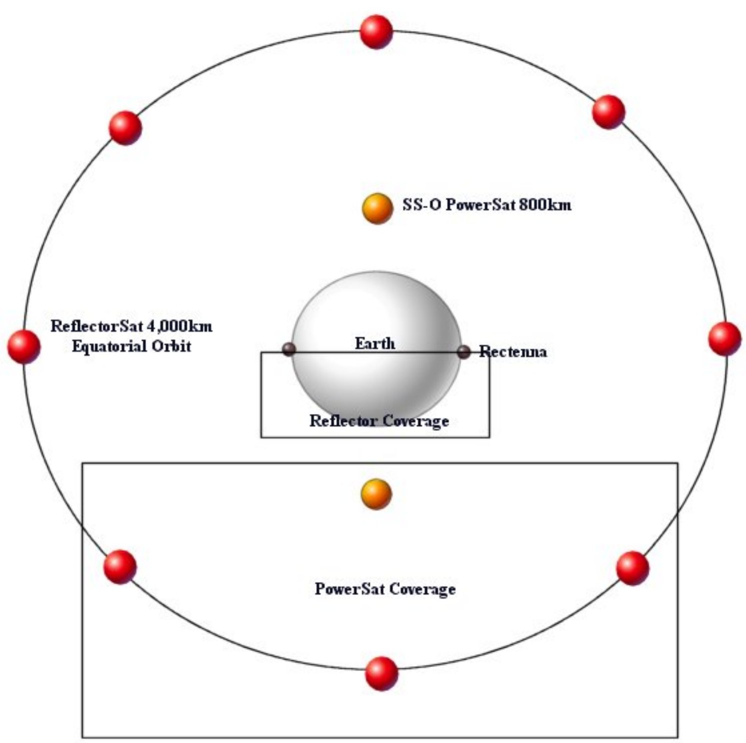

Figure 2: Looking down on the Earth showing the SS-O PowerSat Constellation with two PowerSat satellites and Equatorial ReflectorSat Constellation with eight satellites.

For SBSP, the dimensioning of the RF power transmission system results from an adequate balance between the definition and sizing of the receiver system (rectenna) and the definition of the SBPS transmitting system, the key driver being the transmission frequency. For an SBSP system operating in SS-O and incorporating an SPG in equatorial orbit, the addition of the space-based microwave reflector has to be taken into consideration. Power loss at the reflector should be less than 1% **(4)**. The much smaller transmission distance, which is only 33% of that of a GEO Powersat, means that both the transmitter and rectenna can be 67% smaller than a GEO based system which increases the economic viability verse concepts based in GEO.

In comparison with proposed alternatives, the Space Grid approach has clear potential to enable radical improvement in terms of higher performance, lower cost, less mass, higher reliability, improved safety, and ease of manufacturing and maintenance. Placing a SBSP satellite in SS-O can be very beneficial as it would allow the satellite to produce constant power. By using SS-O dawn-to-dusk orbiting PowerSats, these could produce the same power levels of as those of PowerSats located at geostationary orbits, as it was originally proposed by Peter Glaser in 1969 (1) and which is still discussed by many in the space community. Moreover, by locating a PowerSat in the SS-O (800 km) it would be much closer to Earth than a PowerSat on GEO (36,000km), therefore allowing for the use of much smaller transmitters and rectenna (Drummond 2, Jones 3) and so consequently reducing the amount of mass to be transported into the operational orbit. There is a launch mass penalty of approximately 20% for launching into near polar orbits verse launching from the equator. Therefore, the tradeoff is a lower mass space transmitter verse the reduced mass launched into SS-O.

Using the Space Grid for Space Settlement

Reusable in-space transportation systems must be capable of both high fuel efficiency and high utilization of capacity, or economic costs will remain unacceptably high. BSEP systems can provide high fuel efficiency and with enough high thrust to support cargo and crewed missions. The major contribution of beamed power to the development of space is its unique ability to transfer energy across long distances and across large differences in gravitational potential. This technology can also be applied to a Spaceship in LEO orbit propelled by electric thrusters whose power is supplied by a microwave beam originating at SS-O.

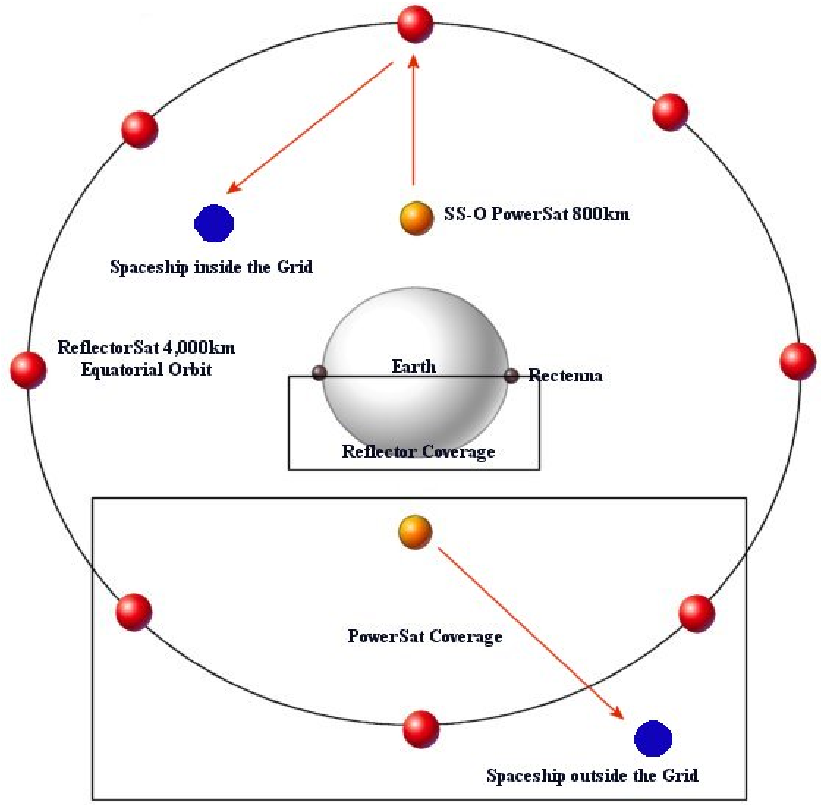

Figure 3: Looking down at the Earth's North Pole. The space grid is powering tow orbiting spaceships, it shows one spaceship operating inside the grid and another spaceship operating outside the grid.

Power generation is one of the crucial elements of space vehicles and of future infrastructures on planets and moons. The increased demand for power faces many constraints, in particular the sizing of the power generation system. The SPS Space Grid system is a candidate solution to deliver power to space vehicles or to elements on planetary surfaces. Beaming energy to spacecrafts could lower spacecraft mass and improve mission-economic potential. A BSEP system with SS-O PowerSats beaming to equatorial Ion Spaceship would reduces the ships's mass by a factor of 30 compared to direct drive solar or nuclear ships. This promises a significant reduction in the cost of space transportation.

Conclusion

Newer concepts for SBSP have substantially reduced the mass of the satellites by using large solar inflatable concentrating reflectors, thereby reducing the mass of the solar cells and supporting structure. The mass of power relay satellites (PRS) can also be reduced using similar large reflector technology. Reflectors satellites with a mass of 5,000kg can be launched into a 4,000km orbit using a small launch vehicle or an entire constellation could be launched using a single Falcon Heavy.

The development of a Space Grid using SS-O SBSP PowerSats with Equatorial orbiting ReflectorSats appears to offer all of the advantages of GEO PowerSats, including constant power production for base-load energy. Additionally, it appears to offer many advantages over GEO stationing including, no LEO-GEO transportation, ease of maintenance due to closer positioning, much less mass to orbit due to transmitter sizing and the ability to direct more energy to the day side of the Earth. While operationally the concept is more complex than GEO stationing, this is overshadowed by the large reduction in the minimum size verse GEO since the minimum size of the PowerSat is reduced from 5GW to only 2GW. What this means is that you can start producing power in space by launching only 11,494,720 kg rather than 34,000,000kg and this can move humanity closer to clean energy from space. It also means that we can power in inner solar system and open space settlement to humanity.

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