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Alternative Orbits: A New Space Solar Power Reference Design

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Abstract

This paper offers a new space solar power reference design based on an elliptical 3-Hour sub-Molniya orbit. Most studies of space-based solar power (SBSP) systems to date have assumed that satellite stationing and photovoltaic (PV) solar energy conversion will take place in geostationary orbit (GEO). This paper argues that GEO/PV systems are not the most feasible solutions for SBSP, not technically and not economically.

Thirty six thousand kilometers above earth is a logical destination for a number of reasons, but that orbit is already largely committed. What is more, this great height and the mass and number of space solar systems proposed for GEO will not be cost-justifiable anytime soon. Decades will pass before this promising location will be a major solar power satellite (SPS) destination due to incumbent player resistance over possible signal interference. Also, dramatic improvements in space-based PV cell technology will be needed, as will reductions in the cost of space launch. SPS systems will be a predictable contributor to our energy future when these birds are built to operate in space at costs competitive with energy systems on Earth. Successful SPS designs will be those that are technically feasible, economically affordable and can be proven to work.

One way to shorten time-to-term, and thereby alleviate some of these constraints, will be to look for a workable non-GEO orbit. The author suggests a highly elliptic 3-hour orbit similar to the Molniya orbits used by the Soviets only operating much closer to Earth. This orbit will provide about 2 hours of transmission time per orbit and 1 hours of non-transmission time. When compared to the GEO location, this new class of sub-Molniya orbits has the potential to substantially reduce SSP satellite mass.

SPS Reference Designs ?

The 1979 SPS designs consisted of large, erected infrastructures. These massive units required a two-stage Earth-to-orbit (ETO) transportation system to lift the needed material as well as a large construction facility in space and hundreds of astronauts. The financial impact of this deployment scheme was significant. In 1966 dollars, more than $250 billion was estimated to be required before the first commercial kilowatt-hour could be delivered. (Mankins, 1997)

The dimensions of the NASA baseline SBSP concept from 1981 are shown in Figure 1 below. The concept has a system mass of approximately 51,000 metric tons.

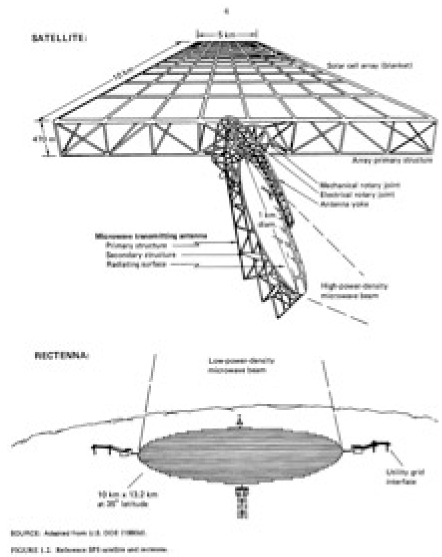

Figure 1.
Source: Electric Power from Orbit: A Critique of a Satellite Power System. National Research Council of the National Academy of Sciences, 1981
(click image for larger view)

The U.S. National Research Council (NRC) and the Congressional Office of Technology Assessment (OTA) concluded that solar power satellites were technically feasible, but they were declared "programmatically and economically unachievable" based on the 1979 SPS Reference designs. Although the NRC recommended that related research continue and that the issue of solar power satellite viability should be revisited in about a decade, in fact all serious effort on solar power from space by the U.S. government ceased. (Mankins, 1997) The NRC report stated, "Too little is currently known about the technical, economic, and environmental aspects of SPS to make a sound decision whether to proceed with its development and deployment. In addition, without further research an SPS demonstration or systems-engineering verification program would be a high-risk venture." (NRC, 2001)

The National Aeronautics and Space Administration (NASA) re-examined the technologies, systems concepts and terrestrial markets that might be involved in future space solar power systems during 1995-1997. Its principal objective was to determine whether solar power satellites (SPS) could deliver energy "to terrestrial electrical power grids at prices equal to or below ground alternatives in a variety of markets, do so without major environmental drawbacks, and which could be developed at a fraction of the initial investment projected for the SPS Reference System of the late 1970s."(Mankins, 1997)

Three architectures were identified as promising: a sun-synchronous low Earth orbit (LEO) constellation, a middle Earth orbit (MEO) multiple-inclination constellation, and one or more stand-alone geostationary Earth orbit (GEO) SPS serving single, dedicated ground sites. Of particular interest was the Sun Tower concept because it offered a much smaller transmitter size hosted in a closer orbit.

Sun Tower: The "Sun Tower" concept illustrated in Figure 2 includes a constellation of medium-scale, gravity gradient-stabilized, RF-transmitting space solar power systems. Each satellite resembles a large, Earth-pointing sunflower in which the face of the flower is the transmitter array, and the "leaves" on the stalk are solar collectors.

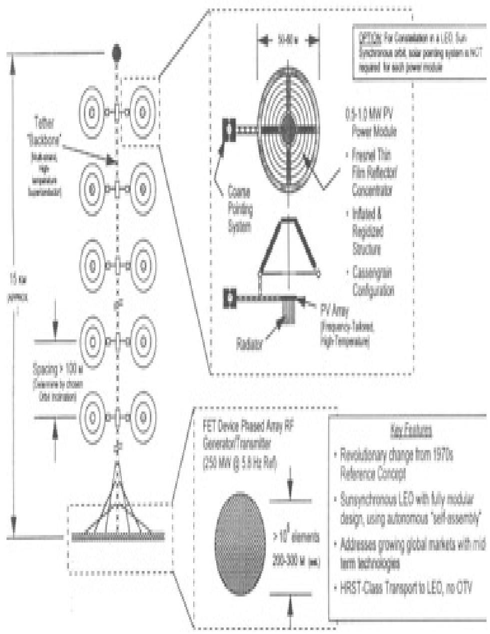

Figure 2: The "Sun Tower" SPS Concept (MEO constellation)
Source: A Fresh Look at Space Solar Power: New Architectures, Concepts and Technologies, page 11 (click image for larger view)

It is easy to see that the Sun Tower concept located in MEO is a major improvement over a GEO location due to its much lower mass to orbit. Even so, papers are still published that are based on GEO concepts with high mass requirements. There are even papers that move the MEO Sun Tower to GEO. Most such papers come from the U.S. aerospace community which seems to be driven more by the desire to expand man's domain into space that requires building massive new launch vehicles than by the desire to produce power in space.

NASA scientist John Mankins noted, “Since the sun provides about 1365 watts per square meter of energy at the Earth's orbit, generating a megawatt with a 20% efficient array requires an area of about 3700 square meters. However, the SPS concept that emerged by 1979 was not only large, it was also infrastructure-rich because it was based upon the large, astronaut-erected space platform concepts that were common of this era in which Gerard O'Neil and others envisioned the eventual construction of vast, artificial cities in space.” (Mankins, 1997)

The large infrastructure-SPS concepts all required massive financial investments to carry crews and cargo into space necessary for assembling these giant satellites in GEO.

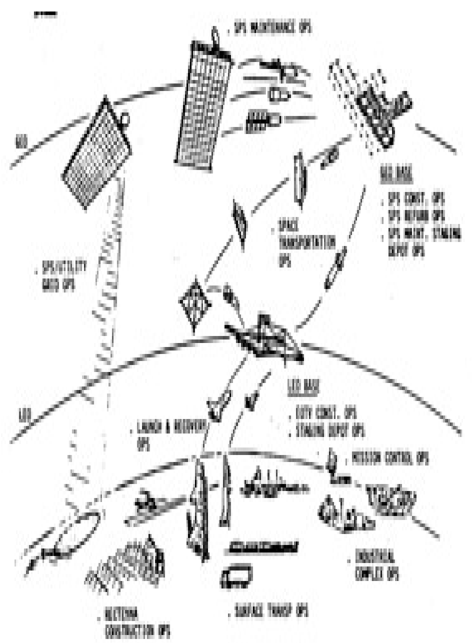

Figure 3: Infrastructure rich SPS.
Source: Integrated Space Operations Overview, Gordon R. Woodcock, Boeing Aerospace Co. 1980 (click image for larger view)

Such approaches are of course counterproductive because economically unviable concepts actually limit progress not only for power production but also in development of new launch vehicles and space infrastructures. While a few investigators were discussing LEO and MEO space-based solar power (SBSP) satellites as far back as the 1970s, their ideas have been largely pushed aside in favor of the GEO location. (Drummond, 1980) This illogical addiction to an unnecessary GEO infrastructure is the principal reason so little progress has been made in SBSP.

The Problem

Most solar power system placement proposals are intended for geosynchronous orbit. This is one reason the GEO solar power satellite (SPS) systems end up having an initial start up cost of tens of billions of dollars. The largest single cost of GEO solar power satellites is the cost of launching the components into orbit. The second largest cost is moving the components from low Earth orbit (LEO) to geostationary (GEO).

The problem with GEO SPS is the 36,000 kilometer distance. This distance from Earth requires large microwave transmitters and large ground receivers. The great distance also results in very high launch costs due to the transmitter size and mass and the very real prospect of interference with the large number of communication satellites located there.

As noted in Figure 4, the reason that the solar power satellite must be so large at GEO has to do with the physics of power beaming. The smaller the transmitter array, the larger is the angle of divergence of the transmitted beam. A highly divergent beam will spread out over a wide land area, and may be too weak to activate the rectenna. In order to obtain a sufficiently concentrated beam, more power must be collected and fed into a large transmitter array.

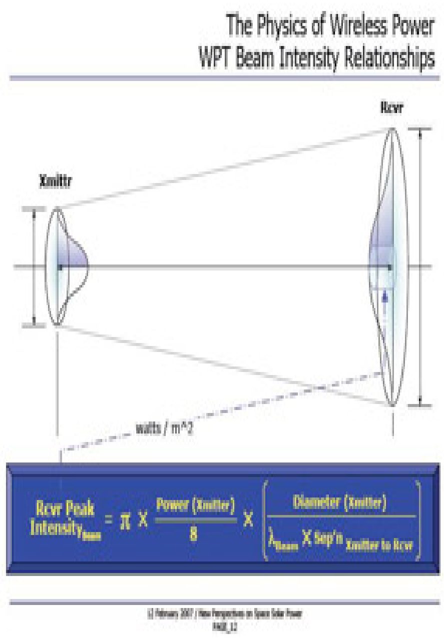

Figure 4.
Source: Space-Based Solar Power as an Opportunity for Strategic Security, Phase 0 Architecture Feasibility Study Report to the National Security Space Office, October 10, 2007, page 27 (click image for larger view)

Power beaming from geostationary orbit by microwaves has the added difficulty that the required "optical aperture" sizes must be very large. The 1978 NASA SPS study required a 1km diameter transmitting antenna, and a 10 km diameter receiving rectenna, for a microwave beam at 2.45 GHz frequencies.

Alternative Orbits

Due to the mass-to-orbit requirements for geosynchronous SPS, other options should be considered. As will be shown, the closer the orbit to the Earth the more efficient space solar power systems can be. But there is a serious limitation. The primary problem with solar power satellites in LEO or MEO is transmission time over the receiver. We think a solution can be found in the use of Elliptical Orbits. Due to the second Kepler law of planetary motion, the satellite spends about two thirds of the time near its apogee where it provides what is very close to a stationary perspective centered over the high latitudes. A powersat operating in a low Molniya orbit can achieve a utilization rate of 70 percent. While this is less than the 100 percent rate of GEO powersats, the mass reduction possible by being located closer to earth more than offsets the handicap of reduced transmission time by allowing for satellites that are smaller and lower cost, which also means the launch costs can be less expensive.

Medium Earth Orbits: Given the physics of wireless power transmission, when compared to geosynchronous (GEO) orbit at 36,000 km, medium (MEO) Earth orbits located at 10,000 km or less, should permit considerable reductions in the size of both the solar power transmitter and the ground receiver. Furthermore, a smaller ground receiver is better suited to servicing such high-density markets as exist in Japan and Western Europe.

If the technical, economic and societal viability of MEO systems can be demonstrated, then space-based solar power systems in LEO could also prove to be of major interest, when the satellites are as close as the International Space Station more or less 600 km above Earth. The first step in demonstrating either of these possibilities is to move away from past concepts based on solar power satellites stationed 36,000 km from Earth.

Elliptical Orbits: A highly elliptical orbit (HEO) is characterized by a relatively low-altitude perigee and an extremely high-altitude apogee over Earth. An elongated orbit can have the advantage of long dwell times over the receiver during the approach to and descent from apogee. Bodies moving through the long apogee dwell can appear still in the sky to the ground when the orbit is at the right inclination, and when the angular velocity of the orbit in the equatorial plane closely matches the rotation of the surface beneath.

Elliptical orbits are useful for communications satellites. Sirius Satellite Radio uses HEO orbits to keep two satellites positioned above North America while a third follow-on satellite quickly rounds the southern part of its 24-hour orbit. A solar power satellite placed in a 3 hour elliptical Molniya Orbit would have a utilization rate of 70%.

SPS in Elliptical Orbit

Successful SPS designs will be those that are technically feasible and economically affordable. One way to shorten time-to-term, and thereby alleviate some of these constraints, will be to look for a workable non-GEO orbit. The author suggests a highly elliptic 3-hour Molniya orbit. These SBSP satellites will generate zero pollution and zero emission energy.

There is no logic to placing SBSP Satellites in GEO. The only advantage is the ability to constantly remain over one area on the Earth's surface. Clearly, this advantage is not worth the massive increase in satellite mass that this single advantage gives. For example, the transmitter mass difference between GEO 24-hour orbit and a circular 12-hour orbit is 50 percent. The mass of the transmitter is cut in half simply by moving it closer to Earth, the ground receiver is half the size and the system is more economically viable. To deliver energy to ground receivers 24 hours per day, the design calls for two equal satellite systems spaced 12 hours apart providing coverage to two ground stations (Figure 6). Each satellite will host a transmitter one-fourth the size of the GEO system.

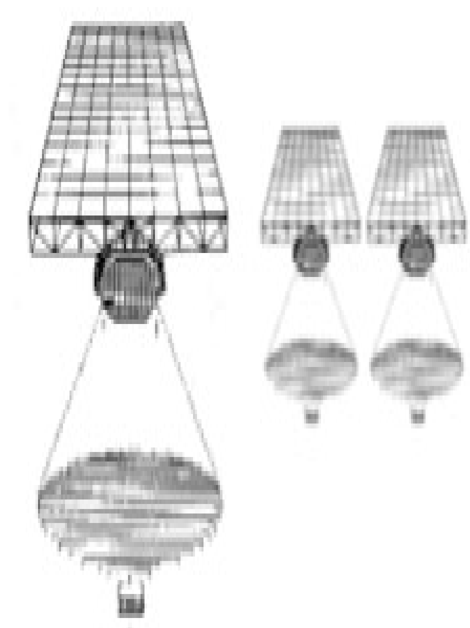

Figure 5: Size of satellites in 12-hour orbit versus GEO.
Source: Author (click image for larger view)

To further reduce satellite transmitter and receiver mass, the powersats can operate in a 3-hour sub-Molniya orbit. This orbit is preferred because it provides more beam time per ground station than a circular orbit. Because the orbit is elliptical, the satellites slow down near apogee and speed up near perigee. This provides a "hang time" of about 2 hours over the receiver.

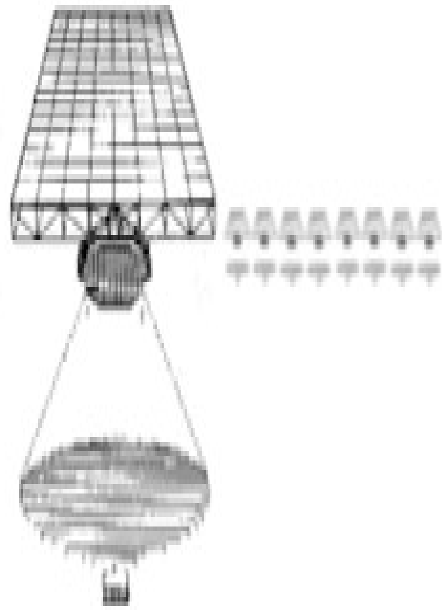

Figure 6: Size of satellites in MEO/LEO versus GEO.
Source: Author (click image for larger view)

New Reference Design

To achieve progress in SBSP satellite design, we need to create a new Reference Standard based on lower cost LEO and MEO satellite placement. The suggested model would be:

- 3-Hour Elliptical Orbit
- Beam time 2 hours per orbit
- Orbit Non-transmission Time 1 hour
- Utilization Rate 70% (without power storage)
- Orbits per day 8
- Total beam time 2 x 8 = 16 hours

The highest priority research areas for solar power satellites are those where major improvement can be made in the technical feasibility and cost of the system. The advantages of space-based solar power cannot be realized in the near-term due to the presumed cost of transmitting power from orbit to receiving stations on Earth. These two components are interdependent due to the need for high efficiency power transmission. Since SBSP microwave transmitter size and mass is a direct function of distance between transmitter and receiver, only sub-GEO satellites should be considered. This can be a shocking revelation for people who have always taken it as a given that SBSP satellites must be positioned in a geosynchronous orbit.

Transmitter mass is a large part of SBSP satellite design and therefore affects the system cost, especially launch costs. Since the power transmission subsystem represents about half the capital cost of the total SPS reference system, it is worthwhile to consider the lower orbit alternatives so the technological, environmental, social and political problems and relative advantages may be assessed in comparison with those of geosynchronous forms.

J. E. Drummond notes that at + 64.4 degrees these two orbits alone would be adequate to supply the base load needs of centers between latitudes 40 and 60 degrees with rectenna an order of magnitude smaller than those required to receive power from an antenna of given area at geostationary orbit." (Drummond, 1980)

Earth Segment

The benefits of SPS deployments in LEO impact not just the space segment, i.e. the space transmitter, but also the ground receiver. According to Kotin, writing in 1978, the total land area required by each rectenna facility, including provision for a microwave buffer zone, based on GEO-located satellites is estimated at approximately 50,000 acres or 200 square kilometers. (Kotin, 1978) By locating the satellites in LEO ground receiver size is reduced by over 90 percent. Past cost estimates for ground systems using the GEO satellite reference exceed $2 billion. Alternately, LEO satellite system ground receivers using the Sunflower concept will require more or less 4 square kilometers of space, costing a small fraction of the GEO system ground receiver.

Affordability

Drummond of Power Conversion Technology, Inc. calculates that smaller power blocks will increase market penetration by opening smaller markets (including those in the Third World), by lowering costs of service to decentralized markets, and by smoothing introduction of the SPS power into the Grid." (Drummond, 1980) What is being proposed is the need to break up the satellite system into more economically affordable systems. By having several smaller SBSP satellites operating in network, the system can be deployed incrementally and is therefore more affordable than building a single giant satellite.

The ability of space solar providers to begin delivering power early in the constellation deployment and to be able to incrementally increase constellation size can add to the affordability factor. Following this model, space energy providers don't need to spend hundreds of billions of dollars to build a single massive satellite when smaller systems will serve the purpose.

Conclusion

The current baseline concepts specifying GEO powersats are flawed. They are poor design concepts that do nothing to advance SBSP development because they advance system strategies that are uneconomical and unaffordable. These concepts actually discourage SBSP development. Until we develop new, more realistic and more economically viable systems concepts for solar power satellite implementation we will be wasting our time trying to sell it to governments and to the people of this planet. By establishing economically viable models for SBSP we can move closer to pure green energy and accelerate man's move into space at the same time.

A new baseline model is needed that substantially reduces mass to orbit. The proposed 3-hour sub-Molyina orbits for SBSP satellites could provide the better model. This orbit will be especially useful in providing power to the higher latitude markets of Canada, Russia, US-Alaska and Europe.

Accelerating the development of space based solar power is important to the future of mankind. A continuous and clean source of energy is greatly needed to sustain growth and for the protection of the Earth's environment. New and innovative approaches to in-space power production in space networks have the potential of offering cost effective supplies of power, more quickly. Such an innovation in powersat design is the use of a low Earth sub-Molniya orbit in which constellations of smaller satellites operate in elliptical orbits. Such an approach could diversify delivery of power to multiple rectennas while keeping ground stations to acceptable size.

The primary challenge for space solar power towers is economics. Over half the cost of SPS is associated with launch costs. To reduce launch costs, the size of the system must be reduced. This proposal reduces the system mass substantially. The sub-Molniya orbit places the satellites closer to Earth and allows for their servicing.

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