Solar Power Satellite Development: Advances in Modularity and Mechanical Systems

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Abstract

Space solar power satellites require innovative concepts in order to achieve economically and technically feasible designs. The mass and volume constraints of current and planned launch vehicles necessitate highly efficient structural systems be developed. In addition, modularity and in-space deployment will be enabling design attributes. This paper reviews the current challenges of launching and building very large space systems. A building block approach is proposed in order to achieve near-term solar power satellite risk reduction while promoting the necessary long-term technology advances. Promising mechanical systems technologies anticipated in the coming decades including modularity, material systems, structural concepts, and in-space operations are described.

1.0 Introduction

For four decades, the concept (Ref. 1) of deriving terrestrial energy from space-based solar-electric systems using wireless power transfer has captured the imagination of government and private stakeholders. Various studies of this concept were conducted during the 1970s, by NASA and the Department of Energy (Ref. 2). This study resulted in the 1979 Reference Solar Power Satellite (SPS) System, shown in Fig. 1. As described by Mankins (Ref. 3), the 1979 SPS architecture entailed deploying a series of as many as 60 SPS into geostationary Earth orbit with each system providing power ranging from 5 to 10 GW of continuous energy. While the 1979 SPS reference architecture was deemed technically feasible, it was assessed as being programmatically and economically unachievable.

In 1995 NASA's Advanced Concepts Office initiated a new “fresh look” at the requirements and technology for a space solar power system (Ref. 3). The Mankins' study identified new system concepts including the "SunTower" - a gravity gradient stabilized, space tether-based SSP system concept. In the late 1990's, NASA developed a new SPS concept based on optical concentrators. As shown in Fig. 2, the Integrated Symmetrical Concentrator concept utilizes thin film optics to concentrate the solar radiation and thereby reduces the photo-voltaic array size. More recently the National Security Space Office (NSSO) studied the use of Space-Based Solar Power (Ref. 4). The NSSO study also adopted the symmetrical concentrator SPS concept. In each of the SSP concepts studied to date, very large structural systems are an enabling attribute. Since the system cost is highly dependent on mass and complexity, development of advanced mechanical systems is crucial to achieving economical designs.

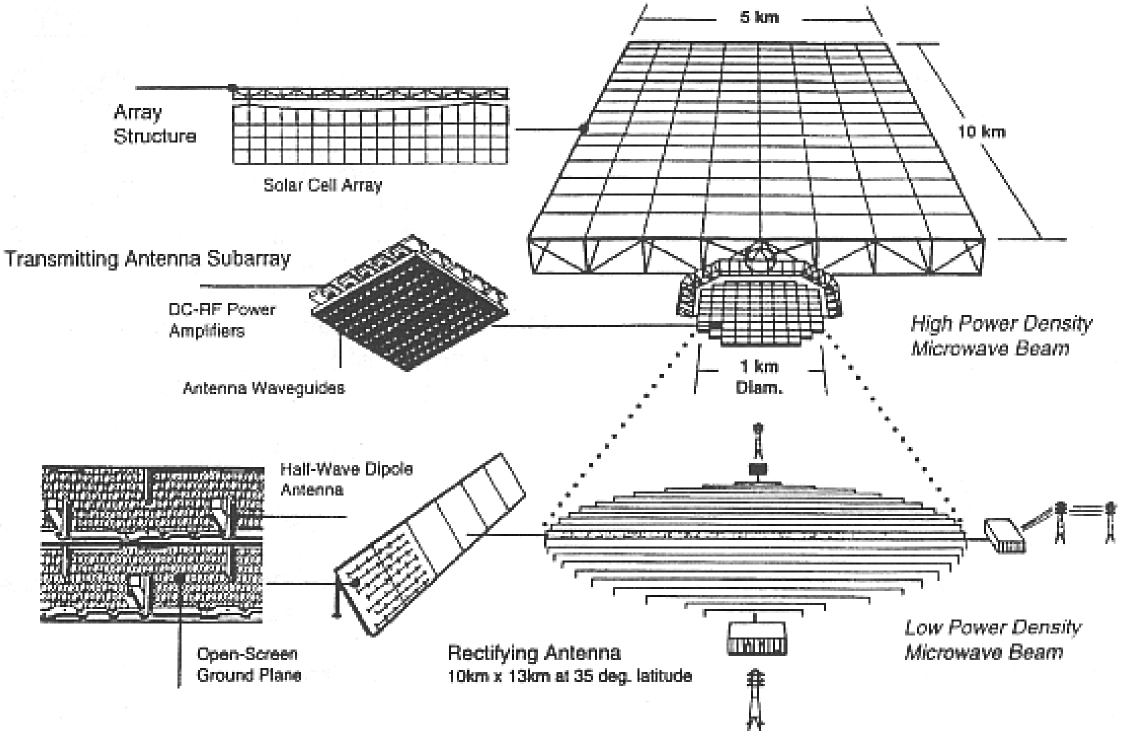

Figure 1: 1979 Reference System Concept (5 GW , GEO Based)

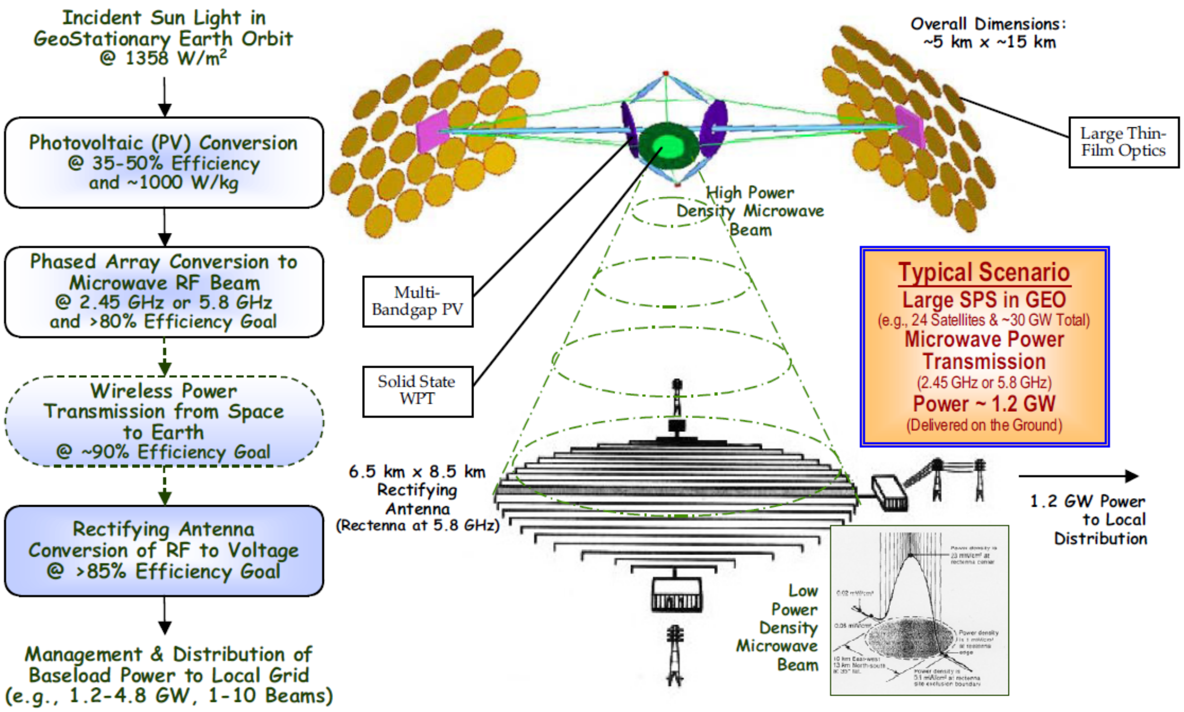

Figure 2: Integrated Symmetrical Concentrator Concept

In this paper, a two-phase building block approach is proposed to develop and validate large SSP systems. The first building block is a near-term, low power, tactical system with application to customers willing to pay a premium for consistent and uninterrupted power. This smaller low power system would validate fundamental technologies as well as technical and operational models. The proposed second phase of SSP development would involve focused investments in advanced technologies required for systems capable of producing commercial levels of power and transferring that to the terrestrial power grid. The materials, structures, and mechanical systems (MSMS) technologies that can be employed in a near term tactical demonstrator and for very large SPS systems are briefly described. A more detailed discussion of these technologies can be found in Ref. 5.

2.0 Building Block Approach: A Two Phase SSP Development

The first phase focuses on a near term application/customer of SSP that is willing to pay a premium for consistent and uninterrupted power. An example of this would be military bases in remote and hostile regions, where the logistics train for fuel (to run generators) is very expensive, dangerous, and subject to constant disruption. Low power SSP systems may also be used in orbit around the Moon, Mars and other solar system planets and moons to provide power to surface rovers, outposts, etc. The power generation level (at the source) for this first phase application might be from 100-5000 KW. This application would use current and near term technology (structures, solar cells, ion propulsion/station keeping, avionics, power beaming, etc.) for spacecraft subsystems and automated rendezvous and docking for spacecraft assembly.

The goal of the second phase would be to develop the advanced technologies required for a SSP systems capable of producing 100-2000 MW of power for commercial transfer to the Earth’s power grid. Such large satellites would only be developed when appropriate systems and technologies were sufficiently advanced to make them commercially viable. Using block upgrades on first phase systems to develop and demonstrate the advanced technologies as they become available would reduce the cost, schedule and performance risks of very large system implementation. In addition, the probability of commercial system development success would be maximized because development would not begin prematurely.

2.1 Example of First Phase SPS System

Reference 6 presents a design concept for a Solar Electric Transfer Vehicle (SETV) as shown in Fig. 3. The SETV class satellite could be readily augmented with wireless power transfer technology and demonstrated as a phase 1 SPS system. The SETV is designed to transfer cargo from Low Earth Orbit (LEO) to Low Lunar Orbit (LLO). The SETV tug uses photovoltaic solar transport a 60 metric ton payload from LEO to LLO and return in less than one year.

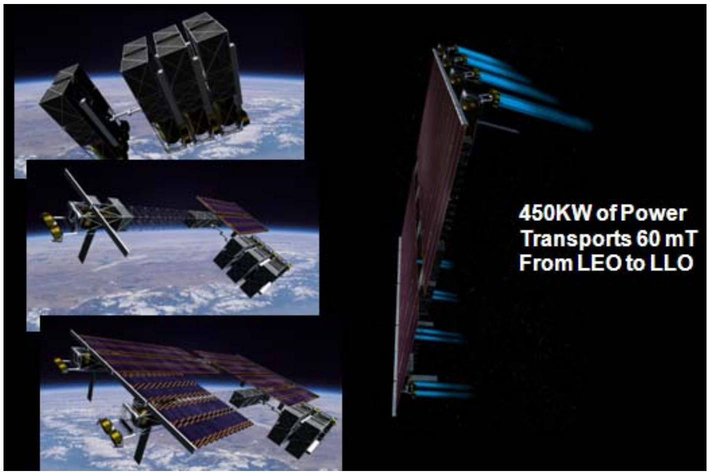

Figure 3: Modular SETV Concept

General design features that significantly contributed to the SETV configuration and applicable to a first phase SPS include: 1) the system be composed of modular units that can be replaced in situ; 2) the configuration be amenable to a variety of design implementations and system decomposition, allowing it to be packaged on a variety of launch vehicles; and, 3) the launched components be capable of being assembled on orbit using both human and robotic resources and capabilities.

Individual sub-modules and components that make up one 50 KW-class SETV System Module are show in Fig. 4. The reference 450 KW-class SETV is composed of eight of these SETV System Modules. With a few modifications, the near term SETV could form the basis of the first phase SPS system. Instead of all of the power in each SETV module being routed to its associated thrusters, the bulk would be routed to a wireless power transmitter (microwave or laser) mounted at the center of the spacecraft for transmission to the Earth’s surface. The system was sized such that a 50 KW-class module could be launched by a Delta 2-Heavy, or four pre-assembled modules launched in a Delta 4-Heavy class launch vehicle. Automated on-orbit rendezvous and docking is an established technology and is used to dock modules to assemble the complete SPS system. The system could be assembled in LEO, to allow for checkout, and then it could propel itself to its service orbit.

2.2 Second Phase SPS System

The sucessful first phase SPS demonstator will provide the knowledge in terms of validated performance/economics models and operations experience to permit large scale system architecutres to be developed for a 1000 MW class SPS. As indicated in Fig. 2, the Integrated Symmetrical Concentrator Concept is one of those promising architectures. The choice of wireless power transfer technology, specifcally the wavelength (RF or Laser), can have a substantial influence on the SPS antenna size and thermal requirements. Moreover, large inflatable concentrators have been proposed to reduce the photo-voltaic area (and cost) with little attention to space durable materials. These geometric and

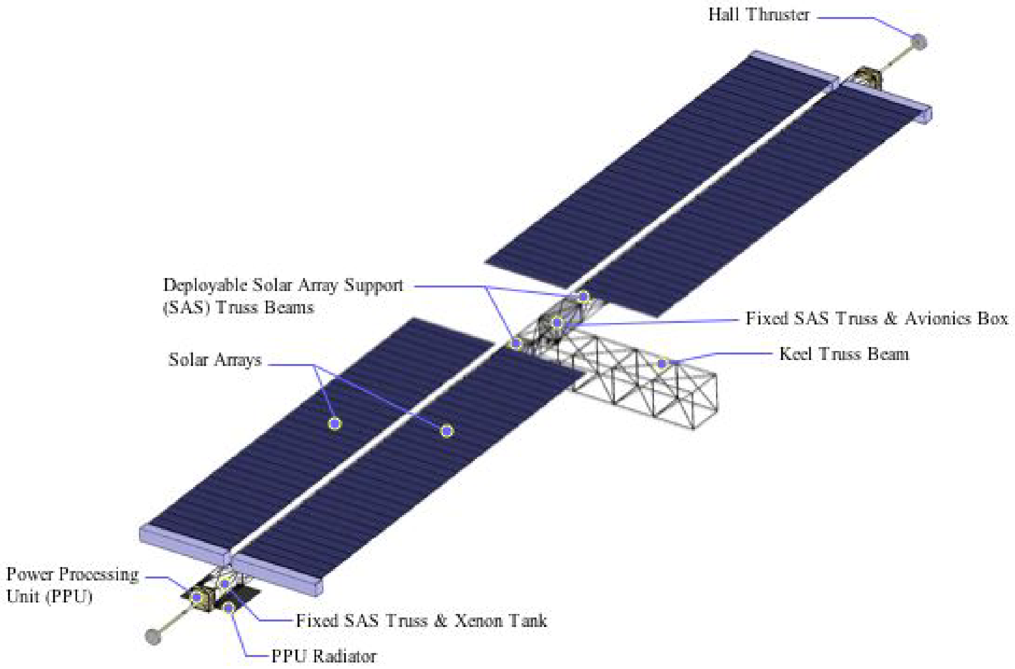

Figure 4: Subsystems making up a 50 KW-Class SETV module.

environmental requirements necessitate the continued advancement of materials, structures and mechancial systems (MSMS) for a second phase, 1000 MW class SPS. To this end, specific advances in MSMS technology that would benefit very large space structural systems in the coming decades are discussed in the following section.

3.0 Materials, Structures and Mechanical Systems (MSMS) Technology

The MSMS technology areas selected for this discussion include:

- Modularity (Module Based Assembly and Upgrade)
- Material Systems (Space Durable, High Temperature, and Thin Films)
- Structural Concepts (Inflatable, Rigidizable and Gossamer Concepts)
- In-Space Operations (Deployment, Assembly, and Repair)

Detailed discussions of these technology areas can be found in Ref. 5.

3.1 Modularity

The goal of modularity is to simplify space-platform design by developing versatile repeating units that have a range of common features and interfaces. Modularity reduces mission risk, and allows spares and replacements to be available during system assembly. Modularity, together with a robust capability to perform in-space assembly, has the potential to greatly enable the SPS mission. The modular assembly approach was used as a basis for designing the previously described Solar Electric Transfer Vehicle (SETV).

The modular assembly design approach is significantly more complex than simply the design of repeating and versatile units. The complete and comprehensive modular assembly system-of-systems encompass all of the following: 1) the mission-level system that utilizes the modules and the associated module specifications and designs; 2) the agents that assemble, service and repair the modular subsystems (robots or astronauts); 3) the operations, and associated planning, required during assembly (positioning, aligning, joining), servicing and repair; and 4) the infrastructure (cranes, mobile platforms, etc.) required to facilitate operations and enhance agent capabilities. All of these systems must be considered simultaneously in order to develop a modular architecture that maximizes the potential benefits.

3.2 Material Systems

Materials are enabling for any structural system. For SPS systems, lightweight materials are needed that exhibit the proper combination of mechanical, thermal, and electrical properties for long periods of time in the space environment, particularly radiation and micrometeroid and orbital debris (MMOD) exposure. Space durable and high temperature material systems with high specific strength and stiffness are needed both for the primary structure and devices and sensors. A survey by Harris, et al. (Ref. 7) in 2002 identified aerospace materials in current use and those with high potential for the future. The study indicated that single wall carbon nanotube based materials offer the potential for a 3 to 5 increase in specific stiffness and nearly two orders of magnitude increase in specific strength as compared to state-of-the-art polymer matrix composites. Much research has occurred to advance the knowledge of carbon nanotube materials (CNT) and more recently Boron nitride nanotubes (BNT) materials. Both CNT and BNT materials are attractive for application to SPS because of their unique thermal, electrical, and mechanical properties.

In addition to high stiffness and strength properties, materials conditioned to undergo large strains during deployment and capable of post-deployment rigidization are highly desired to facilitate packaging for launch and deployment of SPS systems on-orbit (Refs. 8, 9). Finally, damage due to MMOD impact on large systems such as SPS concentrators and arrays makes the development of materials with self-healing properties critical to achieve long term operations. In particular, recent and future advances in high temperature materials, rigidization technology, and self-healing materials will provide lower cost, longer life SSP systems.

3.3 Structural Concepts

A high level metric during the “Fresh Look Study” (Ref. 3) was to achieve a structural design for the primary SPS structure at less than < 3-4 kg/KW. For a 1000 MW SPS, considering the launch cost to be $1000/kg, this would require an investment of $3-4 billion to launch just the primary structure. For most aerospace systems, the primary structure is approximately 20% of the dry mass. Thus, a 1000 MW SPS would require $15-20 billion for launch costs alone. Clearly, structural concepts that enable a lightweight architecture will have a first-order impact on SPS economics. In addition to low mass, the structural concepts must also support a flexible and modular approach to achieving SPS long-life (15+ years).

The integrated symmetrical concentrator SPS concept (Fig. 2) requires multi-kilometer size concentrator/reflector arrays. While these structural components will be gossamer thin film tension stabilized membranes, they will also require shape control to keep solar light reasonably focused (in a non-coherent manner) on the photovoltaic arrays. Thus, the concentrator designs will be both mass and stiffness driven designs utilizing high performance materials. NASA solar sail technology investments over the past decade have provided lightweight structural concepts directly applicable to SPS concentrators (Refs. 10, 11).

3.4 In-Space Operations

In order to field a SSP system, a variety of in-space operational capabilities are needed. Since each SPS will be very large, it is assumed that multiple launches will be required to place the subsystems into low Earth orbit (LEO). Two options exist for completing the system, either assembling in LEO and then transferring the completed system to its final orbit, or transporting all of the subsystems to the final orbit and performing final assembly there. Either approach will require a robust set of in-space operational capabilities, including; automated rendezvous, docking and berthing, assembly, and servicing and repair. Recent robotics missions have significantly matured the key in-space operations technologies needed for SSP (Refs. 12, 13).

4.0 Summary

It is proposed that a building block approach (at least two phases) be employed in the development of Solar Power Satellites (SPS). The first building block is proposed to be a near-term, low power, tactical system with application to customers willing to pay a premium for consistent and uninterrupted power. This smaller low-power system would validate fundamental technologies and models, thereby reducing technical and economic risk. The goal of the second phase would be to develop the advanced technologies required for a SSP system capable of producing commercial levels of power and transferring that to the Earth's power grid. The spacecraft in this phase would be producing on the order of 100 – 2000 MW of power. Using block upgrades on first phase systems to develop and demonstrate the advanced technologies as they become available would reduce the cost, schedule and performance risks of very large system implementation.

Technology investments are needed to meet the materials, structural and mechanical systems (MSMS) requirements for SPS systems in order to acheive technical and economic feasibility. Four MSMS technology areas were discussed, modularity, material systems, structural concepts, and in-space operations. Technology advances in all four areas over the last 15 years make the technical feasibility of an operational SPS system much greater than just two decades ago.

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