Technology Challenges and Opportunities for Very Large In-Space Structural Systems

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Abstract

Space solar power satellites and other large space systems will require creative and innovative concepts in order to achieve economically viable 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/construction will be enabling design attributes. While current space systems allocate nearly 20 percent of the mass to the primary structure, the very large space systems of the future must overcome subsystem mass allocations by achieving a level of functional integration not yet realized. A proposed building block approach with two phases is presented to achieve near-term solar power satellite risk reduction with accompanying long-term technology advances. This paper reviews the current challenges of launching and building very large space systems from a structures and materials perspective utilizing recent experience. Promising technology advances anticipated in the coming decades in modularity, material systems, structural concepts, and in-space operations are presented. It is shown that, together, the current challenges and future advances in very large in-space structural systems may provide the technology pull/push necessary to make solar power satellite systems more technically and economically feasible.

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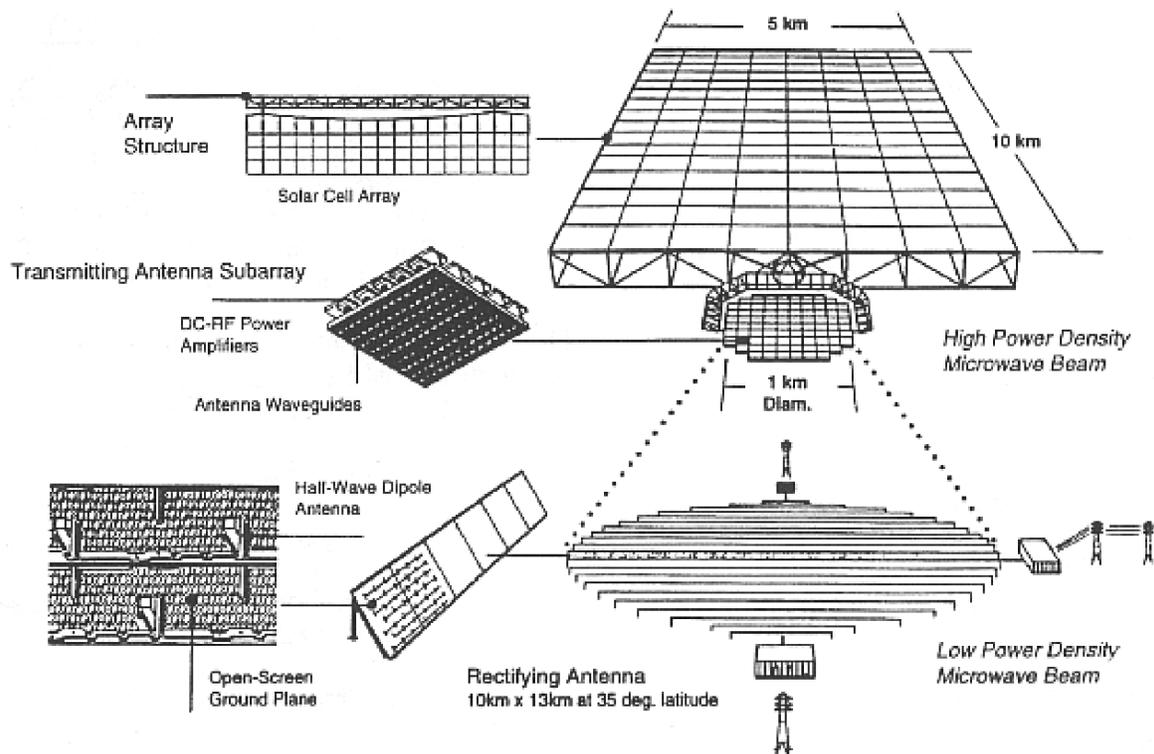
Figure 1: 1979 Reference System Concept (5 GW , GEO Based)

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 as shown in Fig. 2. The SunTower, involves the use of highly-modularized power generation (with inflatable solar concentrators) and power transmission (using mass-produced magnetron segments).

NASA's Space Solar Power (SSP) Exploratory Research and Technology (SERT) program invested in twelve technology thrusts in the late 1990's to the early 2000's. One new SSP concept based on optical concentrators was developed during this period. As shown in Fig. 3, the Integrated Symmetrical Concentrator concept utilizes thin film optics to concentrate the solar radiation and thereby reduce the photo-voltaic array size. More recently the National Security Space Office (NSSO) conducted a feasibility study (Ref. 4) for using Space-Based Solar Power to enhance strategic security. The NSSO study also adopted a concentrator SSP concept as shown in Fig. 4.

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 materials and structural systems, including deployment and assembly, is crucial to achieving economically feasible designs. In this paper, a building block approach is proposed

that utilizes a two-phase approach to develop and validate large SSP systems. 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. The goal of the second phase would be to develop the advanced technologies required for an economically viable SSP system capable of producing commercial levels of power and transferring that to the terrestrial power grid.

The paper also describes materials, structures, and mechanical systems (MSMS) technologies that can be employed in a near term tactical demonstrator and the needs and promising opportunities in MSMS technology for future application to very large SPS systems. Recent developments in large gossamer structures indicate that rapid advances are possible in material systems, inflatable structures, in-space operations, and modularity. The SSP challenges and future advances in very large in-space structural systems provide the technology pull/push necessary to make SSP systems more technically and economically feasible.
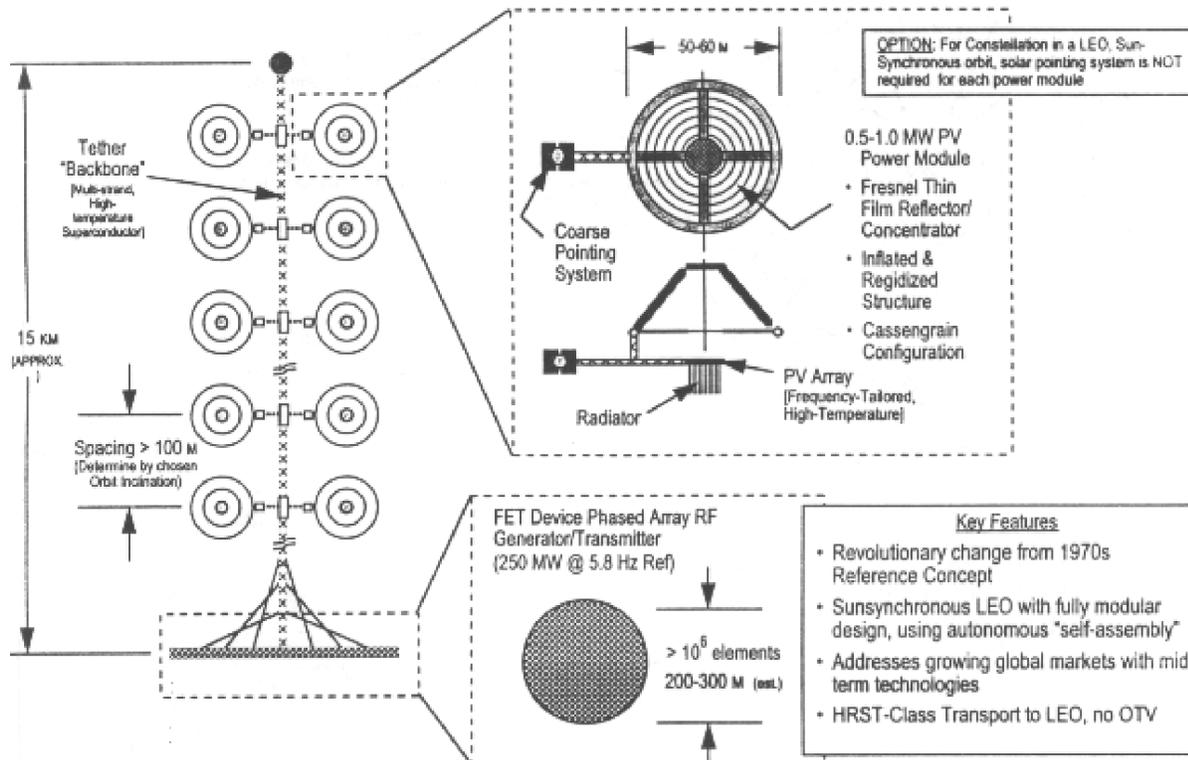

Figure 2: The "Sun Tower" SPS Concept (100-400 MW, MEO constellation)
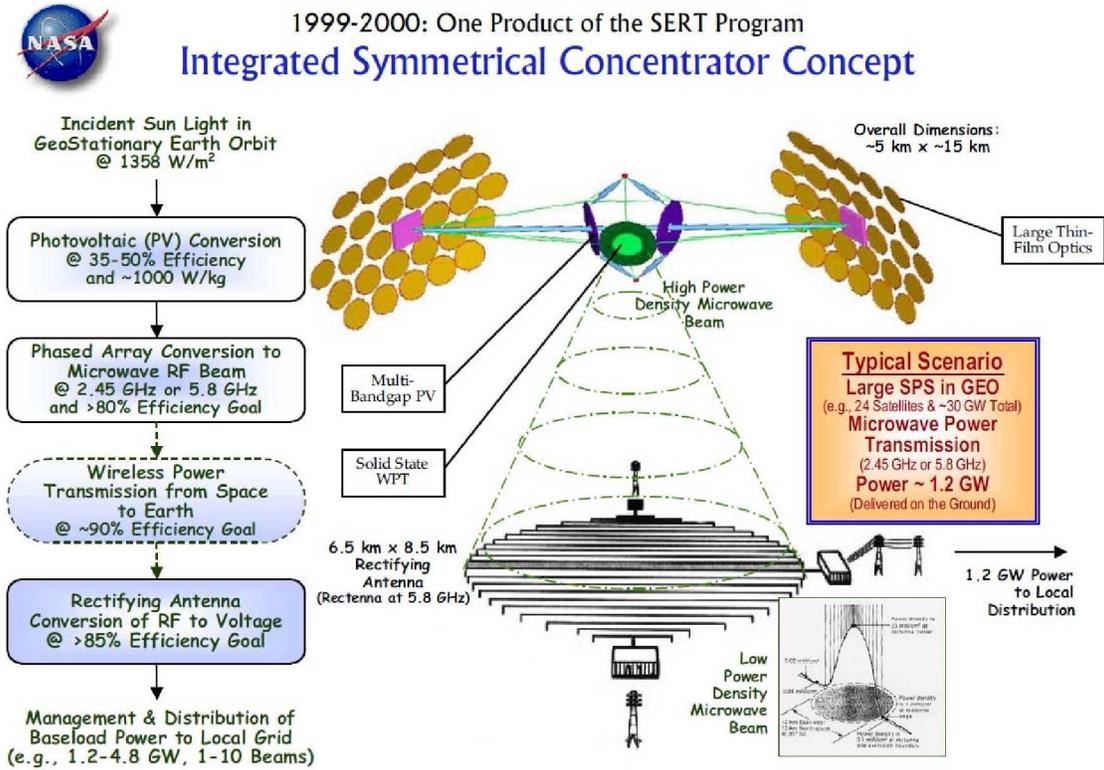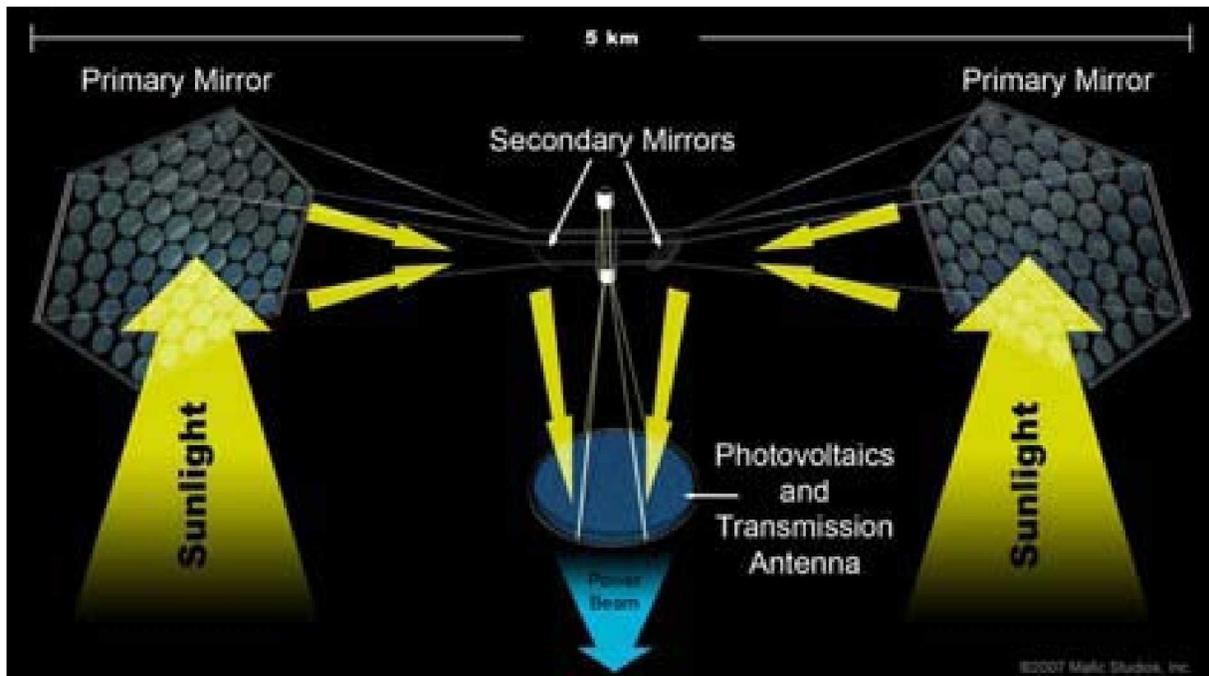
Figure 3: Integrated Symmetrical Concentrator Concept

Figure 4: National Security Space Office 2007 SSP Concept

2.0 Solar Power Satellite Requirements

Many obstacles stand in the way of generating commercial space-based solar power, including launch costs, subsystem mass (solar arrays for example), and assembly and/or construction operations. Numerous technology advnaces are needed to enable large scale Solar Power Satellites (SPS) to become technically and economically pratical. To this end, NASA developed technology roadmaps from the SSP fresh look study (Ref. 3) that included twelve technology development thrusts:

- Solar Power Generation
- Wireless Power Transmission
- Power Management and Distribution (PMAD)
- Structures, Materials & Controls
- Thermal Management & Materials
- Robotic Assembly, Maintenance and Ops
- Platform Systems
- Ground Segment Systems
- ETO Transport & Infrastructure
- In-Space Transport & Infrastructure
- Environmental & Safety Factors
- Systems Integration

Investments to develop technology in the twelve thrust areas were made by NASA's Space Solar Power (SSP) Exploratory Research and Technology (SERT) program. During this time, it was found that the materials, structural and mechanical systems (MSMS) requirements for SPS were highly dependent on the architecture, power/size, and orbit (as it affects control dynamics and environmental degradation). For example, structures, materials, controls, thermal management and PMAD were highly coupled even in the early concept definition. Moreover, it was determined that integrated, multifunctional components were needed to reduce the mass (and volume) requirements for Earth to orbit transport.

In addition, for any very large space structural systems, risk management becomes a key design driver. Risk considerations include:

- Can the system be verified through ground testing?
- Is there a single point failure? What level of redundancy?
- Deployment and robotic assembly reliability?
- Repair or replacement capabilities needed on the ground and/or in space?

These risk based design considerations lead the MSMS discipline towards modularity. Module based design has the potential to lower costs through fabrication of multiple nearly identical

elements. However, experience has been that modular systems have some degree of mass penalty as compared to a single optimized system. In the view of the authors, modularity is an enabling feature to realize very large space structural systems in order to manage risk.

SSP requirements definition is especially daunting if the first focused application is to field a system to produce ~500-1000 Megawatts to supplement the country's commercial power grid. To overcome this all or nothing approach, the next section proposes a two phase phased approach that reduces risk, yet permits verification of fundamental technologies and models. This phased approch allows near term technology advances to be demonstrated early and advocates continued technology advances for future large scale SSP systems.

3.0 Building Block Approach: A Two Phase SSP Development

The first phase of the building block approach 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. There may also be some civilian applications, scientific bases in remote and inhospitable locations for example, for which near term space based solar power would also be a viable option. Finally, these systems might 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 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. 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 system development would not begin prematurely. Attributes of the two-phase approach are summarized in Table 1.

Table 1. Attributes of building block approach to SPS development.

Attribute	First Phase System	Second Phase System
Applications	Military Remote Scientific Sites Moon/Mars/Etc. Surface Power	Commercial Power
Power Level	Up to 100-5000 KW	100-2000 MW
Technology	Current and Near Term	Advanced, Requires Development, Low TRL
In Service	Less than 10 years	Less than 20 years
Build Up Approach	Modular Spacecraft Units, On-orbit rendezvous and docking	Modular Spacecraft, Tension-Stabilized and Inflatable Structures, Robotic on-orbit assembly

3.1 Example of First Phase SPS System

Reference 5 presents a design concept for a Solar Electric Transfer Vehicle (SETV). The SETV class satellite could be readily augmented with wireless power transfer techonology and demonstrated as a phase 1 SPS system. The purpose of the SETV is to transfer cargo from Low Earth Orbit (LEO) to Low Lunar Orbit (LLO) and other locations as specified in the Vision for Space Exploration (Ref. 6). The SETV tug uses photo-voltaic solar arrays to generate electricity, which is used to power Hall Effect ion thrusters. Xenon is baselined as the propellant for the ion thrusters. Details of the SETV flight mechanics and controls design are given in Ref. 7. At its largest size, the tug develops approximately 450 KW of power, and can transport a 60 metric ton payload from LEO to LLO and return in less than one year. The SETV is designed using technologies that are currently available. Because of its large size and mass, the SETV requires multiple launches and some amount of on-orbit assembly, with the amount depending on the specific design implementation. The SETV is also designed for a service life of 30 years, with regularly scheduled servicing and maintenance. For example, the SETV must be refueled after every roundtrip and the solar arrays and Hall ion Thrusters are both designed to be replaced at 4-year intervals.

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. Operational requirements have been developed for the SETV, along with requirements for all of the major systems such as control, electrical power, communications, data, structures, thermal management, propulsion and payload integration and are summarized in Ref. 8.

Individual sub-modules and components that make up one 50 KW-class SETV System Module are show in Fig. 5. The reference 450 KW-class SETV is composed of eight of these SETV System Modules (see Fig. 6a). The general structural arrangement of the SETV consists of a central backbone keel truss beam with 16 (in opposing pairs) Solar Array Support (SAS) Trusses mounted transversely to the keel truss at 5 bay intervals, using a fixed-bay keel truss section (to which opposing fixed SAS truss and avionics boxes are also connected) that is 0.8 meters long (see Fig. 5). Both the keel beam and the SAS trusses are single-fold sequentially-deployable trusses with square bays, having bay sizes (longeron and batten lengths) of 1.6 meters and 0.8 meters respectively. The keel beam bay dimension was chosen to allow packaging of a complete 50 KW-class SETV System Module on a Delta II-Heavy class launch vehicle for SETV Modular Assembly Scenario 3 (Ref. 5), with the SAS truss dimension chosen as one half of the keel beam dimension to allow for simple structural integration and attachment of the two structures.
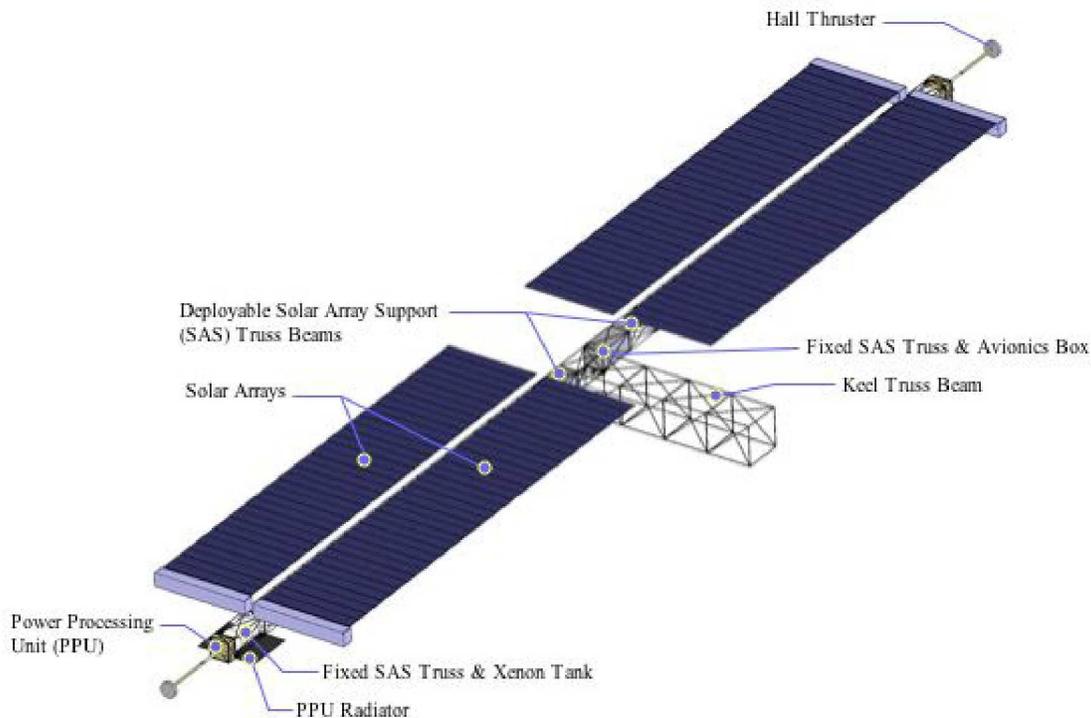

Figure 5: Subsystems making up a 50 KW-Class SETV module.

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 microwave transmitter mounted at the center of the spacecraft for transmission to the Earth's surface. A transmitting antenna would be added at the spacecraft center and perhaps additional backbone truss also added to provide support and separation from the solar arrays. The propulsion system would be resized for the mission of transferring the modules to their operational orbit (such as geosynchronous) as well as providing long-term station keeping at their service location and the power transmitted to the propulsion system modified accordingly. The system shown in Fig. 5 was sized such that a 50 KW-class module could be launched by a Delta 2-Heavy, or four modules assembled on the ground and 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 either assembled in LEO to allow for checkout and then it could propel itself to its service orbit.

The modular nature of a phase 1 SPS based on the SETV allows for new technologies to be easily incorporated into the spacecraft as they reach maturity. The modules could be improved incrementally, upgrading just the solar arrays for example, or a large number of improvements could be incorporated into a block spacecraft upgrade. Ideally, the newer technologies would be those that are directly applicable and needed for the phase 2 system. Decisions on what technologies to pursue for the phase 2 system will have to be made, and methodologies for evaluating modular assembly (Ref. 9) and truss structure performance and packaging metrics (Ref. 10) of large space platforms would be invaluable. In addition, because the scale of the second phase system will be substantially greater than that of the first phase, the use of automation and robotics technologies (Refs. 11. 12) will be useful to support spacecraft assembly, inspection, maintenance and upgrades.

3.2 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 Figs. 3 and 4, 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 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

for very large space structural systems in the coming decades are discussed in the following section.

4.0 Materials, Structures and Mechanical Systems (MSMS) Technology Advances

To realize the second phase SPS system, technology advances in all areas identified by the SSp Exploratory Research and Technology (SERT) program are needed. Specific to this paper are those technologies in the materials, structures and mechanical systems (MSMS) disciplines that enable very large space structural systems such as SSP satellites. Many of the needed technology advances are of a multidisciplinary nature and require close attention to system level requirements due to multiple function integration. 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)

4.1 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. For maximum benefit and when possible, the modular units should be non-mission specific, allowing for commonality even between spacecraft having different mission architectures. Modularity reduces mission risk, and allows spares and replacements to be available during system assembly. The same modules used for initial construction can be used later if servicing or repairs become necessary. A suite of available modules can provide the building blocks for a variety of spacecraft, allowing rapid development and deployment of new missions at substantially reduced costs. Modularity potentially enables reconfiguration and upgrading through the exchange of existing modules with new modules having different or improved functionality. Modularity, together with a robust capability to perform in-space assembly have the potential to greatly enable the SPS misison.

In Ref. 5, a comprehensive modular assembly system model was proposed which extends the art from just considering hardware, to including in-space assembly, servicing and repair and their critical components of infrastructure, agents and assembly operations. Benefits of modular assembly were identified and a set of metrics defined that extends the art beyond the traditional measures of performance, with emphasis on criteria that allow life-cycle mission costs to be used as a figure of merit. The modular assembly approach was used as a basis for developing the previously described Solar Electric Transfer Vehicle (SETV) concept and three modular assembly scenarios were developed. The modular assembly approach allowed the SETV to be
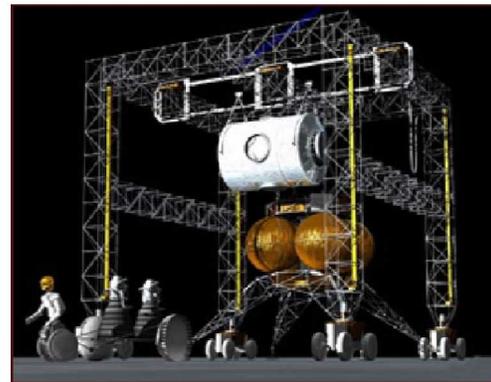
entered into service much earlier than competing conventional configurations and resulted in a great deal of versatility in accommodating different launch vehicle payload capabilities, allowing for modules to be pre-assembled before launch or assembled on orbit, without changing the space vehicle design.

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 (power platform, habitat complex, telescope) 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 (jigs, restraint and load reaction devices, cranes, mobile platforms, etc.) required to facilitate operations and enhance agent capabilities. All of these systems must be considered, defined and designed simultaneously in order to develop a specific mission architecture incorporating modularity and assembly that maximizes the benefits that can be accrued. The approach can be applied to in-space, as well as surface-based exploration systems, as shown in Figs. 6a and 6b, respectively.

In general, previous modularity definitions capture all of the sub-attributes associated with standardization in Table 1. However, they do not consider or address modularity sub-attributes associated with versatility and maintainability. A more comprehensive set of modularity attributes is defined by expanding previous definitions to include those resulting from on-orbit operations, so that the resulting benefits to system life cycle costs can be captured and assessed. The resulting list of modular attributes, associated sub-attributes and their definitions and descriptions are compiled in Table 2.

(a) Modular SETV.   (b) Modular planetary surface infrastructure.

Figure 6: Examples of modular space systems.

Table 2. Modular Attributes.

Attribute	Sub-Attribute	Description, Comment
Standardization	Standard Interfaces	For mechanical, fluid, electrical, etc. connections
	Standard Modules	Standared modules for spacecraft hardware components, on-orbit infrastructure (including tools), and on-orbit robotic agents
	Discrete Performance Levels	Sets of standardzed components with discrete levels of performance or capability, and components are validated and available off-the-shelf (features design heritage)
	Plug and Play	Allows for hardware chages and additions without the need for any redesign
	Only form, fit and function specified	Encapsualted functionality decouples sub-systems form each other (Enright, 1998)
Versatility	Accommodate variety of launch vehicle packaging options	Can readily be packaged on lauch vehicles with different payload mass and volume capabilityes
	Reconfigurable on orbit for new mission or application	Modular components can be disassembled and recombined for a new mission or spacecraft
	Capability for disassembly and reassembly	Operations performed in-situ: in spaceor on planetary surfaces
	Upgradable	Enhanced capability, or insertion of new technology
	Growable, scalable	Growable: part count changes (each part doesn't change), replications added (add modules to grow power production or fuel storage capacities for example, can be incremental). Scalable: part count stays the same, but the size or dimensions change
Maintainability (in space, planetary surfaces)	Servicable	Fluid replenishment and regular (scheduled) maintenance
	Repairable	Unscheduled and unanticipated events

4.2 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. 13) in 2002 identified aerospace materials in current use and those with high potential for the future. Figure 7 indicates that single wall carbon nanotube (SWNT in Fig.7) based materials offer the potential for 3-5 increases 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 and more recently Boron nitride nanotubes (BNT) materials. Both carbon nanotube (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. 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 The following sections describe recent and future advances in high temperature materials, rigidization technology, and self-healing materials.
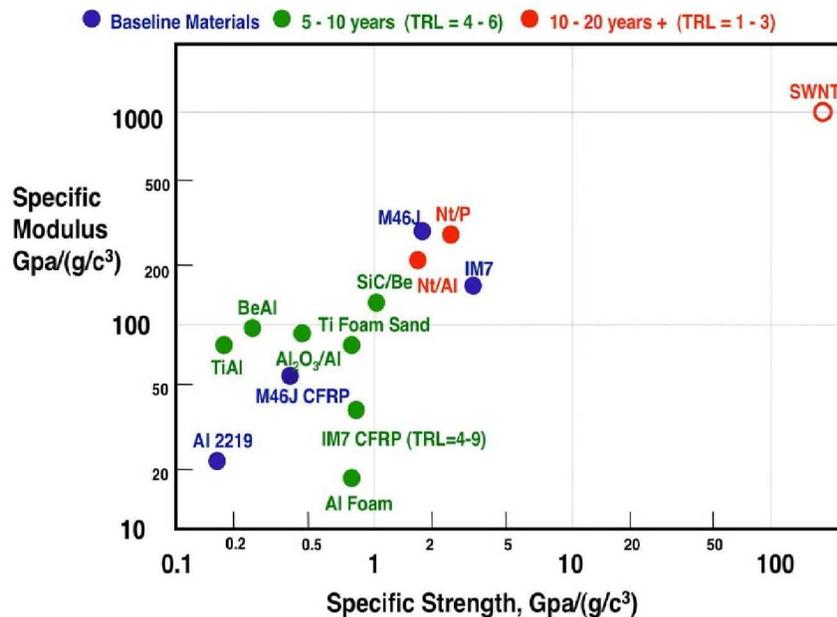

Figure 7: Survey of Emerging Aerospace Materials, (Harris, et al., Ref. 13)

4.2.1 Thermal Materials: While both passive and active (e.g. heat pipe) thermal management systems are feasible for SPS application, passive materials that maintain their properties at high temperature and exhibit very high thermal conductivity are preferred for long duration space systems. Among the various fiber reinforced composites used passively in the aerospace industry (organic, metal and ceramic matrix), metal and ceramic matrix composites are most suitable for passive high temperature applications. Nevertheless, new high cross linking thermosetting polyimides such as LARC[TM] –RP46 (Ref. 14) are very attractive for applications below its glass transition temperature of ~400° C. *(LARC[TM] –RP46 is a trademark of NASA Langley Research Center.)* For very high temperatures, ceramic matrix composites such a reinforced carbon carbon (RCC) composites (carbon fibers with a graphite matrix) can operate at

temperatures of 2000° C. The challenge is to reduce the cost and complexity of fabricating large quantities of metal and ceramic matrix composites for SPS application.

Carbon nanotubes (CNT) materials offer superior mechanical properties (see Fig. 7) and very good thermal and electrical properties. CNT materials are 15 times more thermally conductive and 1000 times more electrically conductive than copper.   Much research is underway to develop CNT-like properties in bulk materials scaled for aerospace applications.   CNT costs and scale-up are the current technical challenges. With continued research and development, these challenges should be overcome in the coming decades. It should be noted that Boron nitride nanotubes (BNT) are far more resistant to oxidation than carbon and therefore suited for high temperature applications in which carbon nanostructures would oxidize. BNT based material systems are also candidate high temperature materials for future SPS systems.

The SERT program identified eight areas for thermal materials research and development for application to SPS, namely:
- High Temperature Devices
- Advanced Passive Thermal Management Concepts
- Active Thermal Management Devices
- Heat "Regeneration" Concepts
- High Temperature Materials
- High Conductivity Materials
- High Temperature Sensors

Table 3 lists the SERT targeted performance metric goals for high temperature materials and device development for SSP. High temperature and high thermal conductivity materials of the future will likely utilize carbon nanotube and boron nitride nanotube composites to achieve the SPS thermal performance goals.

Table 3. SERT High Temperature Performance Metric Goals

SSP Technology	Performance Metrics		
	Area	Current (circa 1997)	Goal
High-temperature superconductors	Operating Temp. (K)	77	> 100
High-temperature devices	Operating Temp. (°C)	60	> 350
High-conductivity materials	Thermal conductivity (W/m-K)	500	> 1000
Passive thermal management devices	Heat Rejection (kW/kg)	0.04	> 0.20
Active thermal management devices	Heat Rejection (kW/kg)	---	> 0.20
Waste heat regeneration	Regeneration Efficiency	---	> 0.20

4.2.2 Rigidization Materials: One of the major advances of the past decade is the development of "gossamer" class structural architectures for very large apertures such as solar sails and large radio frequency (RF) systems. This large area, lightweight class of structure is enabled by deployable compression members and tension stabilized thin film membranes. To reduce the number of deployment mechanisms, motors, and mechanical joints, material systems that are compliant for packaging and deployment and that can be rigidized after deployment have been investigated. Of particular interest are structural materials that can be inflation deployed and rigidized (IDR). A well known example is the ECHO II satellite deployed and rigidized in the 1960's by stressing (beyond yield) a 100 ft. diameter aluminum coated mylar sphere.

Cadogan, et al. (Ref. 15) describe the classes of material systems that exhibit IDR properties. Modern polymer based matrix composites identified for IDR applications are 1) thermosets and 2) thermoplastics (and lightly cross-linked thermosets). Thermosets can be fabricated into structural forms prior to curing. After packaging, launch, and inflation driven deployment, the thermoset materials can be cured through either thermal heating, ultra –violet light, or inflation gas induced chemical reactions. Some disadvantages of on-orbit thermoset material rigidization include the uncertainty in cured structural shape, accidental curing in the packaged or partially deployed state, and contamination from chemical reaction volatiles.

Thermoplastics (and lightly cross-linked thermosets which behave similar to thermoplastics) enable IDR properties with conditioning. Structures formed using thermoplastic polymer composites can be fully cured for fabrication and spacecraft integration. When heated above the glass transition temperature (Tg), the thermoplastic becomes compliant and can be folded and packaged for launch. When cooled below Tg, the packaged structure is rigidized during launch. Prior to on-orbit deployment, the thermoplastic structure is heated above Tg, inflation deployed, and then cooled below Tg for rigidization of the deployed structure. After deployment and rigidization, the inflation gas can be vented, thus, no make-up gas is needed to maintain inflation pressure. Thermoplastic based IDR technology was developed to a NASA technology readiness level (TRL) of 6 during the Innovative Space-Based Radar Antenna Technology (ISAT) program as described in Ref. 16. IDR material systems will be critical to reduce the cost and increase reliability of SPS deployment.

4.2.3 Self-Healing Materials: Micrometeoroid and orbital debris (MMOD) impact on large systems such as arrays and concentrators makes the development of materials with self-healing properties critical to meeting the long-life requirements of SPS systems. Various approaches to achieving self healing behavior of polymers have been identified. The use of embedded microcapsules has been investigated in Refs. 17-19. This engineered healing mechanism involves the fracture of liquid (monomer) filled capsules that post-fracture fill the crack and polymerize. Results for pure polymers have been more promising than has fiber reinforced

composites. The application of this technology to very thin film membranes has not been adequately evaluated.

Other approaches to self-healing materials involve the use of solid-state chemical bonds, and biomimetic materials design. In addition, inflated structural systems can be designed with materials that chemically reactant to the inflation gas to seal small voids. Self-healing materials technology remains a major challenge to enable SPS life requirements to be met if low mass "gossamer" architectures are utilized. Success in the next few decades in the development of self-healing technology will have direct impact on the economics of SPS (longer life and lower mass).

4.3 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).

Ref. 20 discusses four classes of large space systems (LSS) and recent advances in structures technology. Of the four LSS classes shown in Fig. 8, the gossamer structures and large aperture sensorcraft provide structural concepts important to SPS design. The integrated symmetrical concentrator SPS concept (Figs. 3 and 4) require 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 ensure Sun's light is reasonably focused in a non-coherent manner on the photo-voltaic arrays. Thus, the concentrator designs will be both mass and stiffness (passive and active) driven designs. Hedgepeth, Ref. 21, outlines in expert manner the critical requriements for design of LSS.

Table 4 shows the structural (and materials) performance metrics utilized during the SERT program. To meet or exceed these performance metric goals, the following sections describe recent advances in lightweight expandable structures technology for a gossamer class solar sail application and a large aperture sensorcraft class radar application. Finally, the challenge of LSS pre-launch validation is discussed.
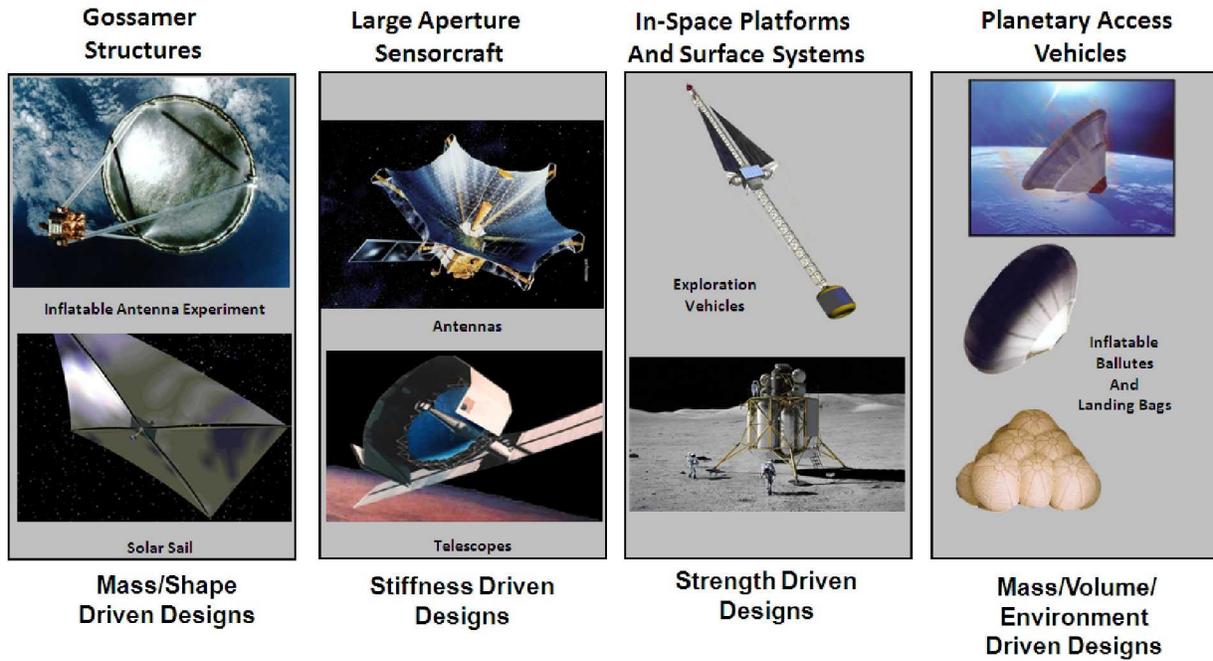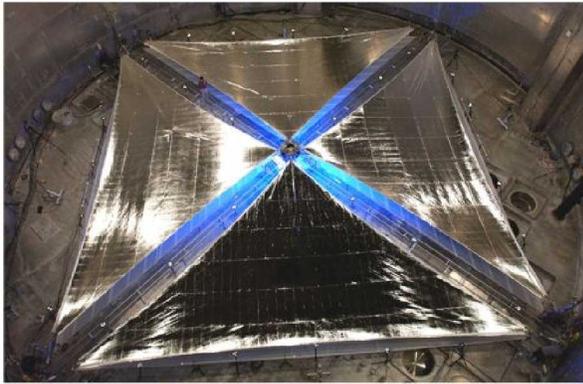
Figure 8: Four Classes of Large Space Systems (LSS)

Table 4. SSP Structural Performance Metrics (SERT Program)

SSP Technology	Performance Metrics		
	Area	**Current**	**Goal**
Very large, lightweight deployable structures	Packaging efficiency	20:1	> 50:1
	Mass/Area (kg/m^2)	2.4	< 0.37
Solar concentrators	Concentration Ratio	10:1	15:1
Distributed control	Pointing Accuracy (deg)	10	< 3
Long-life materials	Operational life (yrs)	3	15
Lightweight, deployable power conductors	Packaging efficiency	---	> 10:1
	Mass/Length (kg/m)	---	< 0.15
Integrated structure / power distribution	Mass /Area (kg/m^2)	---	< 50
Autonomous modular assembly	Positional accuracy (m)	---	< 0.01
Surface figure control	Surface accuracy (m)	---	< 0.01
Efficient thermal management	Heat rejection (kW/kg)	0.04	> 0.20

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(a) AEC-Able Engineering   (b) L'Garde

Figure 9: Solar Sail Technology: 20 m Structural Test Articles

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4.3.1 Solar Sail Structures: In the development of solar sails under NASA's In-Space Propulsion program, two competing teams designed, fabricated, and tested solar sails using system level ground test articles. Figure 9a shows the AEC-Able Engineering 20 m demonstrator (Ref. 22) which consisted mechanically deployed booms (compression members) and four 3.5 micron membrane quadrants made of a polyimide known as LARC™-CP1. *(LARC ™ -CP1 is a trademark of NASA Langley Research Center.)* Refs. 22-25 provide a complete description of the boom and membrane technology and test results for the AEC- Able design.

The L'Garde solar sail design shown in Fig. 9b uses IDR technology to deploy and rigidize the four booms. The membranes are supported by a net design and are made of 5 micron mylar material. References (26-29) provide a complete description of the boom and membrane technology and test results for the L'Garde design. If is noted that high-fidelity computational models, tools, and diagnostics were developed and tested for each solar sail design. These tools are critical to validation of the designs as discussed below.

The gossamer structures technology derived from the In-Space Propulsion program is directly applicable to the SPS concepts whereby large concentrators/reflectors are required. With continued advancement in IDR materials, thin films and self-healing technology, gossamer SPS concentrators of multi-kilometer dimensions will be easily achievable. Perhaps the only "challenge" post deployment will be to maintain the required pointing accuracy. It is anticipated that distributed control will be used for this purpose utilizing active materials.

4.3.2 Inflatable Deployed Rigidizable Structures: DARPA and NASA studies of emerging space technology needs have identified large aperture technology to be enabling for many future space systems. In particular, DARPA's large space based radar antenna system studies have strongly illuminated the need for the development of *very large* antenna structures. To that end,
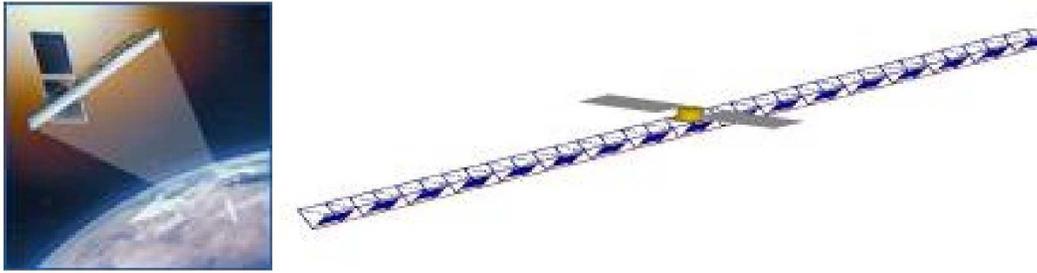
Figure 10: Innovative Space Based Radar Antenna Technology (ISAT) Concept

DARPA funded an Innovative Space Based Radar Antenna Technology (ISAT) program earlier this decade to demonstrate technology for a very long space-borne electronically scanning antenna. The antenna, shown schematically in Fig. 10, is highly compacted (packaged) for launch and deployed in space to a length of ~300 meters. (http://www.defenseindustrydaily.com/darpa-funds-further-isat-development-0590/)

The backbone of these large antennas is a truss-type support structure which provides the stiffness and stability to achieve the desired mission goals. The need to reduce mass and stowed volume of these very large support structures necessitates the use of new technologies to enable higher packaging efficiencies than can be achieved with conventional mechanical deployable structures. To meet this challenge, inflation deployed, rigidizable (IDR) materials and structures technologies appeared to offer the most potential for meeting DARPA and NASA needs.

Both IDR and mechanically deployed concepts were developed. Both concepts achieved packaging efficiencies of 100 to 1 (deployed to stowed length). The mechanical design used localized strain energy hinges whereas the IDR concepts inflated the entire longeron truss member. Heating the IDR composite bays for deployment and cooling for rigidization proved more complex than anticipated and innovative thermal management was required. Continued development is needed to advance IDR deployment and joint technology to simplify implementation.

Preliminary results of the risk assessment program (see Ref. 16) indicated that IDR materials and structures technology is a viable approach to achieving the stiffness and strength requirements for very large antennas. Integration of radar panels during deployment was readily achieved such that deployment of the primary structure was integral (simultaneous) with the radar deployment. Very high packaging efficiencies were achieved using both IDR and state-of-the-art mechanical deployment. Both methods are viable candidates for SPS primary structure, however, the risk of IDR deployment and performance is higher than that of mechanical systems. Further design and development for application to SPS is required before a structural concept can be down-selected.

__4.3.3   The Challenge of Large Space Systems (LSS) Validation:__ The design of large structural systems for LSS often requires development of new technology components and sub-systems. Validation of the new technologies is critical to having them accepted by the user community and other stakeholders. Structural technologies for LSS are particularly difficult to validate using ground tests because test results on large size structures are negatively impacted by the Earth's gravitational forces. For example, solar sail development testing identified several ground test affects that alter test results:

- Gravity Changes Performance
    - Changes Shape
    - Preloads Structures – Differential Stiffness
    - Non-linear character can be masked
    - Requires gravity suspension system for "free-free" testing
    - Scale Models can reduce gravity effects
- Thermal Environment Influenced By Convection/Conduction
    - Small amount of ambient gas changes thermal response
    - High vacuum environment limits test article size
- Gravity Loads Effect Deployment
    - Deployment forces must overcome gravity
    - Non-linear coupling of gravity vector orientation
    - Joints characteristics may differ due to pre-load

The use of a hybrid test/analysis approach is presented in Ref. 30 in order to bridge the gap in ground test validation of structural technologies for LSS. The hybrid approach allows technology readiness levels to be advanced with appropriate considerations of key phenomena and if test validated analysis is used to extrapolate and predict the on-orbit performance of the full-scale system. Thus, adequate resources must be allocated to development of high fidelity SPS analysis models in order to perform the proposed hybrid validation approach outlined in Ref. 30. It is noted that modularity in the design will ameliorate but not eliminate the challenge of LSS validation.

4.4 In-Space Operations

In order to field a Solar Power Satellite (SPS) 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. Both approaches have merits and difficulties, which will not be addressed here. Rather, what is important is that either approach will require a robust set of in-space operational capabilities, including; automated rendezvous, docking and berthing, assembly, and servicing and repair.

Automated rendezvous is the capability to automatically fly a spacecraft to a designated orbit (where assembly is to take place for example), and locating in close proximity to other assets that form the complete SPS. Depending on the final assembly site, this can be accomplished using the upper stage from the launch vehicle or using a separate orbital transfer vehicle (space tug). Automated rendezvous is an established capability in LEO, with examples including International Space Station (ISS) resupply vehicles such as the Russian Progress and the European Space Agency Automated Transfer Vehicle (ATV). In addition to demonstrating automated rendezvous and docking, the Orbital Express (Ref. 31) also demonstrated capabilities for in-space servicing.

Docking and Berthing are operations where large space subsystems are brought together and connected. Docking is the capability for a free flying vehicle to approach the target, match orientation and position, and complete the maneuver by attaching itself to the target. Generally, docking would be achieved by the same system that is performing the automated rendezvous operations, such as the Progress and ATV mentioned previously. Berthing incorporates a manipulator, or robotic arm, to first grasp the target and complete the final positioning and alignment to enable capture and assembly. Examples of current in-space arms are the Shuttle Remote Manipulator System (SRMS) and the Space Station Remote Manipulator System (SSRMS). The SRMS has been used to acquire and berth the Hubble Space Telescope, allowing several telescope servicing missions to be successfully completed (Ref. 32). The SSRMS is routinely used to assemble large components to the ISS. Another example of an arm that is modular, structurally efficient and could be used to position and support robots and end-effectors at a work site is the Space Crane described in Ref. 33.

Assembly refers to the final positioning, holding and joining of space subsystems. The scale of assembly can range from joining very large components, as done to build the ISS, to joining small individual truss members as was done in the ACCESS flight experiment (Ref. 34). During assembly, mechanical, fluid, power and data connections would have to be completed. In some cases, the connections are made automatically, especially during berthing operations. In other cases, the connections might require the use of manual (Astronaut Extra-Vehicular Activity [EVA]) or robotic (arms with end-effectors) capabilities. ISS assembly has demonstrated hundreds of hours of successful EVA assembly operations.

Progress has also been made on using robotics to perform on-orbit assembly. Two scales of reach are generally required to perform tasks in a work envelope when assembling a large system in space. An arm with long reach is required that can position tools and end-effectors in proximity to the work site. Specialized robots or end effectors are attached to the large arm and are used to perform the actual assembly operations. In early efforts, automated assembly (and dis-assembly) of a mockup in-space precision reflector telescope structure was repeatedly demonstrated (Ref. 35). An off-the-shelf robot arm, together with specially designed end-effectors and

automation and control algorithms, were developed and integrated into an automated structural assembly system. Use of robots as space assembly tools has been explored by NASDA in Japan and many lessons have been learned from the experiments performed with their satellite mounted robot arm on ETS-VII (Ref. 36). The Space Systems Laboratory at the University of Maryland has also developed dexterous arms and pursued non-anthropomorphic dexterous end effectors for space operations (Ref. 37). More recently, Robonaut, an anthropomorphic robot with human sized arms and hands that can work with many of the same interfaces designed for EVA astronauts, was used to evaluate and demonstrate techniques for automated assembly, disassembly and reconfiguration of space platforms (Ref. 38).

An integral part of successful robotic operations is a system for coordinating and controlling the various robots. The Human Robotics Systems Project, in NASA's Exploration Technology Development Program, is develop mobility and payload handling robots for planetary exploration and outpost construction and assembly. A key part of the project is to develop control infrastructure that will allow the robots to work autonomously and collaboratively, even if a time delay is present. One aspect of the work involves developing a common support framework to control and monitor lunar robotic assets that integrates a heterogeneous collection of robotic assets into a common work environment. The resulting architecture is referred to as the Robot Application Programming Interface Delegate – RAPID (Ref. 39). The research also includes developing the computer controls and workstation that allow an operator to simultaneously monitor and command groups of diverse robots (Ref. 40). Although currently being developed for planetary surface robots, this capability should be directly transferrable to automated assembly, servicing and repair operations in space.

Servicing and maintenance refer to pre-planned and scheduled operations that are required to maintain the operational performance and capabilities of a space system. Repair refers to unscheduled operations that are required to respond to the failure of a spacecraft subsystem. Operations that fall in the category of servicing and repair include inspection, fault detection and isolation (diagnostics), replacing components at scheduled intervals, replenishing supplies (such as fuel for propulsion/station-keeping system), assessing failures and repairing or replacing systems, and installing upgrades. Because of the long life expectancy of a SPS, designing the system to be easily maintained and repaired will be critical, and incorporating many of the tenets of modularity described previously in this paper will be key to developing a viable SPS. Besides rendezvous and docking, Orbital Express (Ref. 28) also demonstrated autonomous on orbit servicing and repair. Another example of an autonomous space tug that could be used to rendezvous with spacecraft or platforms and perform repositioning, servicing and repair operations is the Spacecraft for the Universal Modification of Orbits (SUMO) project sponsored by the Defense Advanced Research Projects Agency (Ref. 41). Other capabilities being investigated are summarized in Ref. 42.

Although not done robotically, perhaps the premiere example of servicing and repairing a space system on orbit to date is the Hubble Space Telescope, HST (Ref. 43). In preparation for the final HST servicing mission, the HST Development Office spent over a year developing the Hubble Robotic Servicing and De-Orbit Mission, which had the objectives to; autonomously rendezvous with and capture the HST, perform robotic servicing tasks and de-orbit the spacecraft at the end of its useful scientific mission lifetime (Ref. 44). The HST robotic servicing project advanced the technologies and capabilities for; autonomous rendezvous and capture of an uncooperative target, robotic installation of next-generation scientific instruments and life extension upgrades, and controlled spacecraft de-orbit. Additionally, two computer vision systems, one that would allow autonomous capture of the free-flying HST and another that could perform supervised object recognition and pose estimation of objects to within 2 mm and 2 degrees for HST worksite registration were also developed and demonstrated (Ref. 45).

From this discussion, it is clear that many of the in-space operations capabilities needed to embark on developing the first phase SPS are either in hand, or within reach. Robotic rendezvous, docking and assembly of phase 2 class SPS systems appears technically feasible.

5.0 Summary and Recommendations

Solar Power Satellites (SPS) demand highly efficient structural systems of unprecedented size. Fielding a fully operational terrestrial power class SPS (>1000 MW) introduces significant risk in modeling, technology, and operations. The risk based design considerations lead the materials, structural and mechanical systems (MSMS) discipline towards modularity. In the view of the authors, modularity is an enabling feature to realize very large space structural systems in order to manage risk.

It is proposed that a building block (at least two phases) be employed in the development of 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 SPS 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. 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.

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. Many of the technology advances will be of a multidisciplinary nature and require close attention to system level requirements due to multiple function integration. 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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