The Solar Umbrella: a Low-Cost Demonstration of Scalable Space Based Solar Power

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***Abstract*—Within the past decade, the Space Solar Power (SSP) community has seen an influx of stakeholders willing to entertain the SSP prospect of potentially boundless, base-load solar energy. Interested parties affiliated with the Department of Defense (DoD), the private sector, and various international entities have all agreed that while the benefits of SSP are tremendous and potentially profitable, the risk associated with developing an efficient end to end SSP harvesting system is still very high. In an effort to reduce the implementation risk for future SSP architectures, this study proposes a system level design that is both low-cost and seeks to demonstrate the furthest transmission of wireless power to date. The overall concept is presented and each subsystem is explained in detail with best estimates of current implementable technologies. Basic cost models were constructed based on input from JPL subject matter experts and assume that the technology demonstration would be carried out by a federally funded entity. The main thrust of the architecture is to demonstrate that a usable amount of solar power can be safely and reliably transmitted from space to the Earth's surface; however, maximum power scalability limits and their cost implications are discussed.**

I. Introduction

Since the early feasibility studies in the 1970s, Space Solar Power (SSP) has had the potential to fundamentally change global energy production. The concept which involves generating solar power in space and wirelessly transmitting it back to Earth has remained the same; however, it is the changing energy and technology landscape that shapes this particular study's approach to executing a solution. Prior to the 2007, SSP concept studies in the United States were primarily commissioned by National Aeronautics and Space Administration (NASA) and the Department of Energy (DOE) [1]. In 2007, the National Security Space Office (now Department of Defense (DoD) Executive Agent for Space) led a study that explored the viability of space based solar power as a means to ensuring global stability in a resource scarce future [2]. This paved the way for a more in depth study by the Naval Research Laboratory (NRL) that explored possible SSP defense applications and surveyed a range of subsystem technologies [3]. The same year, a California utility, Pacific Gas and Electric, executed a purchase agreement of 200 MW of SSP to be available by the year 2016. Although it is unlikely that the private sector will succeed in delivering on this agreement, it solidified the participation of an additional stakeholder in the development of SSP. Finally in 2011, the first international assessment of SSP was conducted and identified strategies for international cooperation [4].

An idea of such far reaching impact as SSP spans political and economic dimensions that are drastically different than those which existed in the 1970s. In 1979, a reference solar powered satellite concept proved to be economically unachievable [1]; however, recent decades have brought key developments such as modular SSP architectures, low cost commercial space transport, and rising energy costs that have led to renewed SSP interest. In the current policy climate, both the development and outcomes of SSP have tremendous political capital. An SSP technology demonstration fits within the framework of three major US policy issues.

Climate Change: The Clean Energy Standard Act of 2012 proposes a Clean Energy Requirement which calls for 80% of the nation's electricity to be produced from clean sources by 2035 [5]. Although the environmental effects of launching large amounts of cargo frequently into space are not yet fully understood, SSP technology has a near zero operational carbon footprint and has the potential to play a larger role than conventional solar power in electricity production due to the lack of a requirement for energy storage [6].

Energy Independence: With America spending near 700 billion USD/year on oil imports [6], bipartisan support for domestic energy production is mounting. One regulatory measure to reduce foreign oil consumption is found in the Fuel Efficiency Standards for 2025 proposed by the Obama administration. The abundant resource of SSP can be sold and delivered to any nation with the potential to make America the world's largest energy exporter.

Innovation and Job Growth: The President's Strategy for American Innovation calls for breakthrough space capabilities and applications [7]. Additionally, the America COMPETES Reauthorization Act of 2010 (H.R. 5116) grants prize authority to all federal agencies which could enable the creation of an SSP prize having the potential to accelerate private sector growth at the intersection of the energy and aerospace industries. The International Academy of Astronautics estimates total annual jobs created by SSP technology on the order of 5 million [4].

Despite rising political capital, there exist serious economic

realities that have stalled SSP development. With rough estimates near 3 billion USD [8], it is unlikely that the design, development, test, and evaluation efforts for SSP technology can be undertaken completely by any single start-up business. If the development of SSP was facilitated by interested government agencies, it is conceivable that acquisition costs could be financed by a group of private stakeholders [8]. A majority of SSP subsystem technology is readily available; however, demonstrating that these core technologies can be integrated at both subscale and full scale levels is an objective of this study.

In 2012, NASA made investments in the technology demonstration area of next generation solar arrays. The proposed concept seeks to leverage the ongoing solar array development and will concentrate on wireless power transmission (WPT) components of the architecture. WPT demonstration is critical for further development and eventual market viability. Recently, the DoD and a host of international collaborators have been added to the conventional government stakeholders representing potential SSP technology demonstration customers. The DoD, in particular, has unique military scenarios in which they pay upwards of $1/kW-h for reliable power in remote locations [8]. An SSP demonstration similar to the concept proposed would bolster confidence in a prototype system that could meet unique customer needs.

II. System Design Overview

The system performance capabilities for the technology demonstration mission evolve from the governing laws behind wireless power transmission. Due to the preliminary nature of this concept study, the Friis transmission equation assuming far field conditions was used to roughly size the aperture of the transmitting and receiving antennas involved in the SSP architecture. The Friis transmission equation can be expressed by the following:

$$\epsilon_{trans} = \epsilon_r \epsilon_t \frac{A_r A_t}{\lambda^2 R^2} \tag{1}$$

where λ is the wavelength, R is the distance between antennas, A_r and A_t are the receiving and transmitting antenna aperture areas respectively, and ϵ_r and ϵ_t are the internal power efficiencies of the receiving and transmitting antennas respectively. Further, the free space transmission efficiency, ϵ_{trans}, in Eq. 1 can also be defined as the ratio of power received, P_r, to power transmitted, P_t, described in 2.

$$\epsilon_{trans} = \frac{P_r}{P_t} \tag{2}$$

The frequency of transmission was selected based on minimizing both the power losses associated with the Earth's atmosphere and the safety concerns associated with power beaming. In line with previous SSP concepts, 5.8 GHz was chosen based on its minimal losses in a variety of atmospheric conditions. It will be demonstrated subsequently that the proposed architecture operating at the transmission frequency can meet public safety requirements.

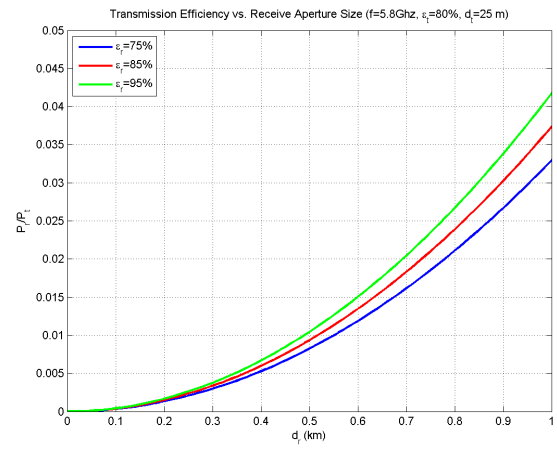

Fig. 1. Transmission efficiency as a function of rectenna diameter

After weighing the benefits associated with a Geosynchronous Earth Orbit (GEO) or Lower Earth Orbit (LEO) technology demonstration versus the cost of launch support for each, it was decided to pursue a LEO demonstration at 1620 km. The proposed concept is architected to be scalable and viable for GEO demonstrations; however, it is advisable to secure considerably larger funding to compensate for nonlinear cost increases related to size of deployable solar array and transmitting antenna.

Due to a single launch requirement of a technology demonstration, both cutting edge solar array and transmitting antenna technologies must be integrated into the spacecraft design. After review, it was determined that a deployable transmitting antenna with diameter, 25 m ($A_t = 491$ m^2), and nominal efficiency, 80% ($\epsilon_t = 0.80$), would drive the design of all other subsystems in the architecture. The transmitting antenna design criteria were fixed based on the trade-offs of developing a 25 m deployable, phased-array antenna versus developing both solar arrays and receiving antennas (rectennas) of equal or greater size. These development trade-offs will be explained further in subsequent sections.

For fixed transmitting antenna size and nominal efficiency, Eq. 1 can be used to create Fig. 1 which illustrates the rectenna design space assuming $\pm 10\%$ uncertainty on a baseline internal efficiency of 85% ($\epsilon_r = 0.85$). Examining Fig. 1 further, it can be observed that delivering approximately 1% of power generated in space to the Earth's surface will require a rectenna aperture diameter up to 575 m. A disk solar array having outer radius, 35.5 m, and usable surface area of approximately 3750 m^2 is deployed from the satellite and is capable of generating 640 kW of power at the solar array-transmitting antenna interface. The SSP system architecture will yield 6.4 kW on the ground by constructing a rectenna with aperture area of $A_r = 0.26$ km^2. The 6.4 kW of power transmitted can be used in a variety of applications relevant to public interest, and it is received at a peak incident power density of 0.023 W/m^2, less than 1% of the 10 W/m^2 power safetly limit for public access sites. The power density, p_d, at the center of

the receiving antenna can be computed by Eq. 3.

$$p_d = \frac{A_t P_t}{\lambda^2 R^2} \tag{3}$$

The following list summarizes the key system level operational capabilities of the design architecture:

- 5.8 GHz power beam frequency
- Transmitting from LEO, 1620 km
- Thin-film photovoltaic with conversion efficiency 12.5%
- 3750 m^2 disk solar array producing 640 kW and deployed from spacecraft bus
- 25 m diameter transmitting antenna deployed from spacecraft bus
- Free space transmission efficiency of 1%
- Peak power density of 0.023 W/m^2 - below 10 W/m^2 public safety limit
- 575 m rectenna diameter with surface area of 0.26 km^2
- Total spacecraft weight: $4,641$ kg
- Power collected on ground: **6.4 kW**

A. Solar Array Design

By employing recent advancements in thin-film photovoltaic (PV) technology, scalable deployment mechanism configurations can be achieved without suffering the complex configuration of rigid solar panels. In exchange for this mechanism simplicity, there are notable trade-offs.

Although thin-film PV cells such as hydrogenated amorphous silicon (a-Si:H) CP1 polymer film allow compact folding and fabric management, their solar energy conversion is less than that provided by state of the art Gallium Arsenide (GaA) space solar panels. Thin film PV solar cells with 7.5 micron thickness were demonstrated in space flight by the Japan Aerospace Exploration Agency (JAXA) Interplanetary Kite-craft Accelerated by Radiation Of the Sun (IKAROS) mission in 2010 [9]. Although their efficiency in flight is 12.5%, the specific power ratio for an individual bare solar cell is upwards of 4300 W/kg. Power Management and Distribution (PMAD) of the thin film PV solar array has a lower TRL than the polymer film technology by itself; however, the favorable specific power ratio and specific mass justify the additional development effort to mature the PMAD architecture.

A thin-film a-Si:H, CP1 solar array deployed in a disk configuration with outer and inner radii of 35.5 m and 1.5, respectively, is capable of producing approximately 640 kW of power while only requiring a total fabric mass of 112.5 kg. The usage of thin film PV solar arrays is an essential first step ensuring the deployment mechanism is scalable to larger areas. The solar array design summary is shown in Table I.

B. Solar Array Deployment Mechanism

Because solar array deployment is mission critical in a system level fault analysis, attention was given to designing a deployable structure with minimal risk for mechanical binding. The modified 'umbrella' configuration is a viable candidate for robust deployment and is shown in its stowed configuration in Fig. 2. Traditional umbrella deployment uses a runner attached to truss-like 'stretchers' that slide along a tube axially. As the runner completes the deployment stroke, it raises support ribs which outstretch a continuous membrane. Once the mechanism achieves sufficient tension the runner is fixed in the 'shaded' position by the use of a latch-spring mechanism. On a spacecraft, the deployment of the solar array is similar; however, there are a few key differences.

First, the runner and tube sliding stroke configuration is replaced with a hexapod configuration which compresses two support rings generating the force in the truss-like 'stretchers' which raise the ribs (see Fig. 3). The complexity of a locking mechanism is replaced by six telescoping lead screw actuators which are capable of sustaining the load of the deployed configuration. Secondly, through proper selection of mechanical joints and actuation the complete assembly maintains a kinematic arrangement. This allows for smooth, controlled deployment of the solar array ribs which is robust to actuator lag. Finally, after the the solar array ribs are deployed to a perpendicular configuration, the thin-film CP1 solar array blanket is outstretched through the use of a telescoping boom capability of the ribs. As the telescoping ribs extend to 34 m radially from the 3 m diameter upper support ring, they simultaneously unfold the solar film which is stowed in the interior of the spacecraft.

TABLE I
SOLAR ARRAY DESIGN SUMMARY

Specification	Description
Solar Array Type	Thin film PV
Solar Array Efficiency	12.5%
Solar Cell Type	CP1, a-Si:H
Size, Outer Radius	35.5 m
Specific Power per solar cell (W/kg)	4300
Specific Mass per solar cell (kg/m^2)	0.03
Power Density (W/m^2)	170
Power Output (kW)	640
Total Material Mass (kg)	112.5

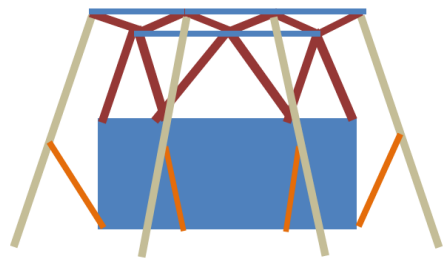

Fig. 2. Simplified sketch of stowed configuration of solar array deployable mechanism

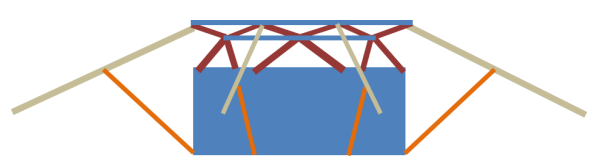

Fig. 3. Simplified sketch of solar array mechanism before full deployment

Telescoping masts (or in this case, ribs) have space flight heritage with a variety of applications. For example, Astro Aerospace has previously developed and qualified a telescopic mast assembly and can reliably ensure deployment up to 34.4 m [10]. The rib actuation will be slow and controlled with the intention of minimizing vibration induced from extension. As the design matures, further dynamics studies may necessitate the addition of damping devices to minimize the operational risk of low frequency mechanical deployment modes.

C. DC to RF Conversion

Electrical DC power from the solar array subsystem must be converted to RF microwaves so that it can be transmitted by the satellite's antenna to the Earth's surface. Early SSP studies proposed configurations that integrated Klystrons or Traveling Wave Tubes (TWTs) with the transmitting antenna reflector. This concept provided multifunctional capability that embedded the microwave power conversion in the structure of the antenna and still allowed beam forming through array phasing as opposed to reflector shaping. Since the early designs, there have been significant advances in Monolithic Microwave Integrated Circuits (MMIC) which have enabled smaller and more efficient Solid State Power Amplifiers (SSPAs). Both gallium arsenide (GaA) and gallium nitride (GaN) semiconducting materials are well suited for high powered antenna applications. While GaA MMIC technology has been qualified in both military (Raytheon's Terminal High Altitude Area Defense - THAAD - program) and space applications (Iridium commercial satellite antenna) [11], GaN solid state circuits offer lower production cost and higher voltage benefits.

Due to GaN SSPAs recently attaining high Manufacturing Readiness Levels, a transmitting antenna composed of GaN subarrays is proposed for both conversion of DC power from the solar array interface to microwave frequency and the directed transmission of converted power via phased array. Despite the lack of space flight heritage applications, GaN solid state microwave transmitters fabricated on Silicon Carbide (SiC) substrate are capable of producing less than 1 mm thick subarray modules [12]. This thickness is critical for storage and deployment of a large aperture transmitting antenna. The GaN solid state technology enables the conversion of DC to RF power at an efficiency of 90%; however, additional losses are considered in assessing the overall transmission efficiency. Conservatively accounting for DC-DC conversion, amplitude error, phase error, electronic failures, phase/taper quantization, and losses in the aperture, the overall transmitter efficiency is estimated to be 80% [13].

D. Transmitting Antenna Design

For the SSP architecture proposed in this study, the transmitting antenna design represents the most critical subsystem with respect to risk and reward ratio. Developing and demonstrating a phased array antenna with state of the art embedded power electronics mentioned in section II-C and deploying it over large apertures is essential for any SSP system moving forward. This level of transmitting antenna technology is unprecedented in space applications, but is enabling for future SSP systems.

TABLE II
TRANSMITTING ARRAY DESIGN SUMMARY

Specification	Description
Subarray Type	Solid-State GaN
Max Converter Power Output (W)	59
GaN Converter mass (kg)	0.001
Specific Mass (kg/m^2)	33.9
Specific Power (kW/m^2)	1.3

Recalling that the solar umbrella size and power (section II-B) is fixed by the limits of deployable mast/rib technology, the design methodology for the transmitting antenna involves comparison trades with the rectenna only. For fixed rectenna size, increasing the transmitting antenna diameter will favorably augment the free space power transmission efficiency to the Earth; however, unlike the rectenna, the transmitting antenna is flight hardware and has much more severe penalties for increased mass, size, and/or complexity. Also, due to the nature of GaN SSPA circuits, it is likely that the transmitting antenna will have to accommodate panel thicknesses up to 1 cm. Therefore, a thickness accommodating deployable scheme which maximizes aperture area while minimizing weight is desired.

There exist thickness accommodating origami-based concepts which are capable of delivering up to 25 m diameter arrays composed of rigid rectangular-shaped panels of thickness 1 cm [14]. Prototype mechanisms are currently being developed at JPL. Deployment actuation can be governed by a perimeter truss which has high flight heritage having supported the deployment of 12 m reflectors as high as GEO [15]. The origami-based deployment via perimeter truss concept is shown in Fig. 4. The stowed transmitting antenna aperture diameter is 2.8 m with a height of 4 m, and the deployed configuration reaches 25 m in diameter (ratio 1:9). The antenna configuration can be stowed easily in a spacecraft and when deployed must be capable of transmitting power at 1.3 kW/m^2. The 5.8 GHz transmitting antenna design specifications are summarized in Table II.

E. Rectenna Design

The governing objectives motivating rectenna design were minimum sizing, ease of manufacturing/assembly, and durability. These objectives combined with the Earthbound rectenna assembly translate to a lower cost subsystem. The rectenna executes two functions: receiving and rectifying the microwave signal (RF-DC conversion). As the rectenna aperture area grows, the transmitted power efficiency increases with the diameter as shown in Fig. 1. For fixed source power at the solar array interface of 640 kW, the rectenna must meet a minimum size such that technology demonstration capability of collecting 6.4 kW can be met. The minimum rectenna area must fill a circular diameter of 575 m to receive at least 6.4 kW. A modular, element based rectenna design composed

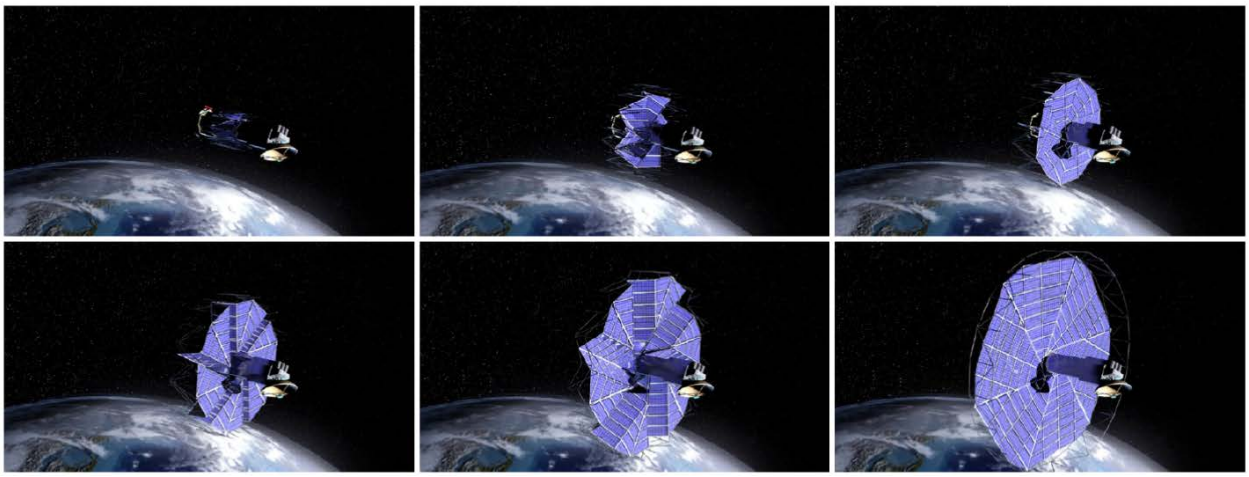

Fig. 4. Transmitting Antenna Deployment via Thickness Accommodating Origami-Based Flasher Model

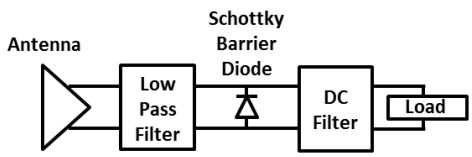

Fig. 5. Rectenna Circuit Schematic

of GaA, Schottky barrier diodes fed by half-wave dipoles is proposed to facilitate rapid manufacturing and optional future expansion of rectenna area. Dickinson *et. al.* demonstrated that the aforementioned rectenna configuration could receive power transmitted via microwaves with efficiency upwards of 85% in the NASA Goldstone tests [16]. A schematic of a rectenna element is shown in Fig. 5 for reference. The critical advantage of using such a simple design is the ability to 'hand tune' the dipole length throughout operational lifetime. At 5.8 GHz, the dipole length should be 0.025 m which allows for a high concentration of dipoles within a m^2 area of the rectenna array. The resulting peak power density of the rectenna when operating within the proposed SSP system design capabilities is 0.023 W/m^2, which is well below the 10 W/m^2 public safety limit.

The rectenna design is not unique to solar satellite design. It is only dependent on the frequency of free space transmission. Therefore by making future investments in installing additional rectenna elements to increase aperture area, the same hardware can be used for future SSP architectures with potentially greater source power and which operate at GEO. The durability of the GaA dipole-diode construction is critical to ensure that the rectenna hardware will be viable for future missions. Durability considerations depend on location and environment. Because Earth environments are generally more benign than space, it should be required that location selection be made based on the rectenna maintaining operational functionality for at least 20 years. Given operational durability, choosing a rectenna location becomes a function of safety and political concerns.

Ideally, a rectenna, when receiving power at greater intensities than the system proposed, should be located away from populated areas while minimizing environmental impact. Large scale rectenna construction presents an opportunity to create a new arena of US manufacturing jobs. These new rectenna manufacturing jobs could be very attractive to states which are seeking to transition workforces that have traditionally produced energy sources with high carbon content, such as coal.

III. Cost Considerations

The SSP architecture presented is designed for the purpose of demonstration and integration of the subsystem technologies. The cost analysis associated with technology demonstration missions serves to bound the cost in an 'order of magnitude' sense and draw attention to areas of relative high cost. Because technology demonstration missions lack similar architectures or implement subsystems with very little heritage, final estimates can have high uncertainties without comparison to historical data. In order to generate a best estimate, it is necessary to employ Cost Estimating Relationships (CERs) which rely on input information such as specification, TRLs, and integration strategy.

A. Cost Modeling

CERs are used to make cost projections during a Pre-Phase A mission study. Although not completely analogous, Pre-Phase A mission study CERs can be applied to portions of the proposed SSP demonstration to facilitate overall cost estimates. A benchmark tool implementing a CER based modeling approach is the NASA/Air Force Cost Model (NAFCOM). NAFCOM relies on a wealth of historical mission data from federally funded space mission programs and can be utilized for early stage cost estimates. Using a variety of assumptions, a combination of the NAFCOM tool and in-house cost models was executed to produce a preliminary total cost for the SSP technology demonstration.

TABLE III
ESTIMATED COST FOR SSP TECHNOLOGY DEMONSTRATION

WBS Element	Flight Unit	DDT&E	Total
1.0 Spacecraft	65.86	460.20	526.06
1.1 Spacecraft Subsystems	56.31	301.36	357.66
Solar Array	3.05	5.43	8.48
Transmitter	1.13	144.63	145.76
Spacecraft Bus	52.12	151.29	203.42
Structures & Mechanisms	30.75	85.47	116.23
Power Management & Distribution	2.79	11.25	14.04
ADCS	5.59	15.28	20.87
Guidance Navigation & Control	0.26	0.54	0.79
CC&DH	7.18	12.84	20.01
Thermal Management System	5.56	25.91	31.48
1.2 System Integration	9.55	158.85	168.40
2.0 Program Support	9.88	69.03	78.91
3.0 Vehicle Level Integration	4.54	31.75	36.30
4.0 Rectenna	0.00	0.00	64.13
5.0 Falcon 9 Launch Services	0.00	0.00	56.5
Total Mission Cost	80.28	560.99	761.9

B. Cost Results and Scalability

A final summary breakdown of the SSP end to end system cost (all cells in FY2012 $M) is presented in Table III. For Table III, the following acronyms are defined: WBS - Work Breakdown Structure, DDT&E - Design, Development, Test, and Evaluation, ADCS - Attitude Determination and Control System, and CC&DH - Comand Control and Data Handling. High relative costs are associated with the transmitting antenna subsystem and the solar array subsystem due to their low technology readiness. Independent technology development programs in these areas could result in significant system level cost reductions. Currently, the subsystems are designed to be scalable with fabric management and weight as limiting factors on scalability. Cost, not material limits will drive scalability due to the trend of decreasing specific weight in thin-film PV and GaN SSPA circuit panels.

IV. CONCLUSION

A complete end-to-end SSP system level architecture - the solar umbrella - was proposed in this study for a preliminary cost estimate of 762 M USD. The system capitalizes on thin-film PV advancements and leverages their favorable specific power to drive development of complementary power management capabilities. The GaN SSPA transmitting antenna sends power through free space at 5.8 GHz via embedded phased array power electronics technology. While the transmitting antenna represents the most ambitious development effort of the SSP system with respect to cost and technology, success in this area is deemed critical for larger scale follow-on systems. Launch cost savings are incurred by demonstrating the SSP system from LEO at 1620 km. A lower orbit also reduces solar array and transmitting antenna geometries and scales back development costs. The proposed rectenna subsystem is low cost and easily manufactured. It can be re-used or extended via additional elements for future demonstrations involving higher power and orbits. The end-to-end SSP system transmits power at beam densities well within the safety threshold for public safety. Increased investments in scaling up the size of the solar array will deliver more power to Earth, but will have to be executed prudently to satisfy safety requirements.

V. ACKNOWLEDGMENTS

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