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A space-to-space microwave wireless power transmission experiential mission using small satellites

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ABSTRACT

A space solar microwave power transfer system (SSMPTS) may represent a paradigm shift to how space missions in Earth orbit are designed. A SSMPTS may allow a smaller receiving surface to be utilized on the receiving craft due to the higher-density power transfer (compared to direct solar flux) from a SSMPTS supplier craft; the receiving system is also more efficient and requires less mass and volume. The SSMPTS approach also increases mission lifetime, as antenna systems do not degrade nearly as quickly as solar panels. The SSMPTS supplier craft (instead) can be replaced as its solar panels degrade, a mechanism for replacing panels can be utilized or the SSMPTS can be maneuvered closer to a subset of consumer spacecraft. SSMPTS can also be utilized to supply power to spacecraft in eclipse and to supply variable amounts of power, based on current mission needs, to power the craft or augment other power systems.

A minimal level of orbital demonstrations of SSP technologies have occurred. A mission is planned to demonstrate and characterize the efficacy of space-to-space microwave wireless power transfer. This paper presents an overview of this prospective mission. It then discusses the spacecraft system (comprised of an ESPA/SmallSat-class spacecraft and a 1-U CubeSat), launch options, mission operations and the process of evaluating mission outcomes.

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1. Introduction

Conventional space missions operate either from an onboard nuclear power source or using onboard solar power generation panels. In the former case, the mission launches with all of the power that it will ever have; in the latter, power utilization is (similarly) limited by generation capability. In both cases, the amount of power being produced declines as the mission progresses. These spacecraft must, thus, be built to satisfy end-of-mission generation needs, possibly meaning that excessive power is generated early in the mission which must be radiated as heat (necessitating a more capable thermal system). The additional generation capability (as well as, potentially, the expanded thermal system) increases spacecraft volume, mass, complexity and costs. The deterioration effectively limits the spacecraft's lifespan.

A new approach has been proposed [1–4] which utilizes space solar power (SSP) satellites to provide power to other spacecraft under a utility-provider model, using

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small spacecraft. Utilizing this approach and an orbital service model [5,6], consumers can procure power for their spacecraft on an ongoing, augmentation contract or ad hoc basis. This power is then transmitted to rectifying antennas (rectennas) on their spacecraft for use. The use of rectennas instead of solar panels increase spacecraft lifespan and can serve to reduce mass and volume due to the greater energy density that can be transmitted in this way the rectenna is also lighter, for a given amount of surface area, than a solar array.

Before a system of this type can be developed commercially, for government use or otherwise, the various technologies and their integrated operations must be tested and space qualified. This paper provides an overview of a mission which is designed to demonstrate the space-to-space microwave wireless power transfer concept, test key assumptions and components and begin the process of space qualifying the individual components and system operations.

In the following section, background material is presented. After this, there is an overview of the mission. Next, an overview of the spacecraft system is provided. Then launch requirements and options are discussed, followed by an overview of mission operations. Finally, before concluding, a set of metrics for mission evaluation are presented.

2. Background

Three areas of prior work inform the mission presented herein. First, prior work related to space solar power is discussed. Next, prospective uses of space solar power are discussed. Finally, an overview of small satellites (both at the ESPA/SmallSat and CubeSat sizes used in this mission) is presented.

2.1. Space solar power satellite systems

A history of SSP is presented by Strassner and Chang [7], McSpadden and Mankins [8] and Bergsrud and Noghanian [9]. The concept of Space Solar Power Satellite (SSPS) systems was conceived by Dr. Peter Glaser at the Arthur D. Little company in 1973 [10]. Glaser's vision was to place large satellites in geostationary Earth orbit (GEO) whose sole purpose is to harvest large amounts of solar energy, transform the solar energy in microwave energy and transmit it to a rectifying antenna (rectenna) array located on Earth's surface. The rectenna array would collect the microwave energy and convert it into usable direct current power that is injected into the terrestrial electric grid system to supply humanity with a clean source of baseload electrical power. SSPS systems may one day supply sufficient amounts of electrical power to Earth and beyond to aid humanity in its continued advancement.

The first major study of SSPS systems was conducted between 1976 and 1980 through a joint collaboration between the Department of Energy (DOE) and National Aeronautics and Space Administration (NASA) [11] as well as many other entities. This period of study resulted in the creation of the foundational architecture for SSPS systems. Large-scale power infrastructure in space consisting of about 60 SPSS, each delivering 5 GW of base load power to the U.S. electrical grid [8] was crafted. In addition, candidate locations for SSPS rectifying antennas on Earth were investigated [12,13] along with rectenna-related atmospheric effects [14] and ways to effect electrostatic protection of the SSPS [15] and lightning protection for the rectenna [16]. This extremely productive period of the Satellite Power System Concept Development and Evaluation Program [8] determined that SSPS systems was a feasible technology and should be pursued in the future [7], and the U.S. National Research Council (NRC) recommended that the concept be re-assessed in about ten years, subsequent to additional technology development and maturation [8].

During the 1980s and early 1990s, international interest in the SSPS concept emerged in Japan, Europe, and Canada. In particular, a Japanese research group from Kyoto University conducted the first successful Microwave Wireless Power (MWP) transmission experiment (in 1983) called the Microwave Ionosphere Nonlinear Interaction eXperiment (MINIX) [17]. Again, in 1993, another Japanese research group completed the International Space Year-Microwave Energy Transmission in Space (ISY-METS) S-520-16 sounding rocket experiment [18]. Both projects utilized a daughter-mother rocket combination to demonstrate MWP transmission technologies and produced results characterizing the nonlinear plasma effects of the high power microwave energy beam in the space environment.

NASA recognized the accomplishments of the Japanese teams and, in 1995 undertook a new study of the challenges of large-scale SSPS systems through the Fresh Look Study [19,20]. The study highlighted recent technological advancements which made SSPS systems more viable than they were at the end of the 1980s [21,22]. In 1998, NASA conducted the SSP Concept Definition Study, in which experts outside the agency were also involved. The SSP Concept Definition Study validated findings in the Fresh Look Study, but it also invalidated some earlier ideas which narrowed the SSP concepts. A key outcome of this study was the definition of a family of strategic Research and Technology (R&T) road maps for the possible development of SSP technologies [8].

The next major advancement of SSPS occurred in 2000 when the NASA Marshall Space Flight Center (MSFC) conducted the SSP Scientific Exploratory Research and Technology (SERT) program. The SERT program broadened the scientific community's involvement and resulted in successful demonstrations of a variety of system level components [7]. It included tightly focused exploratory research targets and rapid analysis to identify promising system concepts and establish their technical viability. Small scale demonstrations of key SSPS concepts/components using nearer-term technologies were initiated [8]. Finally, the SERT program addressed issues related to economic and societal assessment, environmental effects, resource requirements, and legal issues [7].

From the end of the SERT program to today, numerous articles have been written about SSPS systems, but supportive research has been sporadic (at best) due to funding limitations [7]. One MWP transmission project of particular interest was performed in Hawaii. The Hawaii MWP transmission experiment was carried out in 2008 by