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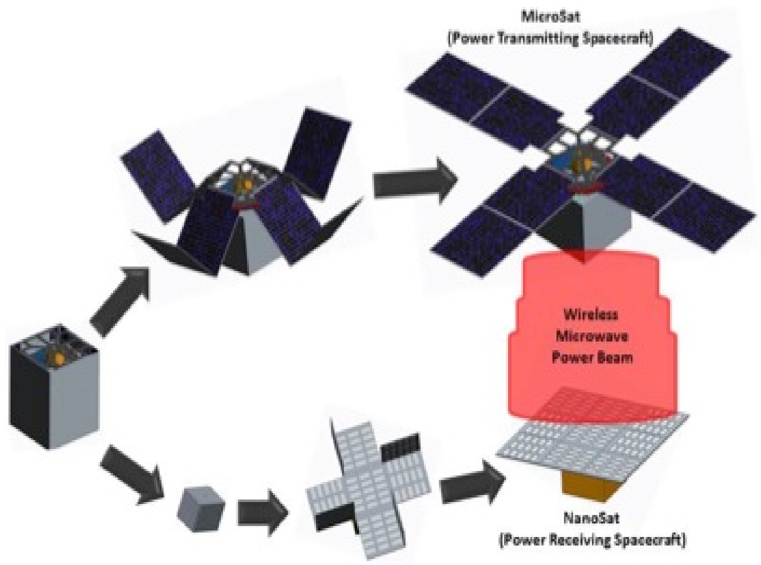

Nano SSP Satellite

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ABSTRACT

This work presents the conceptualization of a Space-to-Space Microwave Wireless Power Transmission (S2S-MWPT) experimental demonstration mission using small spacecraft. Literature reviews [1, 2] suggest a stepwise procedure for technology demonstrations in support of advancing space solar power satellite (SSPS) systems. These technologies should be verified first on Earth and then in-space using small satellites. This project built its S2S-MWPT demonstration concept within the University NanoSat program restrictions (dimensions of 50cm x 50cm x 60cm and mass of 50kg). The idea is to use these upper limit restrictions to develop the MWPT spacecraft (MicroSat). Contained inside the MicroSat is a microwave wireless power receiving spacecraft (NanoSat). The NanoSat has dimensions of 10cm x 10cm x 10cm and mass 1.33 kg. Once the MicroSat is launched into low Earth orbit the NanoSat is ejected out of the MicroSat. Then the MicroSat deploys its solar array and the NanoSat deploys its rectifying antenna

(rectenna) array. The S2S-MWPT experimental demonstration becomes operational and several technical validations are proposed for implementation.

The business venture proposes a S2S electric utility service provider for in-space activities. It is suggested [3] that SSPS systems as a source of power for in-space activities may represent a potentially large market that may be served by SSPS sooner than by terrestrial solar. The space utility proposes a revolutionary new line of consumer spacecraft equipped with a rectenna array architecture rather than a solar array structure. The proposed SSPS power reception structure will require a modified electrical power system on consumer spacecraft. This option may provide several potential benefits: longer mission life, reduced mass (or allow reallocation of the mass to the payload), and added power. These consumer spacecraft may also benefit from the geostationary Earth orbit SSPS as they could potentially fly through the beam and generate needed on-board power. Several challenges for this idea are also addressed.

TECHNICAL BRIEF

The proposed S2S-MWPT experimental demonstration mission consists of two satellites; a MicroSat (dimensions of 50cm x 50cm x 60cm and mass of 50kg) and a NanoSat (10cm x 10cm x 10cm and mass 1.33 kg). The NanoSat is stored inside the MicroSat for launch. Once the MicroSat is launched into space the NanoSat is ejected from the MicroSat. Both satellites then deploy their solar array or rectenna array architectures, respectively, for the power transmitting MicroSat and the power receiving NanoSat. The S2S-MWPT experiments are now able to be implemented. The evolution of the aforementioned sequence is shown in Figure 1.

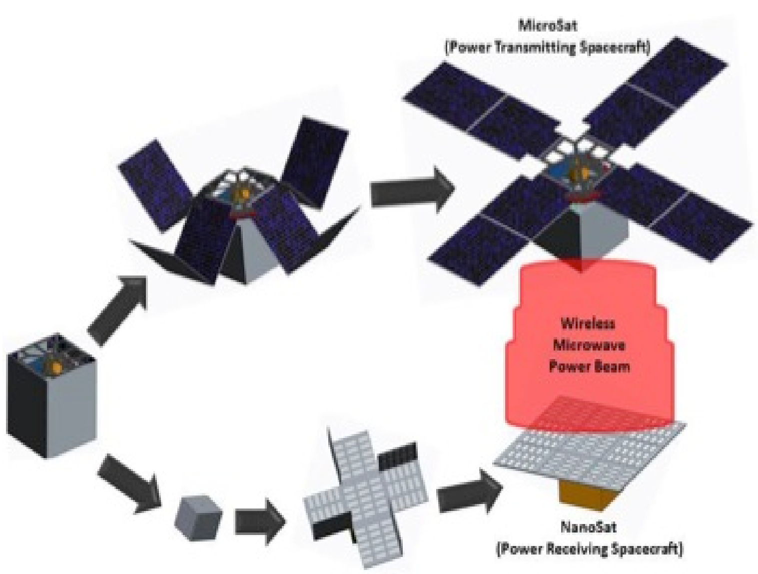

Figure 1 Proposed deployment mechanism and operational S2S-MWPT experimental demonstrations.

There are several key experiments to consider:

- Demonstrating and validating key hardware elements and transmission characteristics
    - Solid State Power Amplifiers
        - Heat energy harvesters
    - Retro-directive array system in space
        - Pilot beam comes from the power receiving spacecraft
    - Transmitting spacecraft
        - Equipped with a Gaussian profiled conical corrugated horn antenna feeding a dual reflector offset Cassegrain reflector
            - The main reflector is proposed to be the sides of the spacecraft during launch and once in-space the main reflector (walls of the MicroSat) is deployed.
        - Mechanical beam steering from sub-reflector
            - Pilot reception is located on backside of sub-reflector
        - Electrical beam steering from an array of feeders
            - This is limited to the space on the spacecraft
            - Another possibility is to place an phased array antennas on the back of the solar panels
- Monitoring system performances for conversion and transmission efficiencies
    - Calibrating for plasma affects
- Monitor characterization of thruster performance
    - The thrusters ensure the two spacecraft (transmission and reception) maintain a range of distances for successful amount of power transfer and possible alignment/orientation during power beaming
- Analyzing system reliability, performances of components under severe thermal shocks, effects on component degradation over time in space, comparisons between land and space experiments.

All these measurements provide information for simulating the space environment on Earth for future component and system testing [4]. Utilizing Small spacecraft may present a less-expensive means of validating key SSPS transmission and reception technologies in the space environment and through utilization of more university based research and developments. The business plan section will highlight this case as well as the concept of a space electric utility service provider.

The electrical power system (EPS) for the MicroSat is illustrated according to its sub-system as shown in Figure 2. The block diagram provides an initial map of the required systems and their power requirements needed for constructing the MicroSat's EPS. A key technology is the gimbal, shown in Figure 3. The gimbal design, inspired by Stanford University [SITE], allows the solar array to collect maximum power longer throughout the satellite's orbit by means of tilting and rotating the solar array towards the sun. The battery requirement was estimated from Figure 4.

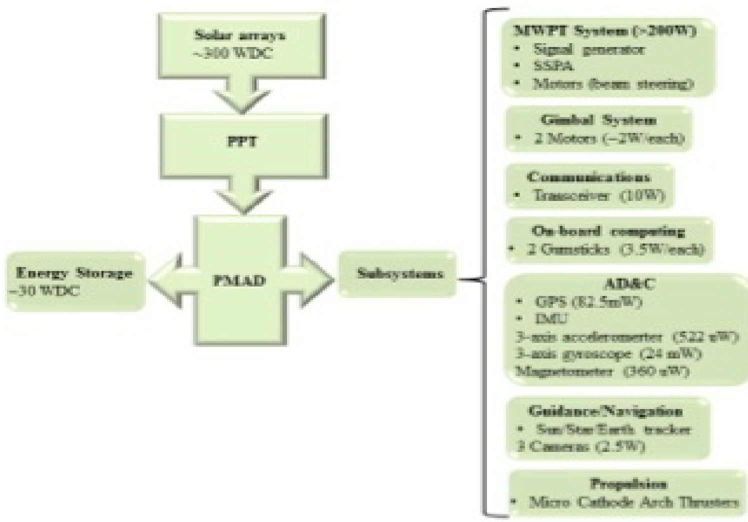

Figure 2 Proposed power transmitting MicroSat EPS.

Figure 3 The gimbal design has a 70 deg. tilt angle and a 360 deg. rotation capability.

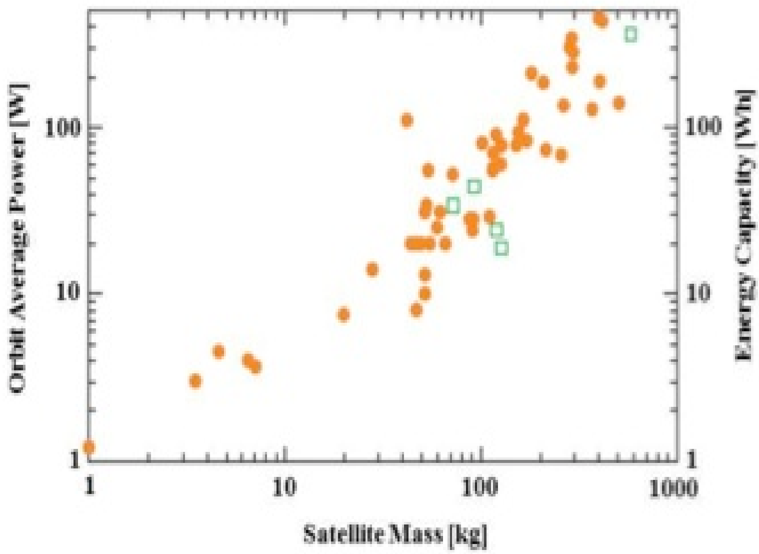

Figure 4 Orbit average power vs. satellite mass [5].

Current state of the art radio frequency (RF) to direct current (DC) rectifiers operating at the microwave frequencies have achieved efficiencies up to 82% [6-9] . In these designs the outputs of the rectennas have been directly connected to a fixed load to maximize the power transfer of the rectenna. The proposed design will implement a buck/boost converter as shown in Figure 5. The goal of the buck/boost converter is to regulate the voltage produced by the rectenna and convert it into acceptable power levels as various power ranges are expected due to changes in the distance between the transmit and receive satellites.

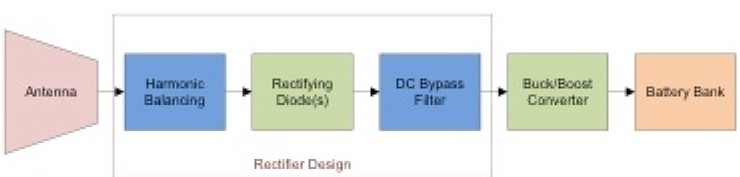

Figure 5 Block diagram of a power receiving rectenna.

Average solar panels operate at an efficiency of 25% in converting the solar energy into electricity, and the rest of the energy is dissipated as heat. Since the whole satellite body receives the heat energy from the space environment. The excess thermal energy can destroy the device by outreaching its nominal operating and survival temperature range. This is why thermal analysis is required to ensure that the operating temperature of the device doesn't exceed its limits.

The continuous operation of all the electrical components is crucial for the full functioning of these satellites, which means that electronic components are kept to their operating temperature range. Thermal analysis of the satellite in the design phase will help to point to considerations that must be taken in extreme temperature scenarios to avoid the system failures as shown in Figure 4.

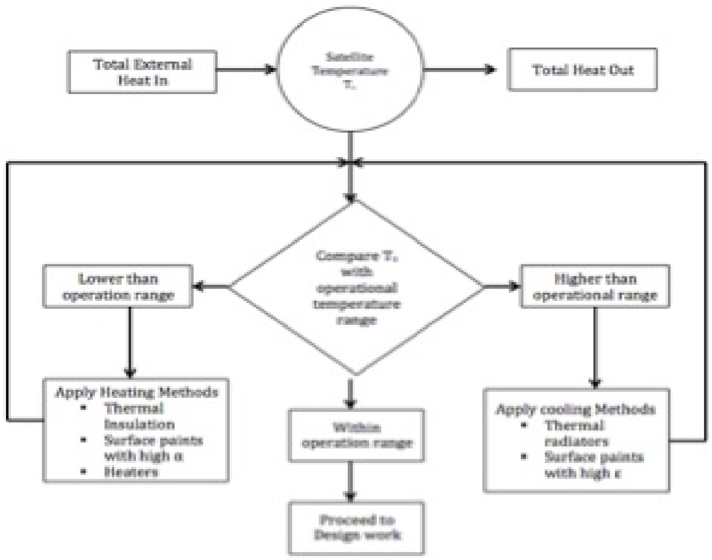

Figure 6 Thermal Analysis Flowchart (based on [5])

Technical Roadmap

Now – Early Design
 	
- Create very high level mission design
- Create very high level spacecraft designs
- Create very high level software design
- Create very high level system design
- Identify prospective funding sources (to the program / solicitation level)
- Promote project to:
  o Technologist community
  o Prospective user communities
- Key Reviews:
  o Mission Concept Review
  o Systems Requirements Review
  o Mission / System Definition Review
	Year 1: 2014-2015 – Design
	
	- High level designs completed
	- Low level designs of opportunity completed
	- Designs of key system areas
	- Rough implementation plan completed
	- Apply for FCC experimental license
	- Key Reviews:
	  o Preliminary Design Review

Year 2: 2015-2016 – Design & Development
- Low level designs completed
- Implement prototypes of key system areas
- Begin development of spacecraft areas with greatest critical path effect
- Control software design completed
- Key Reviews
  o Critical Design Review
	Year 3: 2016-2017 – Development
	- Complete development of all spacecraft systems
	- Complete development of individual component control software packages
	- Complete rough draft of integrating software components
	- Key Reviews:
	  o Systems Integration Review

Year 4: 2017-2018 – Validation, Integration & Refinement
- Test all systems
- Test software control of / interface with individual systems, if possible / applicable
- Integrate systems
- Test integrated system
- Test software control of / interface with integrated system
- Key Reviews:
  o Operational Readiness Review
	Year 5: 2018-2019 – Validation, Integration & Refinement, Management Reserve
	- WRT validation, integration and refinement, see year 4.
	- WRT management reserve, use time as needed for other areas
	- Hand over spacecraft to launch provider
	- Launch
	- Prepare on-orbit operations plan
	- Key Reviews:
	  o Flight Readiness Review

Year 6: 2019-2020 – On-Orbit Operations - Perform experiments - Collect data - Characterize results - Perform experiments to clarify / validate data critical to findings - Identify new possible experiments that can be performed during mission, based on data collected and findings - Key Reviews: o Post Launch Assessment Review	

A Prospective Business Case and Economic Analysis

Predicated on Macauley and Davis's [1] projection of a willingness to pay $500 to $6,700 per annualized watt hour (or 8.76 kwh/year), we determined (in [[2]]) that a constellation of even large orbital craft did not represent a suitable solution for providing power to small and mid-size craft.

The free space loss, given the level of transmitter and receiver antennas that could be supported by these spacecraft, required an excessive amount of generation capability, to the extent that spacecraft development costs for the transmitter spacecraft eclipsed any prospective savings or benefit enjoyed by the receiver craft. In the very long term, the system proposed by McSpadden and Mankins [3] may facilitate low (or potentially even no-cost-to-operator) power reception, by those whose orbits pass through the transmission beam. This system, however, requires a dramatic capital investment to build a 500 m aperture transmitter and associated collection and power processing hardware, making it infeasible to support commercial activities in the foreseeable future.

Similarly, while the work proposed by Komerath [4] may facilitate the use of smaller spacecraft, the hardware required for this is either inefficient or very low technology readiness level (TRL). To facilitate a nearer-term business venture, an alternate solution needed to be found.

To this end, in [5], we proposed a three-phase approach to the creation of a space power utility for servicing in-space activities. However, to 'buy down' the risk of using this technology before either public or private investment is made in the infrastructure required to support it, a test mission is needed. Thus, this becomes a four-phase test mission with the demonstration mission (which we discussed in [6]) becoming the first phase. This brief summarizes the prospective benefit which might be derived, first presented in [5], from the middle two phases of this four-phase approach. These two phases have been chosen as their technology and timeframe facilitates more reliable cost estimation. They are also likely to occur in a close enough timeframe to allow the projected willingness-to-pay figures generated by Macauley and Davis [1] to be valid.

We have estimated the cost, excluding labor, of developing a rectenna suitable for receiving power transmitted from earth or from the system proposed by McSpadden and Mankins [3]. Table 1 depicts these costs for a 1 m2 rectenna, resulting in an estimated cost of $16,364.60 per m2. Given the energy density proposed by McSpadden and Mankins [3] of 200 w/m2 (see Lin [7]). We anticipate the labor cost of this production to add less than $1,000 in additional cost. From this, we calculated the average cost per watt of generated power to be (excluding the nominal labor cost) $116.84.

Item	Cost
Material (RT/duroid 6002) 1550inx1550in	258(62.30) = $16,073.40
Rectifier (@$0.10/unit)	$5.6 for 28x28 pairs of two elements
Voltage Regulator Circuit ($5.10/unit)	$285.60
Total	**$16,364.60**

Comparatively, a solar panel using 27.3% efficient Spectrolabs solar panels would cost $13,340 in materials cost for a 1 m2 panel. The labor costs were estimated at

$3,840, based on the average union entry wage reported by the UAW . From this, using a solar flux density of 1362 w/m2, we estimate the cost to be $46.20 per m2.

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