Online Journal of Space Communication

Volume 11
Issue 18 *International SunSat Design Competitions (Fall 2013 / Summer 2016)*

Article 6

October 2021

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Recommended Citation

Straub, Jeremy; Plante, Tristan; Kading, Benjamin; Holland, Alex; Klein, Landon; and Forbord, Jordan (2021) "SunSat Design Competition 2014-2015 Third Place Winner – Team Martian: Space Solar Power Test Bed," *Online Journal of Space Communication*: Vol. 11 : Iss. 18 , Article 6.
Available at: https://ohioopen.library.ohio.edu/spacejournal/vol11/iss18/6

SunSat Design Competition 2014-2015 Third Place Winner – Team Martian: Space Solar Power Test Bed

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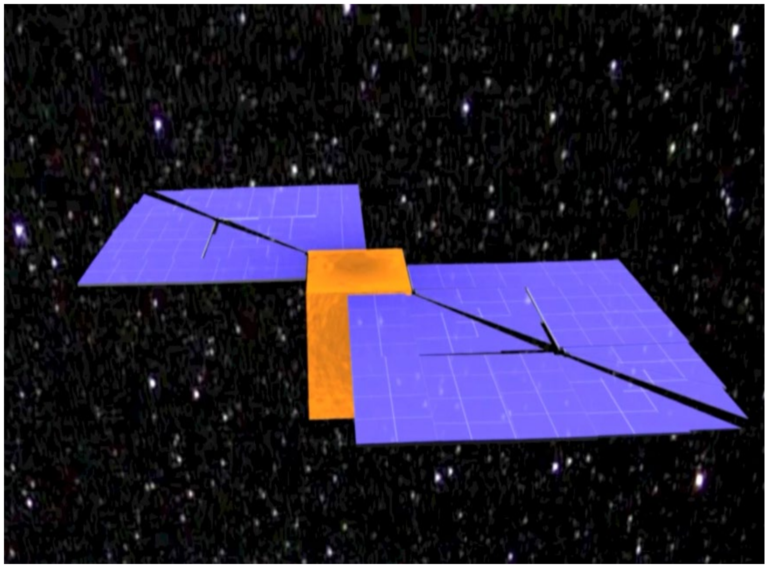

A Martian Test Mission to Enable Space Solar Power on Earth

MaVERIC: The Mars Versatile Electric Power Transfer Readiness Indication Collaborative Demonstration Mission

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ABSTRACT

We propose a four-stage plan to demonstrate the effectiveness and safety of Space Solar Power (SSP) for use on Earth. Our project goal is to achieve Technology Readiness Level (TRL) by means of: 1) a test mission in low Earth orbit using a small spacecraft; 2) that will support a manned mission to Mars; 3) that includes a

bent pipe experiment (power supplied from Earth, to a spacecraft and back to Earth), and 4) to complete system deployment.

The primary impediment to SSP implementation is thought to be the acceptance of the system by those on Earth who may be afraid of the by-products of its use (e.g., radiation) or its misuse (e.g., targeting areas with high levels of radiation).

By gaining operating experience and raising the TRL in ways that are less objectionable, it is believed that the Space Solar Power technology may gain greater acceptance for use on Earth.

Click here to see this team video: [Team Martian - Test Bed for Space Solar Power on Earth]

TECHNICAL BRIEF

This section provides an overview of the mission and the technological development and testing that will be conducted. Relevant background material is first reviewed.

Background

David Hughes, who made the first radio transmission [1, 2], initiated a chain of events that would make space solar power possible. Important contributions were also made by Heinrich Hertz (who demonstrated the wave-property of radio transmissions and their ability to be transmitted across empty space in 1886) [3], and by Nikola Tesla (who suggested the use of radio for power transmission and was granted patents on wireless energy transfer) [4-6].

In the 1930s, the klystron tube [7] and microwave cavity magnetron [8] were developed. William Brown began work on microwave power transfer in the 1950s for aerial power applications [7]. Peter Glaser, in 1968, proposed space-based solar power and received a patent for this concept in 1973 [9, 10].

In the 1970s, a practical demonstration – transmitting 37 kw over a one-mile distance [11] – was performed and numerous studies were initiated [12-16]. The concept of wireless power transfer was further advanced in during the 1980's and 1990's, culminating in the two microwave power transfer experiments [17, 18]. John Mankins performed a longer-distance test in 2008, transferring energy 148 km [19]. More historical information on space-based solar power can be found in [20-22].

A variety of SBSP applications have been proposed including both stationary [20, 23] and mobile aerial power applications [24] in which power is transmitted from geostationary Earth orbit [9, 10] to the Earth. SSP use for lunar missions [25, 26] has been proposed. Additionally, the notion of building power generation spacecraft on the moon [27-30] has also been considered. Zidanšek, et al. [31] advanced the concept further: proposing to launch power generating spacecraft from the moon to geostationary Earth orbit.

On the economic front, several groups [32-34] have considered the plausibility of creating and operating a space power utility. Macauley and Davis [35] have discussed transferring power from one spacecraft to another. Supplying power to small spacecraft [36], for human missions to Mars [37] and in support of lunar industries [38] has also been considered.

Mission Concept

A four-stage plan is proposed to demonstrate the effectiveness and safety of Space Solar Power for use on Earth. This plan aims to build the technology's Technology Readiness Level (TRL) beginning with a test mission in low Earth orbit using a small spacecraft. Then the process will be demonstrated and further advanced through its use in supporting a manned mission to Mars. A bent pipe mission – where power is supplied from Earth, to a spacecraft and then sent back to Earth – will be conducted. Finally, in phase four, complete system deployment will be performed.

It is believed that the primary impediment to system implementation is the lack of acceptance of the system by those on Earth who may be afraid of the by-products of its use (e.g., radiation) or its misuse (e.g., targeting areas with high levels of radiation).

Thus, the goal of the four-phase mission is to gain operating experience and raise the TRL in ways that are less objectionable. Through these experiments, it is believed that the technology will be able to gain acceptance for more general use on Earth.

Phase I

In phase one, a simple test mission (discussed in [39]) will be performed, using a cost-effective small-scale experiment in low-Earth orbit. The project will be launched as a secondary payload. Power will be beamed from the primary satellite to a secondary receiving satellite that will have been deployed, in orbit, from the primary satellite.

During this phase, the cybersecurity system [40, 41] for the spacecraft will be tested in three areas: onboard software operations, ground station software operations and transmission link security. A problem with either of the first two areas could potentially cause the power beaming system to be activated at incorrect times. Lack of transmission link security could cause similar problems.

Compromising any of these systems may result in the spacecraft believing that it is in an incorrect position or has an incorrect orientation. Mistakes in positioning may place the spacecraft in a state where further commands are not possible, or the owner/ operator's command capabilities are denied, or a third party attacker may gain control.

The proposed security system prevents communication failures when determining whether to send power or not. The process of determining whether to transmit or not is depicted in Figure 1.

Figure 2 presents the factors that are to be considered. Note that the trust in the rightness of transmitting power at the proper time and the impact of failing to transmit are both considered.

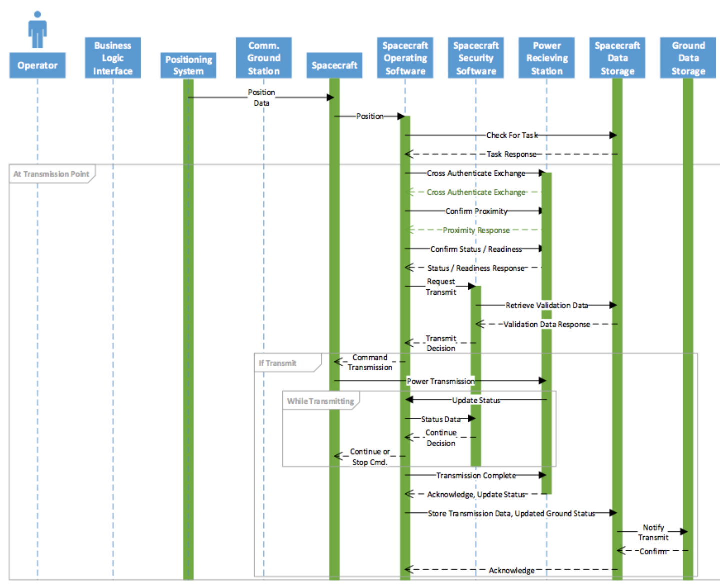

Figure 1. Thermal Power Satellite showing reflector-concentrators, support structures, radiators and transmitter. Not shown: boilers, frame structure, turbines and generators.

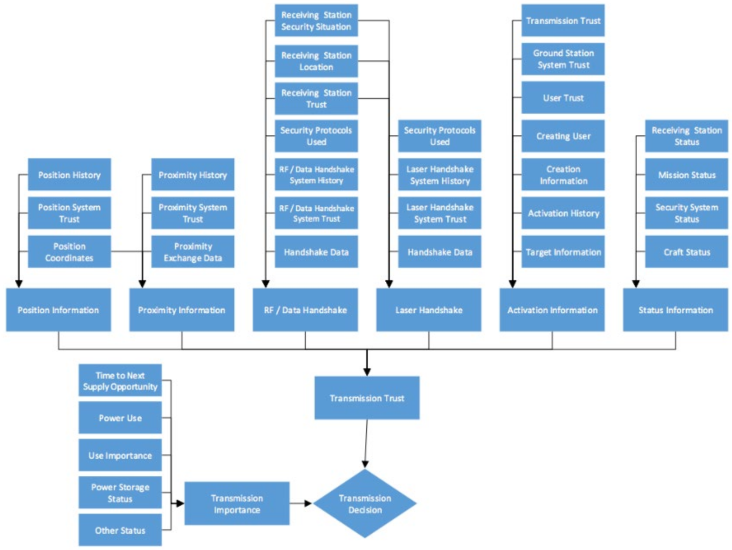

Figure 2. Expert System / Blackboard Architecture-based system for assessing whether to transmit power at a given (triggered) time, to a given location [40].

Phase II

In phase two, wireless power transfer will be used to support a Mars mission. In this context, the generating spacecraft will supply power for base construction (perhaps using basalt 3D printing as discussed in [42]) as well as for operations. Power will be transmitted to a large array of receiving antennas in proximity to the main base. Power can also be beamed (at other points during the orbit) to support spacecraft in orbit, other outpost locations or mobile craft on the Martian surface.

Phase III

Phase three serves as an incremental step to full system deployment. While several scholars have proposed the use of space solar power for augmentation of the power grid in established areas or as a replacement to terrestrial generation techniques, prior work [43] has demonstrated that SSP is not yet cost justified for these uses.

One application that does provide benefits not otherwise easily obtainable is the capability to transfer power – on-demand – into regions that are not otherwise served (or where the local utility is overwhelmed by rapid demand growth or an emergency situation). While other technologies (such as local solar or fuel-based generators) could prospectively solve this challenge, each has a specific limitation (such as daylight only generation for solar panels and the need for fuel). SSP combines an environmentally friendly generation technique with the capability of serving remote areas.

Under the approach taken in phase three, power is generated at one point on the Earth and transferred to an alternate point of need. The power is beamed using microwave wireless power transfer from the terrestrial generation point to an orbiting spacecraft and back down to the terrestrial point of use.

Phase IV

Exactly how SSP can be deployed in Earth orbit is an elusive question, and a precise answer to the eventual nature of such a system is not presumed. However, it is believed that more advanced work during phases one to three will enable eventual Earth-orbiting use.

Use of High Frequency Transmission

This section briefly discusses a key technical implementation decision that has been made for the system we have proposed; that is, to use higher electromagnetic frequencies (such as those proposed by Komerath [44]). This decision could reduce the amount of loss (and/or illuminated area) significantly. While some higher frequency ranges are potentially problematic, as they are blocked by the Earth's atmosphere, even these could be used to support space-to-space operations.

Komerath uses 220 GHz for space-to-Earth transmission, which is a frequency that could open a transmission window through the Earth's atmosphere. Problematically, the efficiency of hardware components required for operation at this frequency is comparatively low, relative to the other commonly suggested frequencies of 2.45 GHz and 5.8 GHz.

Komerath, Guggenheim and Flournoy [45] note that the Gyrotron is only 10% efficient. The prospectively more efficient (as high as 90%) Solid State MMIC is seen as only being at TRL 1 (as compared to the prediction of the Gyrotron being as high as TRL 5) as of 2013. Given the impact of high frequency radiation on humans [46], additional study of 220 GHz radiation exposure remains an area where future work is required.

ECONOMIC DISCUSSION

Economic considerations for each of these phases are quite different. Phase one is proposed as a government-funded technology advancement, including testing and demonstration mission. As such, no specific short-term return-on-investment is expected. The mission is justified by the long-term benefit that space solar power could provide as well as the scientific and engineering gains that could prospectively be attained along the way.

Mars Mission Benefits

For the Mars mission, the space power demonstration does not need to economically justify the manned mission to Mars; such missions have been proposed for quite some time (e.g., [47, 48]). The incorporation of this new technology, however, could and should benefit the mission.

To this end, several benefits can be identified qualitatively. First, the approach to be taken will avoid the entry, descent and landing costs and risk for the power generation system. As these costs (both in terms of dollars and mass/volume) can be significant [49], their elimination can facilitate lower mission cost or alternate use of the mass capacity.

Second, the use of space solar power can enhance the range of robotic and human exploration vehicles. Due to the higher power density of the wireless transmission of energy. these vehicles may be able to travel further due to having lower mass and volume and higher power generation capabilities. Additionally, not having to return to base for fueling (particularly for robotic missions) could expand their range significantly.

Earth Viability

For phases three and four, the viability of the proposed system must be considered in the context of its use on Earth. Thus, it must be compared to terrestrial generation and other approaches. Prior work [43] has found that, while in the long term a space solar power provider may be economically viable, this is not an immediately plausible solution.

McSpadden and Mankins' work [21], while appearing more technically feasible, requires significant up-front investment to develop the large space (500 m aperture, plus generation/ transmission hardware) and ground systems (requiring 7.5 km aperture, plus associated reception hardware). Komerath [44], on the other hand, proposes an approach that, while having a lower cost level, is predicated on advancement occurring in high frequency microwave technologies.

For the present, reaching the target costs proposed by Macauley and Davis [35] does not appear plausible. Space-to-space clustering of spacecraft would appear to be one exception. Such an approach could be part of a user's spacecraft constellation design where close proximity transmission/reception does not lend itself to a utility provider model.

Small clusters of spacecraft may derive peak-power averaging benefits, but that would depend on the cluster's design and operational capabilities. Clusters proposed may have an insufficient number of craft for this to be effective. Alternately, peak demand periods for cluster spacecraft may coincide, resulting in little power being available to share.

CONCLUSION

Several areas of future work are necessary to advance the use of space solar power. The first will involve the development and testing of a transmitter/receiver pair to demonstrate the efficacy of power transmission in close proximity and validate the on-orbit performance of the transmission, control, cybersecurity and other technologies.

The mission we have proposed will advance the TRL of some of the essential technologies. Additional design work on the Martian (phase two) mission is underway and the logistics of the (phase three) bent-pipe mission are also under consideration at the University of North Dakota.

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