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A Bent-Pipe Microwave Wireless Power Transfer Spacecraft for Relay to Unserved Regions

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This paper seeks to begin a discussion about the efficacy of using a ‘bent pipe’ transmission concept (familiar to those in the communications satellite arena) for power transfer. It presents the ‘bent pipe’ concept and provides a brief qualitative consideration of the benefits of this approach. It also begins the process of quantitatively considering the efficacy of a ‘bent pipe’ mission by exploring the trade space related to frequency, antenna size and altitude.

I. Introduction

Solar panels can be utilized to supply power to remote and otherwise unserved regions. Numerous examples of the use of solar-power in remote areas include its use to power medical devices, lighting, and communications equipment, among others. However, these devices must either have local battery storage capabilities, or be used only during the daytime. Moreover, clouds and various weather phenomenon may interfere with the sunlight that these devices require for recharging, denying them the power they need. Given the unpredictable nature of these impairments, this may result in critical devices not having sufficient power at points of critical need.

Microwave wireless power transfer (MWPT) presents a solution to this problem. Some have proposed its use as part of a space solar power (SSP) system where power is generated in orbit using solar panels and transmitted to the Earth. Multiple systems have been proposed; however, most have a method for providing power to regions not illuminated by the sun. Problematically, the collection surface sizes required to generate the levels of power that have been proposed make the creation of a SSP system a monumental undertaking.

This paper considers an alternate approach. It suggests using MWPT as part of a bent-pipe system (where a signal, in this case power transfer, originates from the Earth, is received by the spacecraft and sent back to the Earth). This approach, which is used regularly for communications broadcasts, could allow power to be generated on the Earth (using solar arrays or other generation technologies) and transmitted to an area of need. This prospectively reduces the costs of using wireless power transfer technologies for serving regions. In addition to its prospective immediate utility in supplying power, it may also help drive the development of technologies and their deployment to an initial user base required to support a SSP system in the longer term.

The efficacy of this approach is characterized herein. To this end, multiple system configurations are evaluated. This includes considering multiple transmission frequencies, ranging from 2 to 220 GHz and multiple spacecraft constellation designs. Constellation designs vary both based on altitude of their orbit as well as with regards to the number of spacecraft included. These configurations are evaluated based on the level of power that can be received, the pointing accuracy required and the cost (based on spacecraft cost, mass and volume). The benefits and drawbacks of these approaches are also compared from a qualitative perspective. Additionally, metrics such as survivability, redundancy and the impact of various impairments are considered. A discussion of the factors that can impair each prospectively considered transmission frequency is also provided.

The bent-pipe configurations are compared to the SSP on-orbit generation concept. This comparison includes both quantitative comparisons of cost and the energy levels that can be supplied as well as considering qualitative factors (or factors that can only be considered qualitatively, due to a lack of information) such as system robustness, susceptibility to weather impairment and human health considerations.

The paper ends with a discussion of next steps for implementing such a system. It discusses multiple prospective impediments, at present, including technological limitations and policy / public concerns. Multiple ways of confronting these issues are discussed.
II. Background

Wireless power transmission’s origin lies in the work of David Hughes, who made the first radio transmission in 1879 [1, 2]. Heinrich Hertz, in 1886, demonstrated the wave-property of radio transmissions and also their ability to be transmitted across empty space [3]. Nikola Tesla suggested the use of radio for power transmission [4] and, in 1900, was granted two patents related to the wireless transmission of electricity [5, 6]. Further work, in the 1930s, critical to microwave wireless power transmission (MWPT) resulted in the development of the klystron tube [7] and microwave cavity magnetron [8]. In the 1950s, William Brown at Raytheon actively developed MWPT for applications such as remotely powering a beam-riding helicopter or aerial platform [7]. In 1968 [9], Peter Glaser proposed the concept of space-based solar power (SBSP) and received a patent for this in 1973 [10]. In 1975, the Jet Propulsion Laboratory demonstrated this practically, transmitting 37 kw over a one-mile distance (and receiving and converting 84% of this initial energy to direct current) [11]. A variety of studies of the SBSP concept have been performed by the U.S. National Aeronautics and Space Administration (NASA) and U.S. Department of Energy (DoE), starting in 1976 [12], documenting the growing feasibility [13-16] of the technologies required to support SBSP. During the 1980’s and 90’s interest in the concept was seen in Japan, European and Canada, resulting in two microwave power transfer experiments [17, 18]. In 2008, Mankins demonstrated transmission over a greater distance: 148 km [19]. A more detailed discussion of the foregoing can be found in [20-22].

The use of MWPT has been suggested across a variety of contexts. Building from Brown’s initial experiments, its use for powering aerial craft has been expanded to powering UAVs. In 1980, the Stationary High Altitude Relay Program (SHARP) was designed [23]. A one-eighth (1/8th) size SHARP was tested in 1987 [20]. In 1992, the Microwave Lifted Airplane eXperiment (MILAX) demonstrated the ability to keep a beam pointed at a moving target [24].

The initial SBSP concept was to transmit power to the Earth from geostationary Earth orbit [9, 10]. It has also been suggested for use in powering lunar science missions, by Oda and Mori [25] and Little and Brandhorst [26], such as using a rover to search for resources to support future habitation in the polar regions. Potter [27] and Bock, Burz and Cowgill [28-30] demonstrated the efficiencies that could be gained by launching solar power satellites (SPSs) from the moon which have been largely constructed from in-situ materials. Zidanšek, et al. [31] propose the launch of SPSs from the moon to geostationary Earth orbit. Lusk-Brooke and Litwin [32], Charania, Olds and Depasquale [33], and Xin, et al. [34] looked at the economics of a utility provider (prospectively serving several different classes of customers). Macauley and Davis [35] discussed the utility of SBSP for serving spacecraft craft from other spacecraft. Prior work has also looked at the use of SBSP for supporting small spacecraft’s power needs as part of an orbital service model [36], to support a human mission to Mars [37] and to support lunar industry [38].

III. Context of Use

A four-stage plan to demonstrate the effectiveness and safety of Space Solar Power for use on Earth has been proposed. This plan aims to build the technology’s Technology Readiness Level (TRL) through a test mission in low-Earth orbit (LEO) using small spacecraft, use supporting a manned mission to Mars, a bent pipe (power supplied from Earth, to a spacecraft and back to Earth) and finally complete system deployment. The primary impediment to system implementation is seen to be the acceptance of the system by those on Earth who may be afraid of byproducts 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, we believe that the technology may gain acceptance for more general use on Earth. This paper focuses, in particular, on the phase-three bent-pipe Earth supply mission.

IV. Basic Concept

The basic concept of the ‘bent pipe’ relay solution is quite simple. In [39], it was concluded that space-based generation was unable to meet the prevailing standard for acceptable cost levels. A significant portion of this cost was attributable to generation, which necessitates either large solar panels or an alternate (e.g., nuclear) fuel source. While the nuclear option was not fully explored, the solar-panel based version was not seen to be immediately

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feasible (however, this could easily change with improvement and miniaturization of certain technologies or decreased launch costs).

At the same time, the various space-based solar power systems that have been proposed as utility-type providers seem to suffer from a critical mass problem: you can’t build the critical mass required to support the development and launch of the large orbital asset until you have a large subscriber base; however, you can’t build the subscriber base (save, perhaps, for a few large customers – such as government agencies – who might be willing to pre-commit to obtain particular benefits) without the orbital asset.

Given this, it is proposed to place a much smaller spacecraft in a much lower orbit that can (either directly or via multiple hops) relay power from one point on the surface of the Earth to another point of need. Notably, this would facilitate providing power to locations of particular need, potentially enabling the highest return-on-investment applications and driving the subscriber growth required to support the much larger system. Figure 1 depicts the two mission approaches (direct and via intermediary craft).

![Figure 1. Single ‘Bent Pipe’ Satellite Relay (left) and Multi-Hop Relay (right)](image)

### V. Analytical Consideration

Several considerations exist for this type of mission. These include what altitude to place the spacecraft in and what frequency of transmission to use. As was discussed in [39], the frequency selection – in particular – presents a particular trade-off consideration, as higher frequencies reduce beam spread (and the potential to cover areas that are not paying customers – or do not want to be subjected to microwave radiation), allowing similar power levels to be transmitted with less generation capability and/or smaller antennas. Table 1 presents a comparison of the beam width for multiple frequency and antenna diameter combinations.

<table>
<thead>
<tr>
<th>Antenna Diameter (m)</th>
<th>2</th>
<th>5</th>
<th>10</th>
<th>34</th>
<th>70</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (GHz)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.45</td>
<td>0.11</td>
<td>0.042</td>
<td>0.021</td>
<td>0.0062</td>
<td>0.0030</td>
<td>0.00042</td>
</tr>
<tr>
<td>5.8</td>
<td>0.11</td>
<td>0.042</td>
<td>0.021</td>
<td>0.0062</td>
<td>0.0030</td>
<td>0.00042</td>
</tr>
<tr>
<td>100</td>
<td>0.11</td>
<td>0.042</td>
<td>0.021</td>
<td>0.0062</td>
<td>0.0030</td>
<td>0.00042</td>
</tr>
<tr>
<td>220</td>
<td>0.048</td>
<td>0.019</td>
<td>0.010</td>
<td>0.0028</td>
<td>0.0014</td>
<td>0.00019</td>
</tr>
</tbody>
</table>

The altitude of orbit selected is also a point of significant consideration. Lower orbits decrease the amount of beam spread (and thus free space loss). However, they also limit the amount of time that a spacecraft has access to the power generation and reception locations. This may result in the ability to transmit less power or a need to relay the power transfer across multiple spacecraft. Relaying is, of course, undesirable as it causes multiple instances of

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3 Earth graphic from Microsoft Office Clip Art.

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free space loss. To aid the consideration of these trade-offs, the amount of access time to each of five prospective locations (chosen somewhat arbitrarily, with an aim of covering multiple latitudes) for each of four different altitudes (ranging from 300 km to the geosynchronous/geostationary altitude of 35,786 km).

<table>
<thead>
<tr>
<th>Altitude (km)</th>
<th>Grand Forks</th>
<th>Cairo</th>
<th>Denpasar</th>
<th>Orlando</th>
<th>Sydney</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>731,932</td>
<td>599,636</td>
<td>423,743</td>
<td>569,820</td>
<td>740,209</td>
</tr>
<tr>
<td>700</td>
<td>1,310,149</td>
<td>1,421,971</td>
<td>960,034</td>
<td>1,400,050</td>
<td>1,442,487</td>
</tr>
<tr>
<td>15000</td>
<td>7,032,760</td>
<td>7,268,250</td>
<td>8,212,897</td>
<td>7,321,841</td>
<td>7,109,106</td>
</tr>
<tr>
<td>35786</td>
<td>8,816,268</td>
<td>9,164,765</td>
<td>9,476,840</td>
<td>9,450,703</td>
<td>8,796,457</td>
</tr>
</tbody>
</table>

In the absence of a specific mission concept, requirements, constraints and more definition it is not possible to make more than predictions as to what altitudes may be the most desirable. Higher altitudes certainly offer greater periods of visibility (and would limit the need to relay – or eliminate it, even, in many cases); however, they also result in significantly more free space loss. This can be combined with the consideration (presented in the context of Table 1) of what frequency and antenna size to utilize as well as greater launch costs. Thus, at higher altitudes, access is increased and relaying need is reduced (or eliminated); however, higher frequency transmission (requiring relying on low-TRL technology) and larger antenna sizes are required. The higher altitude and larger antenna size required also drive higher launch cost levels. Of course, higher altitudes also benefit from longer (ignoring the potential for extension by orbit raising maneuvers) mission lifetimes.

VI. Conclusion

This paper has presented introductory work on the notion of using a ‘bent pipe’ transmission concept to wirelessly relay power using microwave radiation. It has presented a qualitative evaluation of this proposed approach. It has also performed a brief quantitative exploration of the trade space related to altitude, frequency and antenna size. The goal of this paper is to start a discussion regarding the efficacy of this approach and elicit feedback from the greater community regarding the desirability of this mission concept as an interim step between initial test missions and the deployment of a much larger system. In this context, the proposed approach would seem to offer significant benefit from providing the ability to begin to grow a prospective subscriber base for the larger system prior to its development and deployment (and the associated costs). This approach would also facilitate enabling the highest value applications of space solar power for the customers that would be most likely, based on the value provided, to be willing to pay a premium to develop and deploy the technology.

References

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