Meeting the Challenges of Implementing Portable Space-Based Solar Power

Frank E. Little

Space Engineering Research Center, Texas A&M University, College Station, TX 77843-3118, USA

Abstract

A space-based solar power system to supply power for disaster relief, humanitarian aid or other temporary local electric power needs using a hybrid laser/microwave wireless power transmission system is briefly described. A space-to-ground experiment to validate retrodirective control of laser and microwave power transmission beams that would use the International Space Station as the in-space platform for the experimental apparatus is described.

1. Introduction

Space-based solar power imports "clean" energy from space by converting solar energy to radio frequency or laser energy in space and transmitting it to earth where it is converted to electricity *via* a rectenna for microwaves or photovoltaic array for laser light and fed into the electric power transmission grid. Unlike a terrestrial solar power station (unless massive energy storage accompanies the station), a solar power satellite located in geostationary orbit can provide almost continuous power since the satellite is in continuous sunlight except for brief periods (at local midnight) occurring around the spring and fall equinoxes.

Space-based solar power originated from the microwave wireless power transmission experiments conducted by William Brown at the Raytheon Company [1]. In 1968, Dr. Peter Glaser patented the Solar Power Satellite concept for a satellite in geostationary orbit transmitting power to earth via microwave beams [2]. Power beaming demonstrations by Brown [3, 4] and Brown in collaboration with Richard Dickinson of the National Aeronautics and Space Administration's (NASA's) Jet Propulsion Laboratory demonstrated the feasibility of the technology to transmit large amounts (tens of kilowatts) of power over a significant distance (one mile) [5] and reasonable end-to-end conversion efficiency (54% in the laboratory) [6].

The US Department of Defense created renewed interest in space-based solar power through its National Security Space Office 2007 study "Space-Based Solar Power as an Opportunity for Strategic Security" [7]. One of the findings of the study was the potential utility of space based solar power to be a game changing technology by delivering moderate (>5 megawatts) power to a forward military base through portable receiving stations.

Traditional space-based solar power designs utilize microwaves in the 2 — 10 GHz range for transmitting energy to fixed ground installations, creating the equivalent of large terrestrial generating facilities, supplying continuous power into a transmission and distribution system for base load power. A study published by the International Space University [8] examined the economic feasibility of wireless power transmission at millimeter wave frequency (35 GHz) for a solar power satellite, the trade being the economic effect of smaller aperture sizes (compared to 2 – 10 GHz microwave) with reduced atmospheric transmission efficiency and increased rain fade. The study identified a potential alternate use for a geostationary satellite generating station operating at high frequency as emergency power for disaster relief using small diameter portable rectennas. An alternative scheme for delivery of megawatts of power to a portable site, including military bases and for disaster relief would be a geostationary satellite based hybrid laser/microwave relay system.

2. Hybrid Wireless Power Transmission

Laser and microwave wireless power transmission each have unique advantages, lasers in requiring smaller apertures and microwaves in being nearly immune to rain and other atmospheric conditions. Proposals have been made to combine the two such that each would operate in the most advantageous environment. The key to the design proposal is a platform operating in the stratosphere at about 20 kilometers height [9, 10]. Lasers would be used to beam power from satellites at geostationary orbit through space (no atmospheric attenuation) to a photovoltaic array on the high-altitude platform using retrodirective control of the laser beam. The use of lasers for this near space link

978-1-4244-6051-9/11/$26.00 ©2011 IEEE

minimizes the beam spot size at the aerostat. In addition, the laser wavelength can be selected such that it cannot penetrate far into the earth's atmosphere, which prevents its use a weapon on earth and is inherently eye safe. A fraction of the power received by the air ship would be used to maintain position and the rest retransmitted with microwaves from the ship to a ground rectenna under retrodirective control. A microwave frequency of 10 GHz would minimize both the size of the satellite transmitter and ground receiver for an all-weather transmission system. At a distance of 20 km (which is in the far-field), a transmitter operating at 10 GHz with an aperture diameter of 30 m broadcasting to a 40 m diameter rectenna would achieve about 90% antenna coupling efficiency. Assuming a Gaussian beam distribution, the maximum beam intensity at the rectenna (center of the beam) would be about three times that of sunlight for each megawatt broadcast, while a uniform beam with edge taper [11] would be approximately equivalent to solar radiation intensity. Drawbacks to such a system include efficiency losses due to the conversion/retransmission step and the likelihood of exceeding microwave beam power density safety standards. However, this is not intended for permanent installation and will be closely supervised by military personnel either as a forward base or a site for humanitarian relief operations.

3. Retrodirective Beam Control

One of the persistent questions for wireless power transmission has been beam pointing and control. Much research, particularly in the US and Japan, has focused on developing microwave retrodirective beam control in which a radio frequency pilot signal from the receiver is used to provide information for the directional control of the power beam from a phased array microwave transmitter. Laser retrodirective systems do not include a separate pilot beam from the target, but utilize corner cube devices that reflect light back to its point of origin. Several terrestrial microwave laboratory scale experiments [12-17] and long range outdoor demonstrations [18, 19] have been attempted for one axis beam steering. The Japanese sounding rocket experiment that deployed the Furoshiki mesh structure also included a retrodirective transmission experiment in which signals were received at the ground station in response to pilot beam transmission [20]. Although it is possible to test two-axis retrodirective beam control terrestrially, a space-to-ground wireless power beaming experiment with retrodirective beam control could do much to advance the technology.

4. Microwave and Laser Retrodirective Beaming Experiment

The experiment outlined below is a single self-contained package that would perform both microwave and laser retrodirective beam steering and control experiments over the period of several months from the International Space Station (ISS), including a "light a lightbulb" demonstration of practicality. The package is to be berthed at the Japanese Experiment Module External Facility (JEM-EF), where it could recharge its batteries, and periodically be removed and positioned by the station robotic arm for power transmission experiments (Fig. 1).

Several constraints are imposed on the design: 1) Mass — hardware must be compatible with requirements for attachment to the Japanese Experiment Module External Facility (JEM-EF); 2) Size — hardware must be less than 550 kg, fit into a Japanese H-II Transfer Vehicle or an European ATV carrier and occupy no more than one and a half docking locations at JEM-EF; 3) Power and thermal — station power and thermal management is only available when docked at the JEM-EF, with limited power through the ISS remote manipulator arm, requiring sufficient energy storage to be able to transmit power for the demonstration and with sufficient on-board thermal management to accommodate the power load; and 4) Electronic — strict constraints are put on possible radio frequency interference with ISS communications.

The design targets include: 1) providing a greater microwave transmitter aperture than the surface of the experiment package; 2) using space qualified components; and 3) maintaining size, mass and time constraints.

The packaging and mechanical design for the experiment is a rough parallelepiped approximately 2 meters long, 2 meters wide and less than 1 meter deep. The microwave antenna aperture is increased by extending three approximately 2 meter by 1 meter antenna trays from the body of the experiment package during transmission and otherwise stowing them within the package. Travelling Wave Tube amplifiers at 35 GHz, with 200W and 60% efficiency have been identified for the microwave power transmission to provide a high microwave flux density consistent with low atmospheric absorbtion.

The laser optic train can be accommodated around the microwave experiment, with the beam exiting on a side normal to the plane of the microwave antenna. The laser will be in the near IR frequency (1060 – 1080 nm), which is close to the absorbtion edge for silicon photovoltaic cells. A fiber laser with near diffraction limited beam properties ($M^2 < 1.1$) operating at 25% wall plug efficiency will be the light source.

For a power transmission experiment, the module would be detached from the JEM-EF by the JEM manipulator arm and passed to the station robotic arm. After deploying the trays and powering up the electronics, the robotic arm would move the experimental package into position to conduct the experiment (Fig. 1). Using GPS information and an inertial sensor on the package, a three-axis gimbal would orient the experimental package to point at and track the ground receiving station as the ISS passed overhead. As the ISS passed above the ground station, a pilot beam would be sent from the ground receiving station, triggering power transmission from the retrodirective phased array transmitter. The use of the gimbal for coarse mechanical pointing allows the transmitting antenna to be designed such that only a few degrees of beam steering are required of the retrodirective phased array for beam pointing and control. The microwave power would be detected at the ground station, either by a sensor array for beam pattern measurement or concentrated by a dish antenna and converted to electricity by a rectenna located at the antenna focus to power an electric device. The laser transmission and control experiments would be similar in that the ISS robot arm would provide coarse mechanical pointing and an onboard retrodirective control system would provide fine pointing and tracking control. Beam detection and power reception would be accomplished by a photovoltaic array.

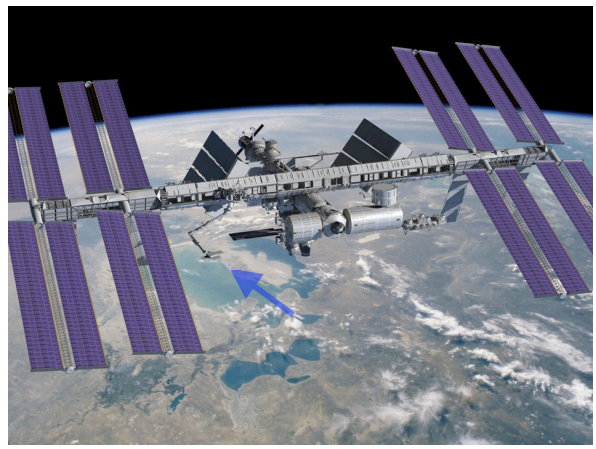

Figure 1. International Space Station with experiment module attached to robotic arm indicated by arrow.

5. Conclusion

An experiment to demonstrate wireless power transmission and test retrodirective control methods for microwave beams and laser beams using the ISS has been provisionally described. The experiment would provide a rigorous test of beam control hardware and software. A successful test would advance the technical readiness of both laser and microwave power beaming for use with a geostationary power satellite and a high-altitude platform in a hybrid wireless power transmission system for portable energy for disasters and other areas with logistics challenges.

References

1. W.C. Brown, “Experimental Airborne Microwave Supported Platform” Tech Rep. RADC-TR-65-188, Contract AF30 (602) 3481, Cec. 1965

2. P.E. Glaser, US Patent 3,781,647 “Method and Apparatus for Converting Solar Radiation to Electrical Power” December 25, 1973

3. W.C. Brown, “Experiments Involving a Microwave Beam to Power and Position a Helicopter”, *IEEE Transactions on Aerospace Electronic Systems.* Vol. AES-5, no. 5, pp 692-702, Sept. 1969

4. W.C. Brown, “Electronic and Mechanical Improvement of the Receiving Terminal of a Free-Space Microwave Power Transmission System,” NASA Contractor Report CR-135194, Contract No. NAS 3-19722, pp. 51-52, 1977

5. R.M. Dickinson, and W.C. Brown, “Radiated Microwave Power Transmission System Efficiency Measurements” Tech Memo 33-727, Jet Propulsion Lab. Cal. Inst. Technol., Mar. 15, 1975

6. R.M. Dickinson, "Evaluation of a Microwave High-Power Reception-Conversion Array for Wireless Power Transmission" Tech Memo 33-741, Jet Propulsion Lab. Cal. Inst. Technol., Sept. 1 1975

7. Department of Defense, "Space-Based Solar Power as an Opportunity for Strategic Security" Report to the director, National Security Space Office, 10 October 2007

8. S. Xin, E. Panier, C. Zünd, and R. Gutiérrez Gómez, "Financial and Organizational Analysis for a Space Solar Power System (A business plan to make Space Solar Power a reality)", A Multicultural Team Project submitted in partial fulfillment for the degree of Master of Business Administration in Aerospace Management at Toulouse Business School, Toulouse, France, May 18, 2009

9. R.M Dickinson, Unpublished results, 2000

10. NASDA Online Space Notes, "Solar-power generation in space: Airship to relay power from space to ground", http://spaceboy.nasda.go.jp/note/Kouso/E/kou106_solar_e.html)

11. A.K.M. Baki, K. Hashimoto, N. Shinohara, T. Mitani and H. Matsumoto, "New and Improved Method of Beam Forming with Reduced Side Lobe Levels for Microwave Power Transmission", 5th International Conference on Electrical and Computer Engineering, ICECE 2008, 20-22 December 2008, Dhaka, Bangladesh pp. 773-77

12. H. Masumoto, "research on Solar Power Satellites and Microwave Power transmission in Japan", *IEEE Microwave Magazine,* Vol. 3, Issue 4, December 2002, pp. 36-45

13. K. Hashimoto, H. Matsumoto, N. Shinohara K. and Tsutsumi, "SSPS Beam Control with Spread Spectrum Pilot Signals", *2003 Japan-United States Joint Workshop on Space Solar Power system (JUSPS'03) Proceedings,* Kyoto University, Uji Japan, July 3-4, 2003 pp. 124-130

14. N. Kaya, Personal communication, 2003

15. F.E. Little, S.J. Kokel, C.T. Rodenbeck, K. Chang, G.D. Arndt P.H. and Ngo, "Development of Retrodirective Control Transmitter for Wireless Power Transmission", *Radio Science Bulletin* 311 (December 2004) pp. 38-46

16. C.T. Rodenbeck, M. Li and K. Chang, "A Phased-Array Architecture for Retrodirective Microwave Power transmission from the Space Solar Power Satellite", IEEE MTT-S Digest, 2004, PP 1679-1682

17. N. Kaya, Personal Communication, 2009

18. Discovery channel series "Ways to Save the Planet", "Orbital Power Plant" segment, broadcast September 2008, http://www.discoverychannel.co.uk/web/ways-to-save-the-planet

19. N. Kaya, Personal Communication, 2010

20. N. Kaya, M. Iwashita, K. Tanaka, S. Nakasuka and L. Summerer, "Rocket experiment on microwave power transmission with Furoshiki deployment", *Acta Astronautica* 65, 202-205