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POWER BEAMING PROVIDING A SPACE POWER INFRASTRUCTURE

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POWER BEAMING PROVIDING A SPACE POWER INFRASTRUCTURE

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ABSTRACT

This study, based on two levels of technology, applies the power beaming concept to four planned satellite constellations. The analysis shows that with currently available technology, power beaming can provide mass savings to constellations in orbits ranging from low earth orbit to geosynchronous orbit. Two constellations, space surveillance and tracking system and space based radar, can be supported with current technology. The other two constellations, space-based laser array and boost surveillance and tracking system, will require power and transmission system improvements before their breakeven specific mass is achieved. A doubling of SP-100 conversion efficiency from 10 to 20% would meet or exceed breakeven for these constellations.

INTRODUCTION

The power system is a major component of a space system's size, mass, technical complexity, and hence, cost. In current design, the energy source is an integral part of the mission satellite. Potentially significant benefits could be realized by replacing the satellite's power system with a receiver and transmitting the power via an energy beam from a distant power satellite.¹ This concept parallels the terrestrial central generating station with its transmission grid. In this paper, the system components required for power beaming implementation are outlined and applied to several proposed satellite constellations to demonstrate the feasibility of implementing power beaming.

BEAM-POWER SYSTEM

In a beam-power system, as shown in Figure 1, the power system and user are separated by $\geq 10^5$ km. The central power system is coupled with a transmitter to transmit power to each remote user; each remote user is equipped with a receiver to receive power from the central power system. Selecting the transmitter and receiver involves optimizing four parameters: 1) the transmission distance, 2) the transmission frequency, 3) the power level transmitted, and 4) the thermal rejection capacity of the components. The power transmission distance is the key parameter for determining the operating frequency because the ratio of power received to power transmitted is a function of the transmitter and receiver aperture area, the transmission distance, and the operating frequency.

Radio frequencies (a microwave system) and optical frequencies (a laser system) are viable options for wireless energy transmission in space. Microwave technology is available today at 2.45 GHz.^{2,3} Solid-state laser technology (a 0.833 micron laser transmitter and photovoltaic receiver) is being developed and would be available early in the next century.⁴ Both technologies are viable in the projected time frames being considered for transition to power beaming. Therefore, system selection becomes a tradeoff among the specific mission or energy application, the transmission distances, and the end-use energy needs.

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FIGURE 1. Beam Power System Constellation

To implement power beaming, an appropriate continuous energy source in outer space is needed. Power systems based on SP-100 technology could provide up to 1 MW of continuous electrical output. The overall SP-100 system efficiency of 5% with thermoelectric conversion could be increased to 25% or more if a dynamic conversion system were used. The higher conversion efficiency would allow electrical outputs as high as 5 MW while using the same basic reactor designs. Reactor designs based on the Strategic Defense Initiative (SDI) Multimegawatt Program could provide power systems developing tens of megawatts.

PLATFORM ASSESSMENT WITH POWER BEAMING

In this study two types of orbiting space platforms, weapons platforms and surveillance platforms, were analyzed to compare the benefits of power beaming with the current architecture. An analysis was conducted to replace the on-board power systems with power receptors that track power satellites in a much higher orbit. For power beaming to be effective (i.e., provide a significant mass savings), the power system to be replaced must be significantly heavier than the power system used to drive the beam-power satellite.

Four satellite constellations were analyzed: 1) space surveillance and tracking system (SSTS), 2) space-based laser array (SBLA), 3) space-based radar

(SBR), and 4) boost surveillance and tracking system (BSTS). The satellite power requirements and their masses are summarized in Table 1.

The continuous power requirements of these constellations were analyzed to estimate the power system mass. The base-line beam-power platform consists of a closed-cycle, continuous-duty nuclear power source powering a solid-state laser. The power source on the user satellite is replaced with an energy receptor using conventional photovoltaic technology with single bandgap gallium-arsenide (GaAs) cells tuned to the transmitter output wavelength. To conduct these trade studies, specific masses of these components are varied depending on the technology time frame being assumed (near-term or far-term technologies).

For each platform, the on-board power system mass includes a station-keeping power system mass as well as an alert mode and/or pulse power system mass. For each constellation, the impact of replacing the on-board power system by a beam-powered system was examined. Power satellite orbits for constellations powered by 2 to 10 satellites were evaluated to minimize transmission distance. Apertures of the transmitter and receiver were varied to remain within operating limits for each system: a maximum power density of 400 W/cm² for the transmitter and 1.1 W/cm² for the receiver. A conservative beam-power transmission efficiency of 20% was selected for the analysis.¹

TABLE 1. Constellation Details

Constellation	SSTS	SBLA	SBR	BSTS
Number of satellites	20	36	20	10
Power per satellite, kW				
Stationkeeping	8 to 14	60 to 100	300 to 600	10
Burst mode	5 to 15	60 to 100	500 to 500	
Combined	13 to 29	120 to 200	800 to 1100	10
Engagement zone, degrees	90	90	90	--
Power transmission efficiency, %	20	20	20	20
Power system mass/satellite, kg	800 to 1100	2500 to 3300	30000	940 to 1600

For each constellation two technology projections were considered: a near-term projection of technology status in approximately 5 to 10 years and a far-term projection of technology status in 10 to 15 years. These projections were directly reflected in the specific masses of the beam-power system components. An SP-100 reactor with a specific mass of 33 kg/kW represented near-term technology. An advanced SP-100 reactor with a specific mass of 2 kg/kW represented far-term technology. For the transmitter, a near-term specific mass of 10 kg/kW was selected while the far-term specific mass decreased to 1 kg/kW. For the receiver, the specific mass was held constant at 3 kg/kW. Details of the analyses are presented for the space surveillance and tracking system constellation. Results for all constellations are listed in Tables 2 and 3.

Space Surveillance and Tracking System Analysis - The Space Surveillance Tracking System,⁵ is a constellation of 20 satellites located in high-Earth orbit. Transmitter and receiver apertures were varied to remain within the operating limits for the systems. These constraints set the receiver diameter at ≥ 1.8 m.

Each satellite requires 8 to 14 kW of continuous power; burst power requirements range from 5 to 15 kW, with the maximum required power of 29 kW (Table 1). A conservative beam-power transmission efficiency of 20% was chosen. The entire constellation would require a beam-power satellite system with a minimum power capacity of at least 925 kW. This assumes that stationkeeping power is available during the entire orbit and burst power is available for one-quarter of the orbit.

The mass trade-off based on near-term and far-term technology maturity is summarized in Table 2. The beamed-power option provides a mass savings for all of the assumptions except the minimum mass assumptions for greater than three beam-power satellites. The far-term assumptions show a significant mass savings in all cases.

Breakeven values for the specific masses of the power system were calculated and are summarized in Table 3. For the near-term transmitter specific mass of 10 kg/kW and a receiver specific mass of 3 kg/kW, the breakeven power system mass ranged from 26 to 52 kg/kW. The second analysis using the far-term transmitter specific mass of 1 kg/kW and a receiver specific mass of 3 kg/kW, showed that the breakeven power system mass ranged from 39 to 61 kg/kW.

With the current approach, SSTS will require the launch of approximately 22,000 kg of power system mass to provide enough power for the entire satellite constellation. By utilizing power beaming, the power system mass required is reduced to 7,000 or 13,000 kg, depending on the specific mass assumptions for the power system.

Space-Based Laser Array - This constellation includes 36 satellites located in mid-Earth orbit. Based on power requirements, receiver diameter is ≥ 4.8 m. Based on near-term technology status, the beam power option does not provide mass savings; however, significant mass savings is obtained when far-term technology projections are considered (Table 2). Analyses to determine the power system-specific mass required to breakeven (Table 3) show that a 25 to 30% improvement in the existing SP-100 system specific mass is needed to reach this point.

TABLE 2. Power System Mass Analysis for State-of-the-Art and Advanced Concept SP-100 Reactor for a Minimum Receiver Diameter

System Technology Assumptions										
Near-Term Technology Specific Mass						Far-Term Technology Specific Mass				
SP-100 power source		33 kg/kW				SP-100 power source		2 kg/kW		
Laser transmitter		10 kg/kW				Laser transmitter		1 kg/kW		
Photovoltaic receiver		3 kg/m ²				Photovoltaic receiver		3 kg/m ²		
Constellation Mass Savings Using Power Beaming										
Mass Savings With Near-Term Technology, kg						Mass Savings With Far-Term Technology, kg				
Power System	Number of Beam-Power Satellites					Power System	Number of Beam-Power Satellites			
	2	3	4	6	10		2	3	4	6
SSTS Min.	686	532	-117	-1010	-3130	SSTS Min.	13380	13369	13324	13326
SSTS Max.	6686	6532	5883	4990	2870	SSTS Max.	19380	19369	19324	19326
SBLA Min.	-104295	-106249	-114479	-125795	-152670	SBLA Min.	75707	75569	74995	74205
SBLA Max.	-75495	-77449	-85679	-96995	-123870	SBLA Max.	104505	104369	103795	103005
SBR Min.	-25506	-31804	-58321	-94783	-181381	SBR Min.	501230	550791	498941	496397
BSTS Min.	-12559	-12654	-13456	-14601	-17518	BSTS Min.	7441	7548	7597	7482
BSTS Max.	-5959	-6054	-6856	-8001	-10918	BSTS Max.	14207	14148	14197	14082

BSTS based on 15-m diameter transmitter.

TABLE 3. Power System Breakeven Point for State-of-the-Art and Advanced Concept Transmitter at a Minimum Receiver Diameter

System Technology Assumptions										
Near-Term Technology Specific Mass						Far-Term Technology Specific Mass				
SP-100 power source TBD kg/kW Laser transmitter 10 kg/kW Photovoltaic receiver 3 kg/m ²						SP-100 power source TBD kg/kW Laser transmitter 1 kg/kW Photovoltaic receiver 3 kg/m ²				
Beam-Power Satellite Power Source Specific Mass To Breakeven										
Breakeven Point With Near-Term Technology, kg/kW						Breakeven Point With Far-Term Technology, kg/kW				
Power System	Number of Beam-Power Satellites					Power System	Number of Beam-Power Satellites			
	2	3	4	6	10		2	3	4	6
SSTS Max.	52	51	49	46	40	SSTS Max.	61	60	58	55
SSTS Min.	35	34	33	30	26	SSTS Min.	44	43	42	39
SBLA Max.	16	16	15	14	11	SBLA Max.	25	25	24	23
SBLA Min.	10	10	9	8	6	SBLA Min.	19	19	18	17
SBR Min.	31	31	29	27	23	SBR Min.	40	40	38	36
BSTS Max.	22	22	20	19	16	BSTS Max.	31	31	28	28
BSTS Min.	9	9	8	7	5	BSTS Min.	18	18	17	16

BSTS Max. based on 20-m diameter transmitter, BSTS Min. based on 10-m diameter transmitter.

TBD: to be determined in the analysis.

TABLE 4. Comparison of Breakeven Specific Masses for Platform Applications

Satellite	Minimum Receiver Diameter, m	Beam Power Satellite Specific Mass, kg/kW	
		State-of-the-Art Transmitter	Advanced Concept Transmitter
SSTS	1.83	26-52(a)	35-61(b)
SBLA	4.81	6-16	17-25(b)
SBR	11.28	23-31(a)	36-40(b)
BSTS	varies	5-22	16-31

Space-Based Radar - This constellation includes 20 satellites located in high-Earth orbit. Based on power requirements, receiver diameter is limited to ≥ 11.3 m. Mass analyses (Tables 2 and 3) show that mass savings are obtained based on far-term technology status. Only a 6% specific mass improvement in the existing SP-100 configuration is necessary to breakeven.

Boost Surveillance and Tracking System - This constellation includes 10 satellites located in geosynchronous orbit. Mass analyses (Tables 2 and 3) show that mass savings are obtained based on far-term technology status. Only a modest improvement in the existing SP-100 system-specific mass is needed to reach the breakeven point. A doubling of the SP-100 conversion efficiency from 5% to 10% would meet or exceed breakeven. Conversion efficiency could be improved by utilizing dynamic conversion (either a Brayton engine or a free piston Sterling engine). Further improvement could be achieved by using an advanced lightweight radiator, such as the fabric heat pipe radiator.^{6,7}

CONCLUSIONS

This study, based on two levels of technology maturity, has shown that with currently available technology, power beaming can provide mass savings to a variety of constellations in orbits ranging from low-Earth orbit to geosynchronous orbit. A summary of the power system breakeven specific masses for the platforms is listed in Table 4. SSTS and SBR can be supported with current technology, while SBLA and BSTS will require power and transmission system improvements before their breakeven specific mass is achieved.

A doubling of SP-100 conversion efficiency from 10 to 20% would meet or exceed breakeven for both constellations.

Power beaming can significantly improve future space missions. Beam-power transmission is technically feasible. The systems, transmitters, receivers, and power sources are expected to be available in a time frame compatible with proposed deployment schedules. Power beaming is most attractive and can provide significant benefit for stationkeeping and alert mode power. With near-term technologies, power beaming can provide the stationkeeping and alert mode power for only one-half of the on-orbit mass of the currently proposed power system.

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