Demonstration Experiment for Tethered-Solar Power Satellite

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The technologies for the Solar Power Satellite (SPS) have been well studied on the ground and now it is highly required to make demonstration experiments in space as the next logical step. One of the important subjects to be verified in space is the microwave power transmission pointing at the rectenna site on the ground. It includes verification of high-power microwave power transmission through the ionosphere and demonstration of the retro-directive phase control technology for the microwave beaming. These studies can be conducted by the "Small Satellite" that is currently promoted as one of the near future space programs in Japan. The conceptual study for the demonstration experiment has shown that 1 kW class microwave power transmission experiment at 5.8 GHz in the low earth orbit is worthwhile and feasible under constraints of current concept of the "Small Satellite" program.

Key Words: Solar power satellite, Small satellite, Microwave power transmission

1. Introduction

Tethered-SPS, consisting of a power generation and transmission panel suspended by tether wires, has been proposed as a realistic SPS concept[1]. Figure 1 illustrates a conceptional image of practical Tethered-SPS. Since this system does not track the sun, the total power efficiency is 36 % lower than that for the sun-pointing type SPS even when the solar cells are installed on both sides of the panel. However, the simple, technically feasible, and practical configuration resolves almost all the technical problems in the past SPS models[2)-5)] .

Before development of the practical SPS, we need to make a demonstration experiment to verify the critical technologies associated with the Tethered-SPS. The most important subject towards the practical SPS at this stage is the verification of microwave power transmission from the orbit to the ground. The main objectives of the space experiment will be;
(1) demonstration of the microwave beam control precisely to the rectenna on the ground from the antenna in orbit,
(2) evaluation of the over-all power efficiency as an energy system,
(3) demonstration of the electromagnetic compatibility with the existing communication infrastructure, and
(4) study of the operational procedure of the SPS.

The "Small Satellite" program just started in Japan is considered as a good opportunity for the first-stage SPS demonstration experiment in orbit. A working group was organized at ISAS in 2007 to investigate a demonstration experiment on the "Small Satellite". This paper describes the outline of the demonstration experiment that has been studied by the working group for two years.

Fig. 1 Conceptual image of Tethered- SPS.

2. Tethered-SPS

Figure 2 shows the construction scenario from a unit

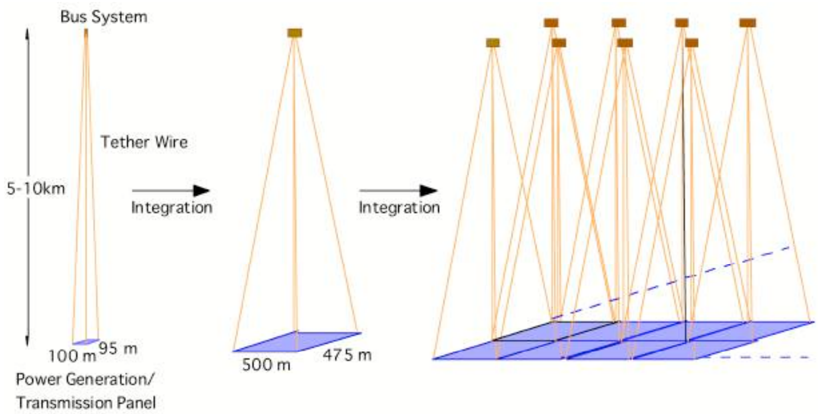

Fig. 2 Construction scenario of Tethered-SPS from a unit to a full scale model of 1 GW class.

Table 1 Summary of Tethered-SPS (multi-bus type, 1GW output)

Configuration Panel size Tether wire length	Power generation/transmission panel suspended by 2500 wires 2.5 km x 2.375 km x (0.02-0.1) m 2~10 km approx.
Total weight Panel weight Bus weight	26,500 MT 25,000 MT 1,500 MT
Unit of Tethered-SPS Size Total number	Power generation/transmission panel suspended by 4 wires 100 m x 95 m x (0.02-0.1)m 625(25x25)
Structural unit panel Size Total number/unit	Folded during transportation, consisting of 10 modules 5 m x 0.5 m x (0.02-0.1) m 3,800
Module Power generation Power transmission Size Total number/unit	Power generation/transmission capability 118 W max 56 W constant 0.5 m x 0.5 m x (0.02-0.1) m 38,000 (10x3,800)
Microwave Frequency Output Power	5.8 GHz 1 GW constant (rectenna DC output)

Tethered-SPS to a full scale model SPS, typically 1 GW. One unit has a power generation/transmission panel of 100 m x 95 m suspended by four 5~10 km tether wires extended from a bus system. The weight of the unit of the Tethered- SPS is 42.5 MT. The unit has a capability of microwave power transmission of 2.1 MW. Each unit panel has 38,000 power generation/transmission modules of 0.5 m x 0.5 m size. There are two versions of Tethered-SPS; single bus model and multi-bus model. The single bus model was originally proposed as a very stable configuration. In the multi-bus model, the power generation/transmission panels are connected, leaving groups of the bus systems unconnected, to construct the larger scale SPS. This configuration has high flexibility, expansibility, and maintenance performance. Table 1 summarizes the system characteristics of the 1 GW class Tethered-SPS with the power storage system. It is composed of 625 units of Tethered-SPS. The size of the power generation/transmission panel and weight are 2.5 km x 2.375 km and 26,500 MT, respectively.

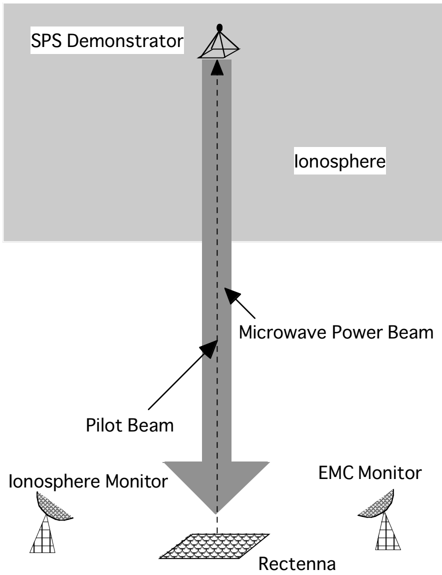

Fig. 4 Outline of the demonstration experiment.

3. Demonstration Experiment

The most important subject towards the practical SPS at this stage is the verification of the power transmission from the orbit to the ground. Figure 3 shows the major concerns about the microwave transmission through the ionosphere; the non-linear effect on the high-energy density microwave beam and the effect of the ionospheric scintillation on the pilot signal. The demonstration experiment will clarify the allowable power density for the microwave transmission and the scintillation effect on the retro-directive beam control. The experiment configuration is shown in Fig. 4. The microwave beam is transmitted to the ground guided by the pilot signal from the rectenna site. The interaction of the microwave beam with the ionosphere is observed by the diagnostic instruments on the demonstrator, as well as the ionospheric monitoring system on the ground. The electromagnetic interference with the ground infrastructure is evaluated by the EMC monitor on the ground.

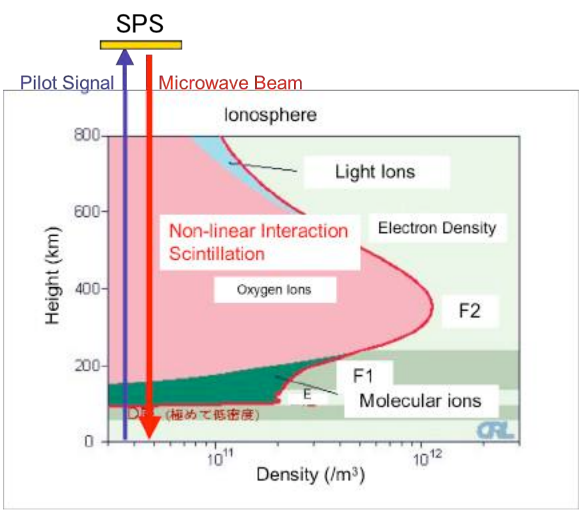

Fig. 3 Interaction of microwave with the ionosphere.

3.1 Experimental System

A new solid booster rocket, now under development in

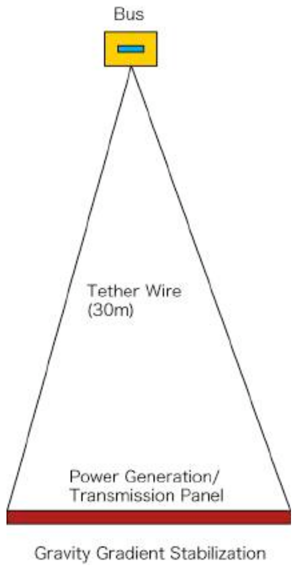

Fig. 5 Configuration of the demonstration experiment for 2.8 kW microwave transmission (option A).

JAXA, is considered as the launch vehicle for the demonstration experiment. The maximum weight of the payload instruments to the low earth orbit is estimated as 200 kg. The subrecurrent orbit (47 revolutions per 3 days) at an altitude of 370 km is selected to compromise the requirements from the microwave power density and orbit maintenance operation. There are two options for the configuration of the demonstration experiment; option A for 200 kg class experiment and option B for 60 kg class experiment, depending on the allowable resource. Figure 5 illustrates the configuration of the experimental system (option A). The attitude of the system is stabilized by the gravity gradient force and the power generation/transmission panel which are connected by four 30m-tether wires. The panel consists of 4 foldable power generation/transmission module. The power generation/transmission module is shown in Fig. 6. Each module is 0.8 m x 0.8 m wide and 0.1-0.02 m thick. There is no electrical wire interface between the power modules. The bus system has a control and data management system and a propulsion system to keep the orbit. The microwave source signal is radiated from the bus system and is amplified by the 625 sets of the active integrated antennas

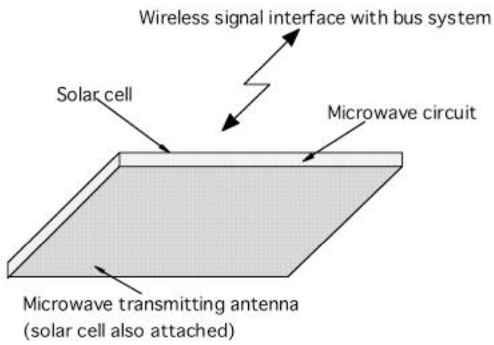

Fig. 6 Power generation/transmission module. The power generated by the solar cells on the upper side is converted to the microwave and transmitted to from the lower side.

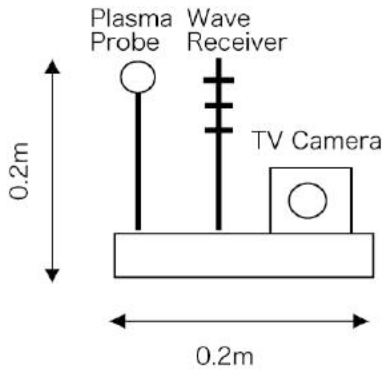

Fig. 7 Diagnostic package.

up to 700W in each power module. The microwave circuit is designed to control the direction of the beam ± 10 degrees from the normal line of the panel. The total microwave power injected from the power generation/transmission panel is 2.8 kW. This level of microwave power injection will generate a power density above 100 watt/m^2 for more than 50 m in the ionosphere. The interaction of the microwave power beam with the ionospheric plasma is measured by a diagnostic package consisting of plasma probes and wave receivers, as shown in Fig. 7. The package will have a TV camera to observe the dynamic behavior of the tether system.

The power density on the ground is calculated as 0.8 μ watt/m^2. This demonstration experiment is not aimed at getting power by the rectenna on the ground, but if a 2 m

Table 2 Summary of demonstration experiment

System	Configuration	Power generation/transmission panel suspended by 4 wires
	Panel size	2m x 2 m x (0.02-0.1) m
	Tether wire length	30 m
	Total weight	100 kg
	Attitude stability	±1°
Power generation	Thin film solar cell array	100 W/module
Power transmission	Frequency	5.8 GHz
	Phase control	5 bit
	Beam control	Retro-directive/Computer control, ±10°
	Output power	250W/module, 1kW(total)
	Power density	250W/m^2 (antenna), 120W/m^2 (50m), 60W/m^2 (100m) 0.8 μ W/m^2(ground)
Ground station		JAXA ground stations

diameter parabola is used to concentrate the microwave power, we will be able to illuminate a photo-diode. The beam shape is measured by scattered antennas in the region of 50 km diameter to verify the function of the retro-directive beam control.

The result of preliminary study on the experiment system is summarized in Table 2. More conservative configuration with less resource has also been investigated (option B), as shown in Fig. 8. In this case, one power module (700 W) is attached directly to the main body of the satellite. The dynamics of the tether system are not studied in this configuration.

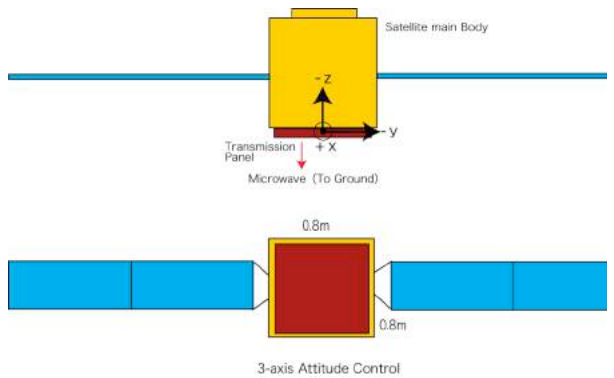

Fig. 8 Configuration of the demonstration experiment (option B).

3.2 Operation

After separation from the rocket at the altitude of 370 km, the experimental system is automatically controlled into the earth-pointing attitude. In case of option A configuration, the satellite and folded power generation/transmission modules are separated and the tether wires are deployed by operating the thrusting system of the satellite. After the tether deployment, the folded modules are extended to the 1.6 m x 1.6 m panel.

The sequence of demonstration experiment is shown in Fig. 9. For the first 2 minutes, the microwave beam at 10 % of the full power is transmitted to the ground. The onboard computer controls the beam direction without the pilot signal from the ground. When the experiment system passes over the ground observation site, the microwave beam at the full power is transmitted to the ground for 16 sec guided by the pilot signal from the receiving site. The beam direction is changed in ± 10° from the normal line of the panel to target the receiving site. After the full power operation, the power transmission at 10 % of the full power is performed for another 2 minutes.

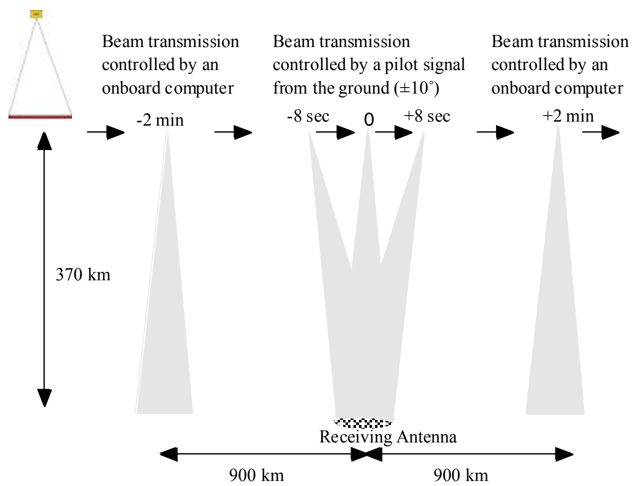

Fig. 9 Sequence of demonstration experiment.

4. Summary

Demonstration experiment using the “Small Satellite” has been investigated. The study has shown that the microwave power transmission experiment at 2.8 kW or 700 W at 5.8 GHz in the low earth orbit is technically feasible. It is expected that the most critical technology for SPS, the microwave beam control precisely to the rectenna on the ground from the transmitting antenna in orbit, can be verified in this experiment. The experiment will establish the engineering basis for 100 kW class experiment as a next step demonstration.

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