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By

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Keywords; solar power satellite, tether, microwave power transmission, demonstration

Abstract: A solar power system, in which a large flat panel with a capability of power generation and transmission is suspended by multi-wires, is proposed as an innovative Solar Power Satellite (SPS). This SPS concept is highly robust and potentially low cost, with special features in the integration, construction, attitude control, heat management, and evolutional development strategy. The power generation and transmission panel is composed of a huge number of perfectly equivalent modular panels, that is essential for low-cost mass production. The electric power generated by the solar cells at the surface of each module is converted to the microwave power in the same module. There are no wired signal/power interfaces between the modules. All modules are controlled by a wireless LAN system. The wireless interface between the modules leads to easy deployment and integration. Since the solar light is not concentrated in this configuration, quite different from the recent SPS concepts equipped with condensing lens or mirrors, the temperature of the module is kept within an operational range for the commercial electrical parts without any active heat rejection. The attitude in which the microwave transmission antenna is directed to the ground is automatically maintained by the gravity gradient force of the suspension system. The tethered panel is composed of individual tethered sub-panels which are loosely connected to each other. This configuration enables an evolutional construction in which the function of the SPS grows as the construction proceeds. A scale model of the tethered sub-panel can be used for the first step demonstration experiment of the SPS in the near future. The demonstration experiment can verify the power transmission from the orbit to the ground, which is the most important subject at this stage of the SPS research. This concept of the SPS has disadvantages that the power to the ground varies with the local time and the working ratio is 64 % on the average as compared with the sun-pointing type SPS, but they are well compensated by the advantages in the electrical, mechanical, thermal and integration aspects.

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1. Introduction

Since the NASA/DOE study of the SPS in the 1970's, various types of the SPS have been proposed in Japan, the United States, Europe, and Russia. Typical examples are summarized in Table 1. The NASA/DOE reference model [1] has a simple configuration consisting of single large solar array panel, a microwave transmitting antenna, and a rotary joint connecting the panel and the antenna, which is quite similar to the Glaser's original idea [6]. But the reference model has critical difficulties in the rotary joint mechanism and power collection. The rotary joint mechanism requires a power transmission mechanism of GW level through a movable contact. There is no practical technology for the rotary joint mechanism without a serious power loss. The mechanism is essentially fragile because one point failure leads to a total loss of the function. For the power collection, the power transmission line of GW level without a serious Joule loss requires a huge amount of conductor or a super conductor system which are both non-practical for the implementation. The power collection system is considered to be feasible only for the demonstration experiment less than 10 MW. A system with movable reflective mirrors combined with the power generation/transmission panel (sandwich panel) has been proposed as a potential configuration to overcome the difficulties in the NASA/DOE reference model. In this configuration, both the rotary joint mechanism and the high-current transmission line can be deleted. By condensing the sunlight on the power generation/transmission panel, the size of the panel can be reduced. However, the system combined with the light-condenser and the power generation/transmission panel requires complicated configuration and highly challenging technologies for the rotation of the large mirror, attitude control and stabilization of the system, and heat rejection from the panel. Furthermore, the movable system even without the power transmission still has a fatal problem to be damaged mechanically by a single point failure, which cannot be accepted for the practical energy system. The major reason why the past SPS concepts has not been recognized as a realistic energy system for more than 30 years since Glaser's first idea is a lack of technical feasibility and robustness. Many SPS models have advertized the achievable cost competitive with that of the existing energy system, but investors have no confidence in the cost analysis because it is based on the non-practical technologies like a castle in the air.

As an opposite approach, we have investigated a simple, technically feasible, and practical configuration SPS which consists of a large power generation/transmission panel suspended by multi-tether wires from a bus system above the panel. An artist conception of the tethered SPS is shown in Fig.1.

Table 1 Concept of typical SPS

	Reference System [1]	NEDO Grand Design [2]	NEDO Grand Design (option) [2]	SPS2000 [3]	Sun Tower [4]	Integrated Symmetrical Concentrator [5]
Organization	NASA/DOE	NEDO	NEDO	ISAS	NASA	NASA
Year	1979	1992	1992	1993	1995	2001
Power	5GW	1GW	1GW	10MW	250MW	1.2 GW
Orbit	Geo-synchronous	Geo-synchronous	Geo-synchronous	LEO	MEO	Geo-synchronous
Configuration	Single rectangular solar array panel, Circular disk antenna	Two rectangular solar array panels, Circular disk antenna	Two condenser mirrors, Sandwich panel	Triangular prism, Solar array on the upper two panels, Transmitter on the lower panel	Tree-like tower, Modular structure for power generation, Circular disk antenna	Two clamshell condenser mirrors, Separated power generator and transmitter
Bus power	Yes	Yes	No	Yes	Yes	Yes
Rotary joint with feed through	Yes	Yes	No	No	Yes	No
Rotating light-condenser Mirror	No	No	Yes	No	Fixed condenser	Yes

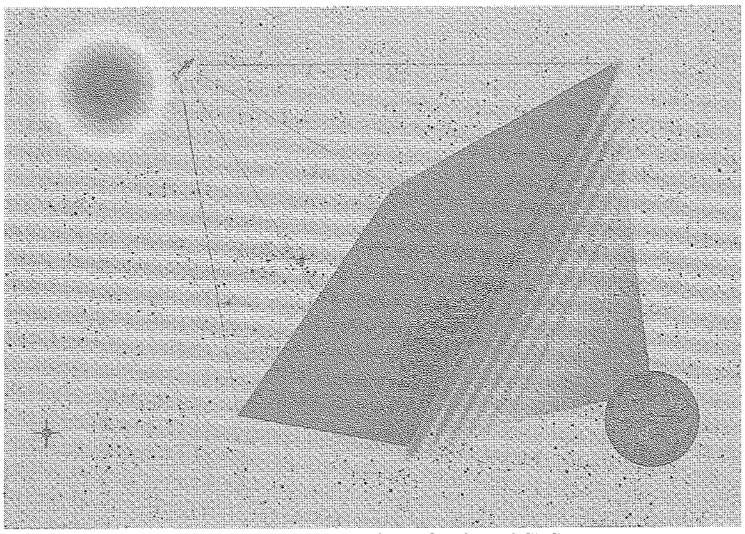
Fig. 1. Artist conception of tethered SPS.

This concept has been developed by a study team organized by Institute for Unmanned Space Experiment Free Flyer (USEF) in 2001 and 2002 [7]. The attitude is automatically stabilized by the gravity gradient force in the tether configuration without any active attitude control. Since this system has no mechanism to track the sun for the power generation, the total power efficiency is 36 % lower than that for the NASA/DOE reference model or other sun-pointing type SPS. However, the simple concept resolves almost all the technical difficulties in the past SPS models. No moving structure in a large scale makes this system highly robust and stable. Since the light condenser is not used for the power generation, a large-scale power generation area of km size is required, but the heat generated in the panel can be released into the space without any active thermal control. The power generation/transmission panel consists of perfectly equivalent modules, which greatly contributes to the low cost production, testing, and quality assurance. Another innovative feature of the module is the cableless interface using a wireless LAN system, which leads to the reliable deployment, integration, and maintenance. The tethered SPS is an assembly of equivalent miniature tethered SPS elements. This configuration makes it possible to verify the function of the SPS phase by phase during the integration. In most of the past SPS models, the concept of the phased construction has not been implemented, but is very important for the large space infrastructure. The miniature tethered element, a part of the practical SPS, can be used for the demonstration experiment in the near future. This strategy gives a straightforward scenario for the evolutional development from the demonstration model to the commercial SPS in the technology road map.

2. Tethered SPS

Figure 2 illustrates the concept of the tethered SPS which is capable of 1.2 GW power supply maximum and 0.75 GW average on the ground. It is composed of a power generation/transmission panel of 2.0 km x 1.9 km suspended by multi-wires deployed from a bus system which is located at 10 km upward. The panel consists of 400 sub-panels of 100 m x 95 m with 0.1 m thickness. Each sub-panel has 9,500 power generation/transmission modules of 1 m x 1 m size. In each power module, the electric power generated by the solar cells is converted to the microwave power and no power line interface exists between the modules. Figure 3 shows the concept of the power module. The power module has thin film solar cells both on the upper and lower planes. The microwave transmitting antennas are on the lower plane. The module contains a power processor, microwave circuits, and their controller. Each module transmits a microwave power of 420 W maximum. The power conversion efficiencies for the solar cells and the DC to RF converter are assumed to be 35 % and 85 %, respectively. The weight of the module is 5 kg or the specific weight of the module is 12 g/W. These values are beyond the existing technologies by factor 2-3 for the power conversion efficiencies and approximately 10 times for the specific weight, but are considered to be realizable in 20-30 years. There is no wired signal interface

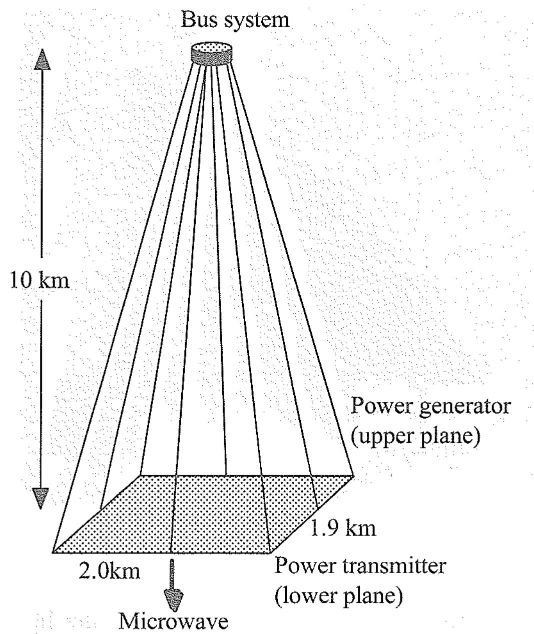

Fig.2 One GW class tethered SPS.

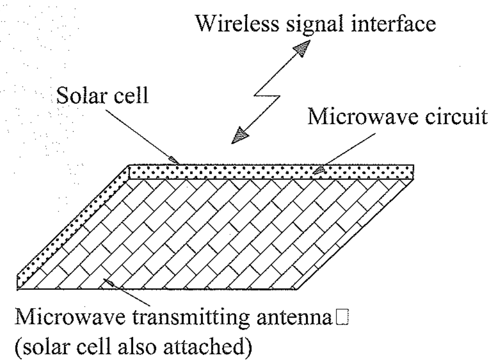

Fig.3 Concept of power generation/transmission module.

between the power modules. The control signal and frequency standard for each module are provided from the bus system by the wireless LAN. The system characteristics of the tethered SPS are summarized in Table 2.

Table 2 Summary of tethered SPS

Configuration	Power generation/transmission panel suspended by multi-tether wires
Panel size	2.0 km x 1.9 km x 0.1 m
Tether wire length	10 km approx.
Total weight	20000 tons
Panel	19000 tons
Bus	1000 tons
Sub-panel	Power generation/transmission panel suspended by 4 wires
Size	100 m x 95 m x 0.1 m
Total number/panel	400
Structural unit panel	
Size	10 m x 1 m x 0.1 m
Total number/sub-panel	950
Module	Power generation/transmission capability
Power generation	490 W max
Power transmission	420 W max
Size	1 m x 1 m x 0.1 m
Total number/sub-panel	9500
Microwave	
Frequency	5.8 GHz
Output Power	1.2 GW maximum, 0.75 GW on average

3. System Analysis

3.1 Construction

The tethered sub-panel is composed of a 100 m x 95 m sub-panel (47.5 tons) suspended by 4 wires connected to a bus system (2.5 tons). The 100 m x 95 m panel with 0.1 m thickness is regarded as a solid panel with a flatness required for the phase control in the microwave power transmission. The sub-panel consists of 950 structural unit panels of 10 m x 1 m x 0.1 m. The over all construction scenario is illustrated in Fig.4. The structural unit panels are folded in a package of 9.5 m x 10 m x 10 m which is a unit cargo transported from the ground to the low earth orbit by reusable launch vehicles (RLV). The cargo is transferred to the orbit transfer vehicle (OTV) in the low earth orbit around 500 km and transported to the geo-synchronous orbit. Delta-V required for the transportation is 4500 m/s. To avoid the degradation of the solar cells by the trapped energetic particles in the radiation belt, the cargo is contained in a radiation shield vessel. If we use an OTV of 270 tons equipped with an electric propulsion of 240 N thrust, the cargo is transferred to the geo-synchronous orbit in two months. The total dose during the transportation will be kept less than 10 krad. The tethered sub-panel is deployed automatically in the geo-synchronous orbit. After the function test of the tethered sub-panel is completed, it is integrated to the SPS main body. Docking assistant robots which are manipulated from the ground control center will be required for the integration. This strategy makes it possible to verify the SPS function during the construction phase from the low power to the full power.

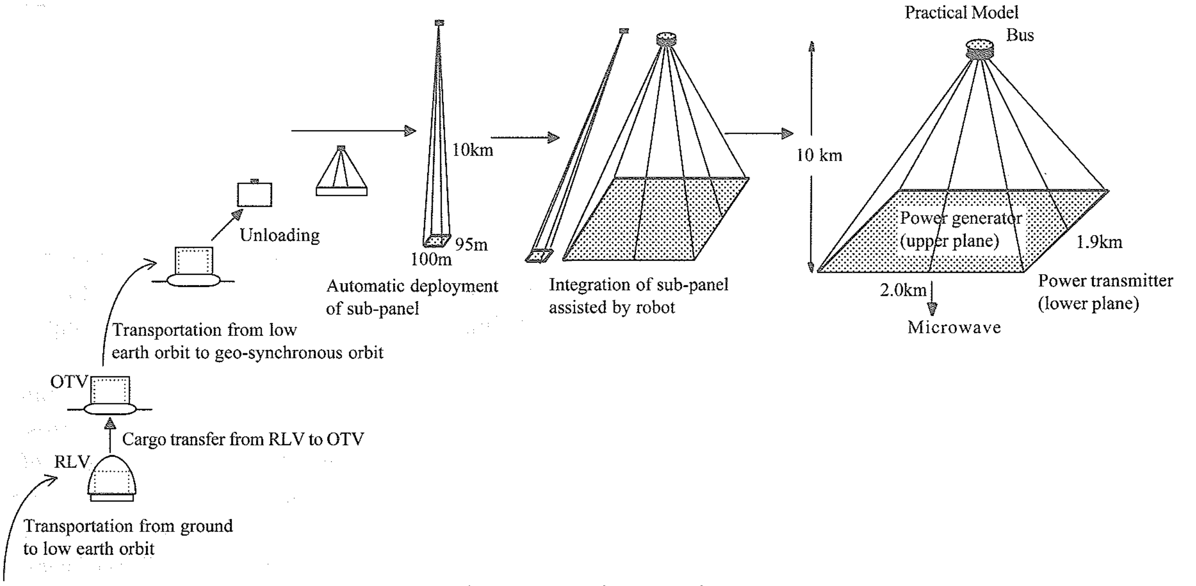

Fig.4 Construction scenario.

3.2 System Dynamics

The gravity gradient force for the tethered sub-panel is 10 gw per wire in the geo-synchronized orbit. The gravity gradient force for the complete tethered SPS is about 150 N, while the light force to the 2.0 km x 1.9 km panel is 17 N at maximum. Based on a quasi-static analysis considering the solar light pressure, it has been shown that the variation of the attitude is largest along the pitch axis, but is still less than 0.18 degrees [8]. The inclination of the sub-panel due to the temperature difference between the wires is less than 1 ° for a temperature difference of 30 ° C in case of Kevlar wire. Since the temperature difference between the tether wires is expected less than 30 ° C and the pointing capability of the microwave transmission for each sub-panel is assumed to be a few degrees, the inclination control of the sub-panel will not be required. However, if the panel control is required by some other reason, the inclination can be easily controlled by adjusting the length of the wires of each tethered sub-panel. This technique is usually used for the surface shape control of the primary mirror of the large telescope at the astronomical observatories.

3.3 Power Generation

Since the lower plane of the power generation/transmission panel is always faced to the earth, the power generation varies with the local time as the sun angle changes as shown in Fig.5. The average power amounts to 64 % of the maximum power. Since the average solar power on the ground is about 10-15 % of that in orbit, this system still has the advantage to the ground solar power system. The power consumption on earth is not constant, depending on the local time and the service area. For example, if the peak of the power consumption is 2 PM local time, we can synchronize the peak power generation with the peak power consumption by declining the panel angle by 30 degrees. This strategy can improve the cost effectiveness of the power from the tethered SPS [9].

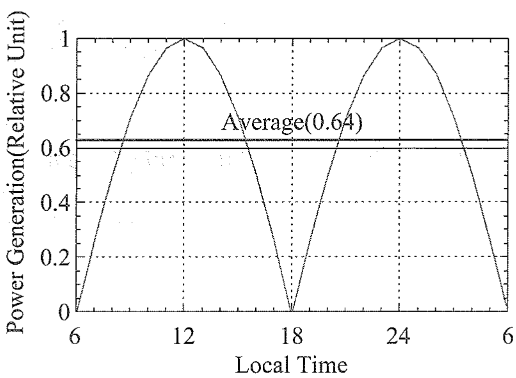

Fig.5 Variation of power generation with local time.

3.4 Thermal Analysis

All the heat generated in the system in orbit must be radiated into space for any energy system in space. The amount of the heat radiation depends on the surface area, its thermal optical properties, and the temperature. In the present configuration in which the panel is composed of the perfectly equivalent modules, the thermal analysis for one module is sufficient to show the feasibility of the total system. The equilibrium temperature for the module is calculated from the Stefan-Boltzman's low. Since both sides of the module are mostly covered by the solar cells, the coefficients, 0.8 and 0.7 are used as the typical values for the solar absorptance and emittance, respectively. If we assume the efficiency of the solar cell array and the conversion efficiency from DC to RF are 0.35 and 0.85, respectively, the equilibrium temperature is approximately 10 ° C maximum, which is well within the operating temperature of the commercial parts usually below 80 ° C. This argument suggests that the light-condenser more than 2.5 times is

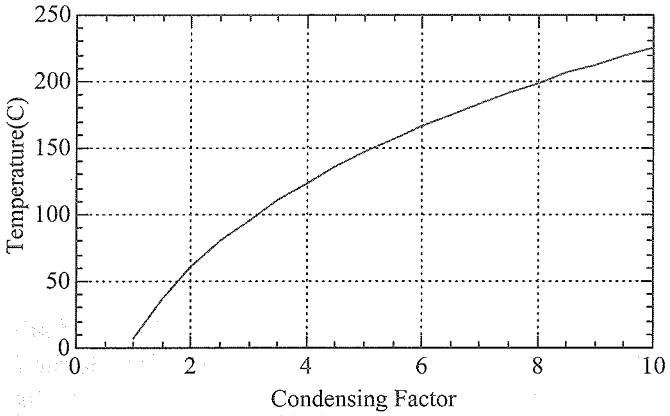

Fig.6 Equilibrium temperature.

not feasible for the power generation/transmission module as shown in Fig.6.

3.5 Power Transmission

The profile of the microwave intensity for the transmitting antenna has been premised 10 dB Gaussian commonly in the past SPS and current models to concentrate the microwave beam power in the main lobe. For the 10 dB Gaussian taper, the main lobe contains 95 % of the total power, while it has about 87 % power for the flat distribution of the transmitting power profile, as shown in Fig.7 [10]. The peak power of the side lobe for the flat distribution is larger by approximately 10 dB than the 10 dB Gaussian distribution. The flat distribution requires a larger rectenna area and evacuation area, approximately twice as compared with that for a 10 dB Gaussian taper to collect the same power, but it has more important advantages. By adopting the flat power distribution, we can use perfectly equivalent modules and we need not any active thermal control as described in 3.4. Based on the power profile calculated for 2.4 GHz in Fig.7, it can be shown that a rectenna of 4 km size in diameter is enough for 5.8 GHz to collect the 90 % power including the main and the first side lobes for the flat distribution. In that case, the peak of the power density is 1000 W/m^2 at the center of the microwave beam, which is higher by 4.4 times than that of the NASA/DOE reference model, but is still less than the power density of the sun light.

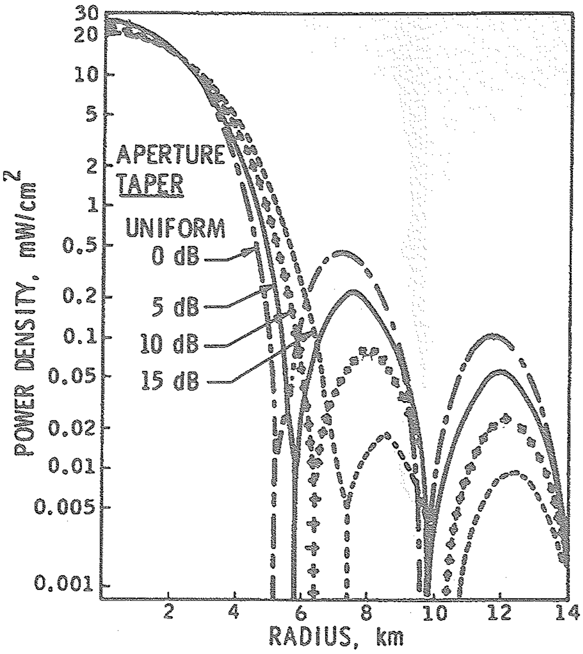

Fig.7 Power profile in case of 2.45 GHz and 1 km diameter transmitting antenna [10]. The power density is larger by 22 times and radius is smaller by 0.2 for 5.8 GHz and 2 km size transmitting antenna.

4. Demonstration Experiment

4.1 Demonstration Experiment in Orbit

It is not feasible to develop the GW class SPS in the near future. Before the development of the practical SPS, we need to make a demonstration experiment to verify the critical technologies associated with the SPS. The most important subject towards the practical SPS at this stage is the verification of the power transmission from the orbit to the ground as shown in Fig.8. The main objectives of the experiment will be;

(1) demonstration of the microwave beam control precisely to the rectenna on the ground from the large panel antenna in orbit,

(2) evaluation of the over-all power efficiency as an energy system,

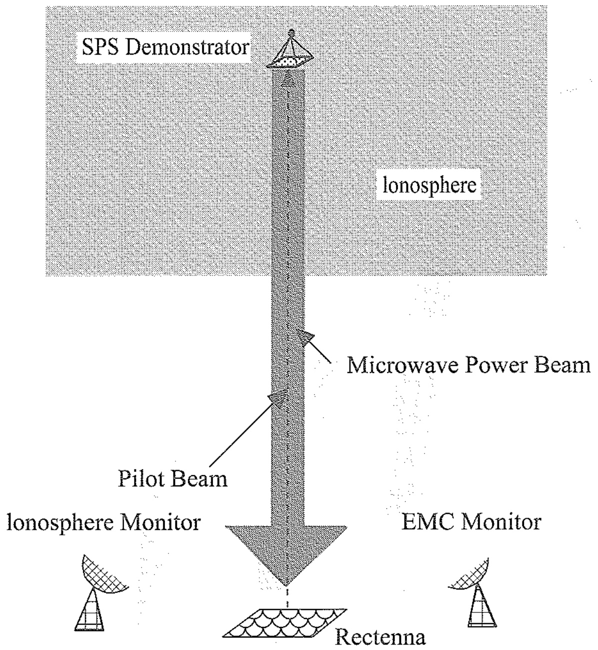

Fig.8 Outline of the demonstration experiment.

(3) demonstration of the electromagnetic compatibility with the existing communication infrastructure, and
(4) study of the operational procedure of the SPS.

For the demonstration experiment, a scale model of the tethered sub-panel, a part of the practical SPS can be used. The basic concept of the power generation/transmission module and the gravity gradient stabilization by the tether system are verified in the demonstration experiment. Evolutional relationship from the demonstration experiment to the practical SPS is shown in Fig.9.

H2A rocket, an advanced type, is considered as the launch vehicle for the demonstration experiment. The subrecurrent orbit at an altitude of 370 km is selected to compromise the requirements from the microwave power density and orbit maintenance operation. Figure 10 illustrates the configuration of the experimental system. The attitude of the system is stabilized by the gravity gradient force of the H2A second stage as an end mass and the power generation/transmission panel which are connected by a truss and 4 tether wires. The truss is used to support the bus system at the center of the gravity to operate a propulsion system to keep the orbit. The truss also works to give a tension to the wires under the low gravity gradient force for the 30 m scale tether. The truss is peculiar to the demonstration experiment and will not be used for the sub-panel of the practical SPS. The panel consists of 88 foldable structural unit panels. The structural unit panel is 0.8 m x 4 m wide and 0.1 m thick. 80 structural unit panels are used for the power transmission, while the other 8 are blank panels to stabilize the yaw motion. The structural unit panel contains 5 power generation/transmission modules of 0.8 m x 0.8 m. There is no electrical wire interface between the power modules. The cylindrical bus system is installed on the truss at the center of gravity. The bus system has a control and data management system and a propulsion system to keep the orbit. Either a hydrogen thruster system or an electric propulsion system is considered for the propulsion. Since the large panel interrupts the direct communication between the bus system and the ground station, a communication relay system needs to be installed in the part of the panel.

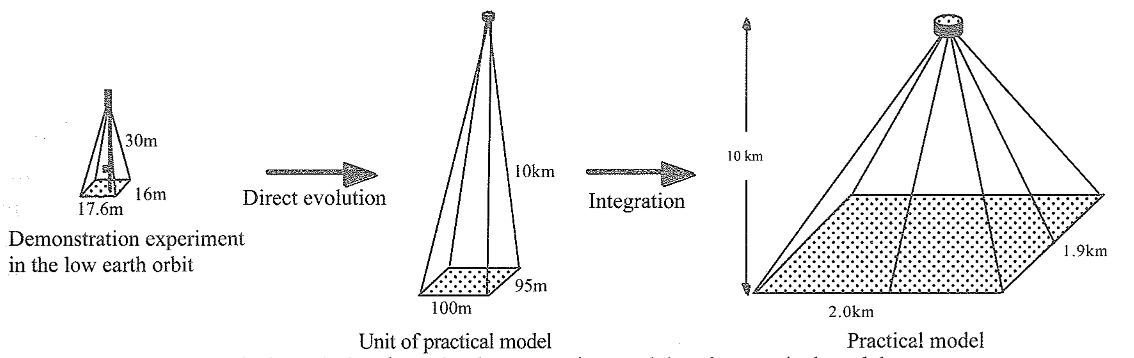

Fig.9 Evolution from the demonstration model to the practical model.

For the microwave power transmission system, two kinds of constructions are considered. One is the combination of a PCM (Phase Control Magnetron) and integrated antennas with a phase shifting capability composed of semiconductors. In this configuration, the microwave power of the PCM typically more than 1 kW is divided into the 625 antenna elements in each power module. Another system is a combination of a PCM in the bus system and the active integrated antennas (AIA) in each power module. In this configuration, the microwave source signal is radiated from the bus system and is amplified by the 625 sets of the active integrated antennas up to the total power more than 1kW in the power module. The selection of the two configurations depends on the efficiency of the power amplification of the semiconductor in the AIA. 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 140-420 kW depending on the design of the microwave transmitter. This level of the microwave power injection will generate a power density above 100 watt/m^2 for more than 10 km in the ionosphere. The power density on the ground is calculated as 0.1-0.3 watt/m^2. It is necessary to use a parabola to concentrate the microwave power to be rectified by the existing diodes. If we have a rectenna area of 500 m in diameter, the output power from the rectenna will be more than 10 kW.

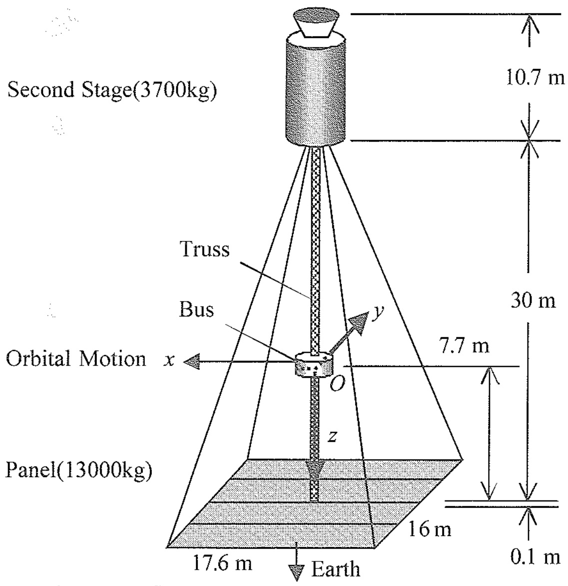

Fig.10 Configuration of the demonstration experiment.

The analysis of the microwave beam pattern transmitted from the panel indicates that the misalignment and the gap between the structural unit panels need to be less than 5 degrees and 10 mm, respectively, from the standpoint of the allowable beam divergence and avoidance of the unnecessary radiation. The analysis of the dynamic motion of the system in orbit has been conducted to find out the orbital and structural conditions to satisfy the requirements from the microwave beaming. The results of the computer simulation have shown that the pitch (pendulum) motion is within 3.5 degrees for the orbit eccentricity less than 0.01, which is in the capability of the beam control. Based on the linear elastic analysis, the characteristic frequency of the oscillation of the panel is less than 10 Hz for the realistic range of the stiffness of the panel, truss, and wires. Since the feedback frequency for the beam control is expected to be more than 100 Hz, the direction of the beam can be well controlled regardless of the dynamic motion of the panel. The structural unit panels are latched to each other in two dimensions to keep their gaps within 10 mm.

The thermal analysis is conducted for the power module composed of the PCM, batteries, integrated antennas, and the other electric parts. The analysis results show that the temperature is maximum at the PCM, but can be kept below 100 °C for the intermittent operation if a thermal capacitor is combined with the PCM.

The orbit analysis shows that the fuel of 500 kg is required for the two years mission if we use the hydrogen thruster system. The dominant force to the system is the air drag force to the H2A second stage used as an end mass. The electric propulsion system can be more beneficial considering the amount of the fuel and attitude disturbances during the operation, but additional solar array paddles extended from the bus system will be required to supply the electric power to the electric propulsion system.

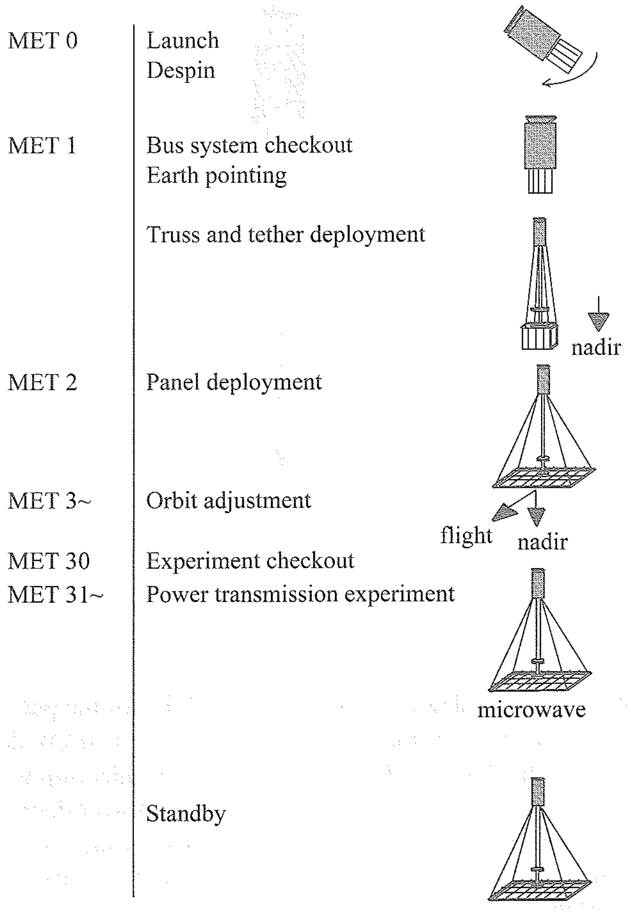

Fig.11 Sequence of mission operation.

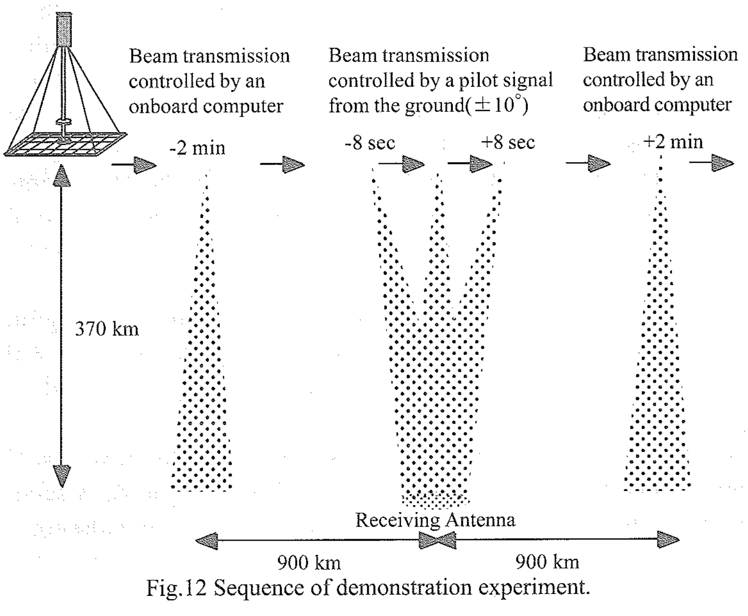

Fig.12 Sequence of demonstration experiment.

The sequence of the mission operation is shown in Fig.11. After separation from the H2A rocket at the altitude of 370 km, the experimental system is automatically controlled into the earth-pointing attitude. First the bus system and folded structural unit panels are deployed from the H2A second stage by extending the truss and tether wires. Then the folded structural unit panels are deployed from the bus system by another truss. Finally the folded structural unit panels are extended to the 16 m x 17.6 m panel. The microwave transmission experiment will be started approximately one month after the launch when the possibility of the electric discharge in the high voltage system is completely excluded. During the one month, evacuation of the fuel from the H2A second stage, checkout of the experimental system, and orbit adjustment to the subrecurrent orbit (47 revolutions per 3 days) are conducted.

The experiment sequence is shown in Fig.12. 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 rectenna site, the microwave beam at the full power is transmitted to the rectenna for 16 sec guided by the pilot signal from the rectenna site. The beam direction is changed in ± 10° from the normal line of the panel to target the rectenna. After the full power operation, the power transmission at 10 % of the full power is performed for another 2 minutes.

4.2 Demonstration Experiment on the Ground

A smaller scale demonstration experiment using a balloon on the ground has been investigated as a precursor experiment to the demonstration experiment in orbit. The configuration of the experiment is shown in Fig.13. A super-pressure balloon of 1000 m^3 capacity can lift an experimental system of 800 kg. The balloon is moored to the rectenna site on the ground. The length of the mooring cable is 1 km. It takes about one hour to deploy and to retract the system, which makes it possible to conduct the experiment in a day. The experiment time for the microwave power transmission will be 2 - 4 hours per day. A tethered power generation/transmission panel of 4 m x 4 m which is a 1/4 scale model of the demonstration model in orbit is used for the experiment. The transmitting power is 16 kW. If a rectenna of 30 m diameter is prepared, approximately 7 kW power is obtained on the ground. This experiment is regarded as a systems test to verify the function and operation of the space and ground segments for the demonstration experiment in orbit.

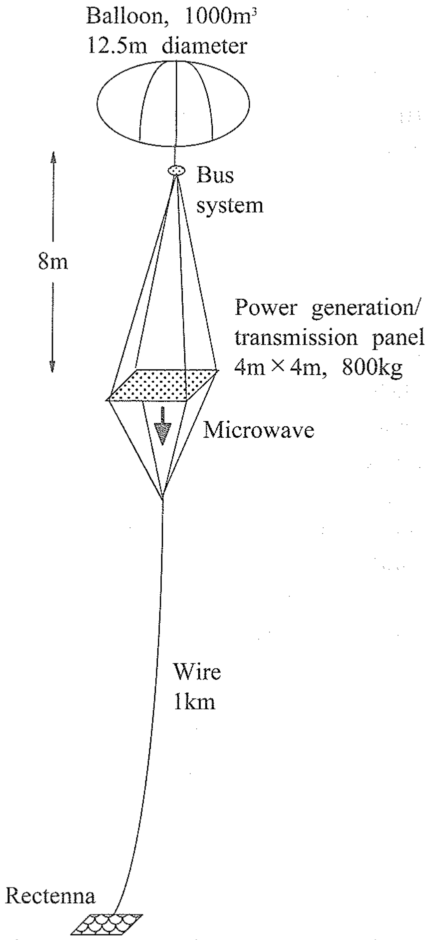

Fig.13 Demonstration experiment using a balloon on the ground.

5. Summary and Conclusion

A tethered SPS in which a power generation/transmission panel is suspended by multiple wires from a bus system above the panel has been investigated in a conceptual level. There are a lot of innovative features for this concept as compared with the past SPS models. They are listed as;

(1) Since the attitude is stabilized automatically by the gravity gradient force, no active attitude control is required.
(2) There is no moving structure, which makes the system highly robust and stable. Especially one-point failure mode peculiar to the rotary mechanism is excluded.
(3) The tethered system is composed of equivalent tethered sub-panels, which enables the phased construction and leads to easy integration and maintenance.
(4) The sub-panel consists of equivalent power generation/transmission modules, which enables the low cost mass production.
(5) There are no wired signal/power interface between the modules, which leads to easy deployment of the sub-panel.
(6) Active thermal control is not required because of the flat distribution of the transmitting power.
(7) A scale model of the tethered sub-panel can be used for the demonstration experiment on the ground and in orbit in the near future, which assures an evolutional scenario for the SPS development from the initial demonstration to the commercial SPS.

On the other hand, the tethered SPS has several disadvantages in the performance as compared with the past SPS models that have a sun-pointing capability for the constant power generation. They are summarized as;

(1) The power efficiency is 64 % as compared with the sun-pointing type SPS, even if the solar cells are attached to both sides of the power generation/transmission panel.
(2) The power generation changes 100 % with the local time as the sun angle changes with time.

(3) A larger size rectenna is required for the flat distribution of the transmitting power as compared with that for the tapered distribution.

The lower power efficiency of the tethered SPS is reflected to the higher cost of the power supply. But the cost can be estimated based on the predictable technologies and used for the evaluation as a realistic energy system. On the other hand, for the past SPS models using highly challenging or non-practical technologies, the cost of the power cannot be estimated and the serious evaluation as a practical energy system is not possible. The change of the generated power with the local time for the tethered SPS could be accepted for the commercial system in the mixture of varieties of the power resources on the ground, especially in the initial phase of commercialization with a ratio of the SPS power to the total less than 20 -30 %. The rectenna size for the flat distribution of the tethered SPS is relatively larger than that for the tapered one, but the actual size is not so large as compared with the past GW class SPS, because the tethered SPS has a larger transmitting antenna by approximately twice than the past SPS. In case of the current study model, a rectenna 4 km in diameter can collect 90 % of the total power for the flat distribution.

As a conclusion, the tethered SPS is a highly practical SPS model, with a number of advantages in the production, integration, construction, and operation as compared with the past SPS models. This model can be used as a realistic reference model to evaluate the cost and CO_2 load as a future energy system for human society. However, the current study still remains at an initial conceptual stage. Further studies are required to confirm the technical feasibilities, especially on the technologies for the microwave transmission and the construction of the large system in orbit.

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