Japanese concept of microwave-type SSPS

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Abstract

There are two major models of microwave-type SSPS (Space Solar Power Systems) currently studied in Japan. One is a simple configuration using a power generation/transmission panel system without a sun tracking mechanism. The typical example is the Tethered-SPS in which a power generation/transmission panel is suspended by tether wires and stabilized by the gravity gradient force, which has been studied by USEF/METI, called "basic model. The other is a combination of reflective mirrors to track the sun, power generation solar arrays, and a microwave transmitter panel. The typical example is the formation flight model of reflective mirrors combined with the power generation/transmission complex, which has been studied by JAXA, called "advanced model". This paper provides the details of the two microwave-type SSPS models and near future demonstration plan towards these models.

1. Introduction

There have been a number of microwave-type SSPS models more than thirty proposed since Peter Glaser's first concept in 1968 [1]. From a standpoint of power collection, they are categorized into 4 types as shown in Fig.1. For the non-concentrator SSPS, there are two types of configuration; bus-power type and distributed-power type. The typical examples of the bus-power SSPS without the concentrator are the NASA reference system of 1979 [2] and the NEDO grand design of 1992 [6]. For the bus-power configuration, the weight of the power collection cables is usually extremely large. Actually 1 GW power system for the solar array panel of several km diameter requires more than 5,000 MT cables even if a high voltage bus at 1 kV is used. In order to track the sun, a rotary joint mechanism is

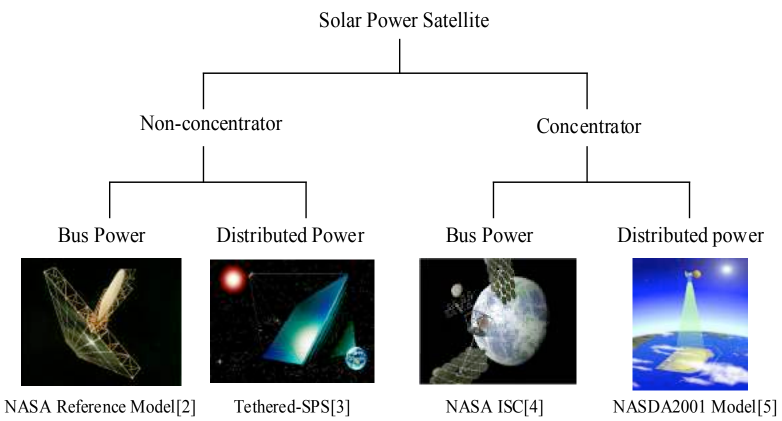

Fig. 1 Classification of microwave-type SSPS models and typical examples.

required, but, there are no practical technologies for the joint mechanism without a serious power loss.

The distributed-power type without the concentrator is the model that has no critical difficulties based on the existing technologies. Since this type SSPS does not track the sun, the total power efficiency is 36 % lower than that for the sun-pointing type even when the solar cells are installed at both sides of the panel. The example is the Tethered-SPS [3] studied by USEF.

Light concentrator-type SPS using large reflecting mirrors can reduce the size of solar array panel considerably and can track the sun without a feed-through rotary joint mechanism. But the steering mirror concept is very difficult to be realized because of its complicated configuration and also has a serious problem in the thermal condition of the solar array panel. The typical examples are the NASA IPC model [4] and JAXA microwave-type SSPS model [7].

Each type SSPS has its own advantages and disadvantages. Thus we set up the position of the two types of the SSPS well studied in Japan as a basic model and an advanced model. The basic model is the Tethered-SPS which has a higher feasibility but a lower power efficiency. The advanced model is the formation flight model of reflective mirrors and power generation/transmission complex, which has a lower feasibility, but a higher power collection efficiency. This is a similar situation to the fusion research in which the D-T system is the basic to be realized first and D-D system is the advanced one targeted in the later phase. The simple configuration, Tethered-SPS, will be realized in the initial phase of commercial SSPS.

2. Commercial SSPS Models

2.1 Tethered-SPS

Tethered-SPS is a simple, technically feasible, and practical configuration SSPS which consists of a power generation/transmission panel suspended by tether wires from a bus system above the panel. Figure 2 shows a unit of Tethered-SPS, in which a power generation/transmission panel of 100 m x 95 m is suspended by four 5-10 km tether wires extended from a bus system. The weight is about 50 MT. The important point is that the unit has the SPS function with a power transmission capability of 2.2 Mwatt. The essential technologies required for this concept are the deployment of the long tether of 5-10 km scale and the large panel of 100 m scale in orbit. The basic parts of theses technologies have been already demonstrated in orbit. Space tether has been deployed up to 20 km three times in 1990's. The solar array panels of 4.6 m x 32 m on the International Space Station were successfully deployed in 2000.

In the initial concept of Tethered-SPS [3], the units are integrated to the commercial system of 1 GWatt level by connecting each bus system to a single bus as shown in Fig.3. In the new Tethered-SPS concept [8], only power generation/transmission panels are connected, leaving each bus system unconnected as shown in Fig.4. This new configuration of separated bus system greatly enhances flexibility, expansibility, and, maintenance performance of the Tethered-SPS. Since this system has no capability to track the sun for the power generation, the total

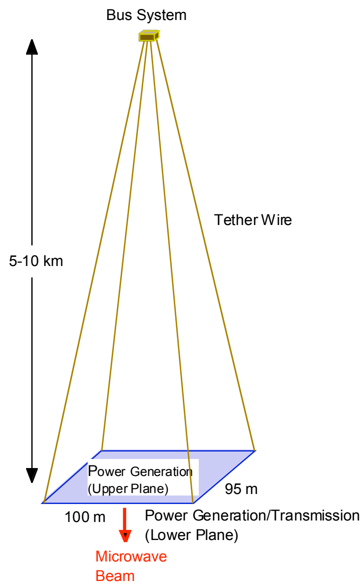

Fig.2 A unit of Tethered-SPS.

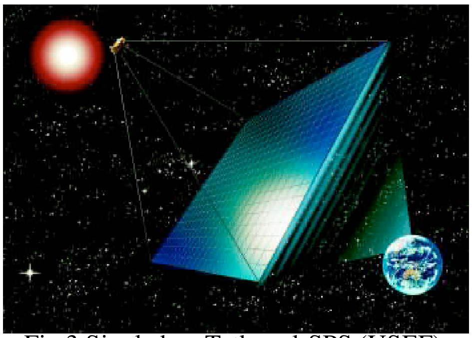

Fig.3 Single bus Tethered-SPS (USEF).

power efficiency is 36 % lower than that for the sun-pointing type SSPS even when the solar cells are attached to both sides of the panel. However, the simple configuration resolves almost all the technical difficulties in the past SSPS models.

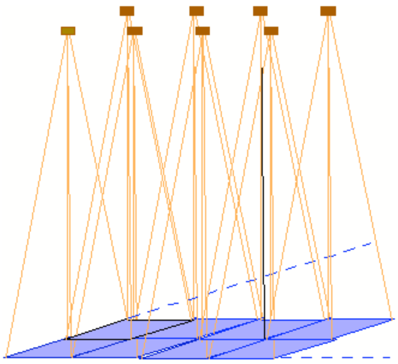

Fig.4 Multi-bus Tethered-SPS (USEF).

2.2 Formation Flight Model of Reflective Mirrors and Power Generation/Transmission Complex

The combination of reflective mirrors and a power generation/transmission panel has been studied in NASDA (former JAXA) since early 2000's. Two pairs of the primary mirrors and secondary mirrors are used to concentrate the sunlight onto the power generation/transmission panel. 4 movable mirrors and one power generation/transmission panel are connected using two pairs of truss beams. The typical example is shown in Fig.5. This configuration has an overheat problem at the power generation/transmission panel and one-point-failure problem at the rotating mechanism. In order to avoid these problems, the configuration has later been modified so as that the solar array panel and the microwave transmission panel are separated and the mirrors are floated free from the power generation/transmission complex using the solar pressure. The conceptual model is shown in Fig.6. This model still has technical difficulties, such as light-weight structure of the free-flying mirrors, dynamics of the system, and thermal condition for the solar array panel, but it can collect the solar energy almost 100 % throughout the year.

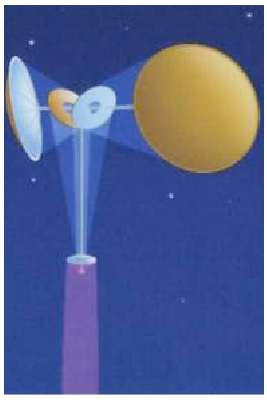

Fig.5 Combination of movable mirrors and power generation/transmission complex (NASDA, former JAXA).

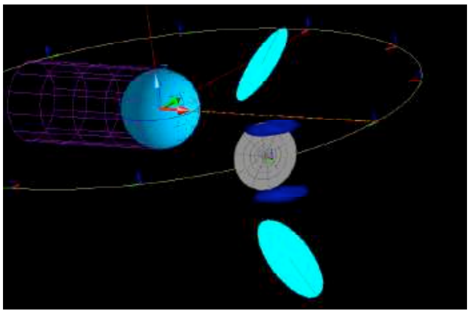

Fig.6 Formation flight model of reflective mirrors and power generation/transmission complex (JAXA).

3. Microwave Power Transmission Experiment on the Ground

For the microwave-type SSPS, microwave beaming technology targeting from 1 km size transmitting antenna in the

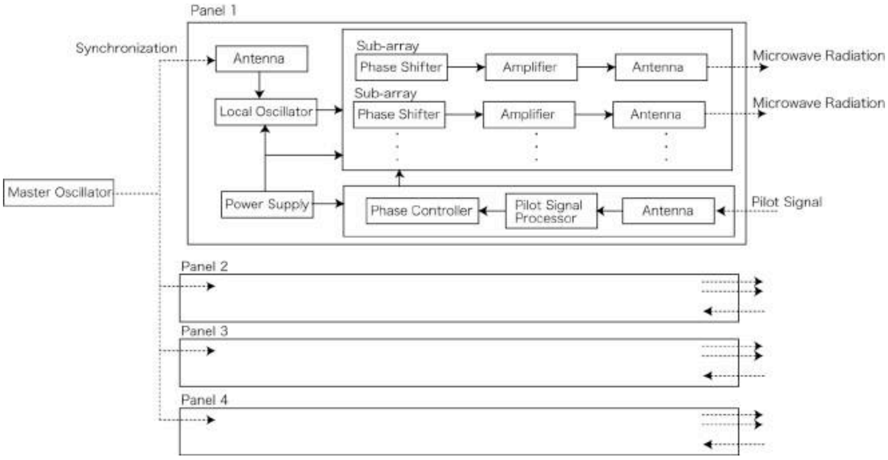

Fig.7 Microwave power transmission system for the ground experiment.

geostationary orbit to several km size rectenna on the ground is most challenging. Such a high-precision beaming/pointing has not been verified so far, although it is believed possible from an analytical point of view. We are now preparing an experiment on the ground to demonstrate the high-precision beaming technology. The basic concept of the experiment is to transmit a kilowatt-level microwave to a rectenna located typically at 100 m apart from the transmitter. The microwave beam is generated by the phased array antenna and the phase of microwave from each antenna is controlled using a pilot signal from the rectenna site so as that the beam is focused on the rectenna. There are several ideas for the retro-directive control combined with a feedback control using an information from the rectenna output power. The most promising method will be selected in the design phase, considering the future application for space use.

The microwave power transmission system for the ground demonstration is shown in Fig.7. The transmitter consists of 4 panels of antenna array that are movable to each other to simulate dynamic motion of large antenna in orbit. One panel is capable of 700 W radiation at 5.8 GHz. Each panel, 0.8 m x 0.8 m, will have 169 sets of sub-array consisting of 2 x 2 antennas, separating at 0.65 λ (wavelength). The thickness of the panel will be as thin as 2 cm. Each antenna transmits 1.04 W power and the amplifier for each sub-array will be 4.5 W. A phase shifter just before the amplifier is controlled so as that the microwave beam from the antenna array is directed to the rectenna by detecting the pilot signal. Software control will be adopted for the retro-directive control. The power efficiency of the amplifier will be more than 50% and the loss of phase-shifter will be less than 6 dB with 4 or 5 bits resolution. Receiving antennas distributed on the same plane of the transmitting antenna are used for detection of the pilot signal. For the microwave beaming from the 4 panels, the frequency and phase of the local oscillator in each panel needs to be synchronized or adjusted. There are several ways to synchronize them using a master oscillator in the transmitter site or an associated information from the rectenna site. The total weight of one panel is estimated less than 30 kg. The power loss (or heat generation) in a panel will be 1kW, which requires a cooling system or low-duty transmission operation

Each panel at 700 W will be tested in a shield room, but the system test using four panels at 2.8 kW ranging about 100 m is conducted in the open field. For the field experiment, a special consideration is required to avoid a multi-pass effect by the ground surface. The surface reflection would give disturbances in the phase of pilot signal when received at the transmitter site and jeopardize the beam pointing control. One idea to avoid the multi-pass effect is to conduct the experiment between two building as shown

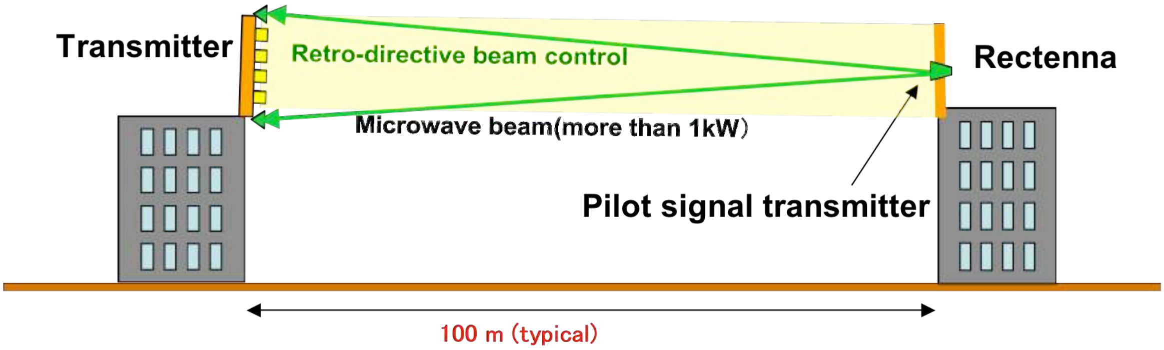

Fig.8 Configuration of the demonstration experiment on the ground.

in Fig.8. Another idea is to use a hill and dale site, preferably near a damsite. The beam divergence from the 1.6 m x 1.6 m transmitting antenna consisting of four panels is about 4 degrees. The beam diameter at 100 m is about 7 m. An 8 m x 8 m size rectenna composing of 16 sheets of 2 m x 2m, which will be flexible type, are used to receive the microwave power. The power conversion efficiency of the rectenna is expected to be 75 %. The maximum power is 1.8 kW, which will be converted to the commercial power to be connected to the household electric apparatus, such as refrigerator, TV set, and vacuum cleaner. The planned specification of the experiment is summarized in Table 1.

Table 1 Specification of microwave power transmission experiment on the ground.

Transmitter configuration	4 panels movable to each other 700W/panel, 30 kg/panel (typical)
Microwave transmission panel	169 sub-array/panel 4 antennas/sub-array 80 cm x 80 cm, 2cm thick microwave conversion efficiency 40 %
Microwave amplifier	5.8 GHz, 4.5 W, efficiency 50 %
Antenna configuration	0.65 λ spacing
Microwave beam control	Retro-directive control using a pilot signal from rectenna site
Phase control accuracy	4 or 5 bits
Rectenna configuration	16 flexible panels, 2m x 2m/panel DC conversion efficiency 75%
Transmission range	100 m (typical)

4. Small Scale Microwave Power Transmission Experiment in Space

After completion of the ground wireless power transmission experiment, we will be ready for a small-scale demonstration experiment in orbit [9]. For the microwave demonstration experiment, power transmission at 3 kW from the low earth orbit to the ground will be conducted. The space experiment will demonstrate the beam control technology for several hundreds km and verify the power beam transmission through the ionosphere without serious loss of power. The major concerns about the microwave power transmission through the ionosphere are the non-linear effect for the high-energy density microwave beam and the effect of the ionospheric scintillation on the pilot signal. The space demonstration experiment will clarify the allowable power density for the microwave transmission and the scintillation effect on the retro-directive beam control.

The weight of the SSPS demonstrator 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. Figure 9 illustrates the configuration of the demonstration experiment using a small satellite. The attitude of the system is stabilized by the gravity gradient force between the bus system and the power generation/transmission panel which are connected by 4 30m-tether wires. The panel consists of 4 foldable power generation/transmission module. Each module is 0.8 m x 0.8 m wide and 0.02 m thick. The design of the microwave transmitter is equivalent to that of the

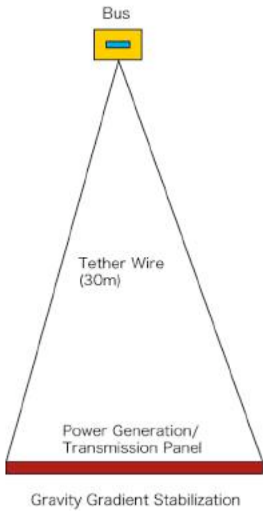

Fig.9 Configuration of the demonstration experiment using a small satellite.

ground demonstration experiment described in section 3. 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 169 sets of the amplifiers 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 the microwave power injection will generate a power density above 100 watt/m^2 for more than 50 m in the ionosphere. The power density on the ground is calculated as 0.8 μ watt/m^2. It is necessary to use a parabola to concentrate the microwave power to be rectified by the existing diodes. About 2 m diameter antenna will give a power to illuminate one photo-diode. The interaction of the microwave beam with the ionospheric plasma is measured by a diagnostic package consisting of plasma probes and wave receivers. The package will have a TV camera to observe the dynamic behavior of the tether. The same type of demonstration experiment can be conducted using the space station JEM as shown in Fig.10. Considering the allowable resources of the JEM experiment, 9 power

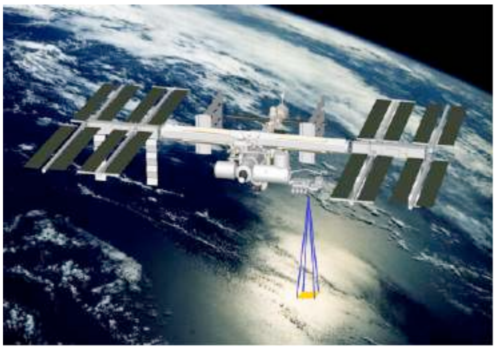
Fig.10 Configuration of the demonstration experiment using Space Station JEM.

generation/transmission panels can be extended to generate 6.3 kW microwave power beam.

5. Summary

Two commercial models of microwave-type SSPS currently studied in Japan are introduced. As the first step towards the commercial models, a project for a ground demonstration experiment will be stated soon. It will demonstrate the technologies to transmit a kW class microwave beam precisely to the rectenna located at about 100 m from the transmitter. The technologies verified in the ground experiment will be used to conduct the next-step kW class demonstration experiment from the low earth orbit to the ground. Based on the results from the small-scale demonstration experiments in space and on the ground, we will make a decision on the technology selection, microwave or laser, for the next phase development. In the next step, we will make a 100 kW-class SSPS demonstration experiment in orbit, and then scale up to a 10 MW-class pilot plant before 2030.

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