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FEASIBILITY STUDY OF TETHERED SOLAR POWER SATELLITE

S. Sasaki[*1], K.Tanaka[*1], K.Higuchi[*1], N.Okuizumi[*1], S.Kawasaki[*2], M.Shinohara[*2], K.Senda[*3], and K.Ishimura[*4]
The Institute of Space and Astronautical Science(ISAS) /Japan Aerospace Exploration Agency (JAXA)[*1]
Kyoto University[*2], Kanazawa University[*3], Hokkaido University[*4]
3-1-1 Yoshinodai, Sagamihara, Kanagawa 229-8510, JAPAN
Tel: 81-42-759-8330, Fax: 81-42-759-8464
E-mail: sasaki@isas.jaxa.jp

ABSTRACT

Tethered Solar Power Satellite (Tethered-SPS) consisting of a large power generation/transmission panel and a bus system which are connected by tether wires has been proposed as an innovative solar power satellite. The concept Tethered-SPS is highly robust and potentially low cost. This paper presents a new version of Tethered-SPS which is integrated by perfectly equivalent units loosely connected to each other. The new Tethered-SPS, highly flexible and expansible, has a lot of advantages over the past SPS models in attitude stability, construction, modularization, thermal characteristics, and robustness.

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 most difficult point in the system configuration of the SPS is to direct the large solar panel to the sun while the transmitting antenna, another large structure, is pointed to the rectenna on the ground. This requires a movable or rotating

Table 1 Concept of typical SPS models

	Reference System [1]	NEDO Grand Design [2]	SPS2000 [3]	Sun Tower [4]	Sail Tower [5]	Integrated Symmetrical Concentrator [6]	NASDA 2001 Model [7]	USEF Tethered-SPS [8]
Organization	NASA/DOE	NEDO	ISAS	NASA	ESA	NASA	NASDA (JAXA)	USEF
Year	1979	1992	1993	1995	1999	2001	2001	2001
Power	5 GW	1 GW	10 MW	250 MW	450 MW	1.2 GW	1 GW	1 GW
Orbit	GEO	GEO	LEO	MEO	GEO	GEO	GEO	GEO
Configuration	Single rectangular solar array panel, Circular disk antenna	Two rectangular solar array panels, Circular disk antenna	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	Flower-like tower, Sun-tracking sail modules for power generation, Circular disk antenna	Two clamshell condenser mirrors , Separated power generator and transmitter	2 primary mirrors, 2secondary mirrors, Sandwich panel	Sandwich panel suspended by multi-tether wires
Bus power	Yes	Yes	Yes	Yes	Yes	Yes	No	No
Rotary joint with feed through	Yes	Yes	No	Yes	Yes	No	No	No
Rotating light-condenser Mirror	No	No	No	Fixed condenser	No	Yes	Yes	No

GEO: Geo-synchronous Orbit, MEO: Medium Earth Orbit, LEO: Low Earth Orbit mechanism in the system configuration, such as rotary joint or rotating mirror. However, there are no practical technologies for the rotary joint mechanism without a serious power loss. The rotating mirrors require complicated configuration and almost infeasible technologies for the attitude control and stabilization of the rotating large thin-film structure. Furthermore, the movable system has a fatal problem to be damaged by a single point failure which could lead to a total loss of the SPS function. One of the reasons why the past SPS concepts have not been accepted as a realistic energy system for more than 30 years since Glaser's first idea is lack of technical feasibility and robustness. Many SPS models have advertised achievable cost competitive with that of the existing energy system, but investors have been doubtful of the cost analysis because it is based on the highly challenging technologies or fanciful schemes.

Now we need to alter our perspective on the SPS system configuration. One important point we have to consider is that the photovoltaic cell is a special element that can semi-permanently produce electric power without movable parts. If we combine the photovoltaic cells with any movable mechanism, it will spoil the special feature of the photovoltaic cell.

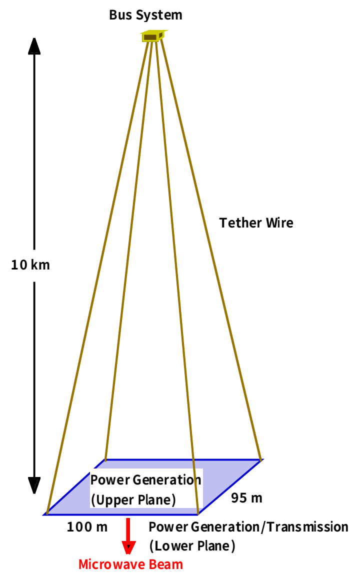

Fig.1 A unit of Tethered-SPS.

As an opposite approach to the past efforts, we have investigated a simple, technically feasible, and practical configuration SPS which consists of a power generation/transmission panel suspended by tether wires from a bus system above the panel. Figure 1 shows a unit of Tethered-SPS, in which a power generation/transmission panel of 100 m x 95 m is suspended by four 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 MW. The essential technologies required for this concept are deployment of the long tether of 10 km scale and the large panel of 100 m scale in orbit. The basic parts of these technologies have been already demonstrated in orbit. Space tether has been deployed up to 20 km three times in 1990's [9]. The solar array panels of 4.6 m x 32 m on the International Space Station were successfully deployed in 2000.

In the former concept of the Tethered-SPS [8], the units are integrated to the commercial system of 1 GW level by connecting each bus system and unit panels to each other, as shown in Fig.2. In the new Tethered SPS concept, only power generation/transmission panels are connected, leaving each bus system unconnected as shown in Fig.3. The 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

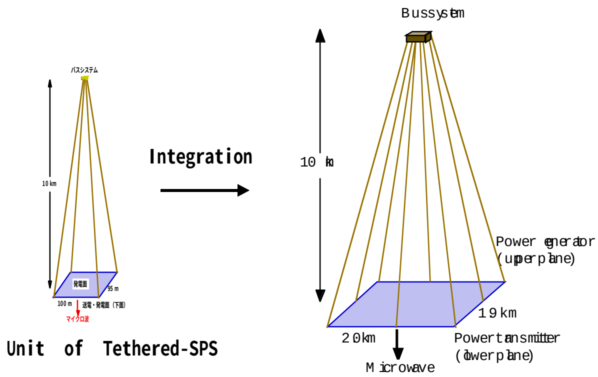

Fig.2 One GW class Tethered-SPS (former type).

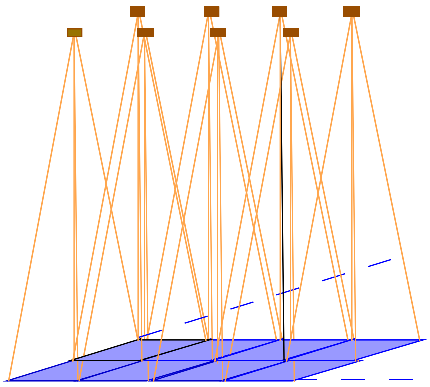

Fig.3 New Tethered-SPS concept with separated bus system.

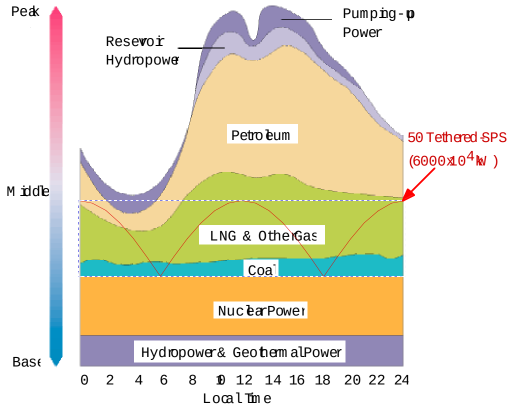

Fig.4 Combination of the power supplies to meet with the diurnal variation of the power consumption in Japan. The power from the 50 Tethered-SPS (60 GW max) is superimposed.

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

2. CHARACTERITICS OF NEW MODEL TETHERED-SPS

There are two versions of the new Tethered-SPS. One is direct power supply from the solar power generator to the microwave power transmitter, which transmits time-varying power as the sun angle of the solar panel changes with local time. The change of the power with the local time 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 SPS commercialization. Figure 4 shows the combination of the power supplies to meet with the diurnal variation of the power consumption in Japan. The power from 50 Tethered-SPS (60 GW max) is superimposed on the same chart for reference. SPS can substitute for the power generated by LNG or petroleum, which greatly contributes to the reduction of CO_2.

Another type of Tethered-SPS is power storage model equipped with batteries to

Table 2 Summary of New Model Tethered-SPS (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 m 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 m 625(25x25)
Structural unit panel Size Total number/unit	Folded during transportation, consisting of 10 modules 10 m x 1 m x 0.02m 950(10x95)
Module Power generation Power transmission Size Total number/unit	Power generation/transmission capability 473 W max (1,350x0.85) 222 W constant (473x095x0.97x0.6x0.85) 1 m x 1 m x 0.02 m 9,500 (10x950)
Microwave_Frequency Output Power	5.8 GHz 1 GW constant (rectenna DC output)

provide a constant microwave power to the rectenna as a base load power supply. It has been considered inapposite to have power storage in the SPS, but recent progress in the commercial batteries suggests a future possibility for implementing power storage in the SPS system. Table 2 summarizes the system characteristics of the 1 GW class new model Tethered-SPS with the power storage system. It is composed of 625 units of Tethered-SPS (2.2 MW each). The size of the power generation/transmission panel and weight are 2.5 km x 2.375 km and 26500 MT, respectively. The size of each unit panel is 100 m x 95 with 0.02 m thickness. Each unit panel has 9,500 power generation/transmission modules of 1 m x 1 m size.

3. DISTINGUISHING FEATURES OF NEW MODEL TETHERED-SPS

3.1 Attitude Stabilization

The attitude is stabilized automatically by the gravity gradient force in the tether configuration without any active attitude control. The gravity gradient force is 10 gw per wire in the geo-stationary orbit. Since the balance of the gravity force and centrifugal force is slightly different for each Tethered-SPS unit when integrated, the direction of the wires slightly deviates from the local vertical, as shown in Fig.5. 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 0.14 degrees in case for the former configuration [10]. The inclination of the unit panel due to the temperature difference between the wires is less than 1 degree 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 unit panel is assumed to be ±5 degrees, the inclination control of the unit panel will not be required.

3.2 Modularization

The unit of Tethered-SPS consists of 950 structural unit panels of 10 m x 1 m x 0.02 m. The structural unit panel has 10 power modules. 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 6 shows the configuration 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 400 W maximum (no power storage type) or 220 W constant (power storage type). 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 power of the module is 0.08 W/g. These values are beyond the existing technologies

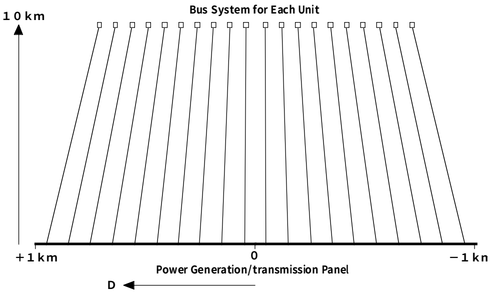

Fig.5 Configuration of Tethered-SPS with separated bus system, moving perpendicularly out of the paper plane.

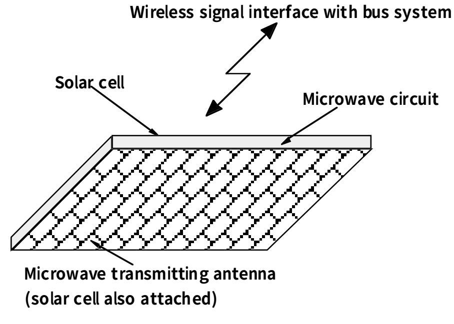

Fig.6 Concept of power generation/ transmission module.

by factor two for the power conversion efficiencies and approximately 10 times for the specific power, but are considered to be realizable in 20-30 years based on the potential progress of the photovoltaic and MMIC (Monolithic Microwave Integrated Circuit) technologies. There is no wired signal interface between the power modules. The control signal and frequency standard for each module are provided from the bus system by the wireless LAN.

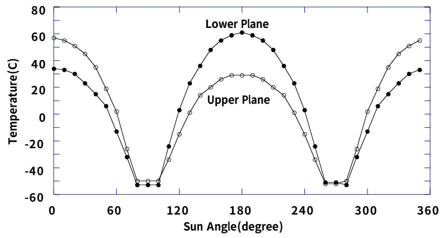

Fig.7 Temperature variation of the two panels in a day.

3.3 Thermal Condition

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.

Figure 7 shows the temperature variation of the two panels in a day calculated for the module without power storage.

3.4 Construction and Maintenance

The over all construction scenario is illustrated in Fig.8. The structural unit panels are folded in a package of 10 m x 10 m x 1.9 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-stationary orbit. Delta-V required for the transportation is 4,500 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 a 200 MT OTV equipped with an electric propulsion of 80 N thrust,

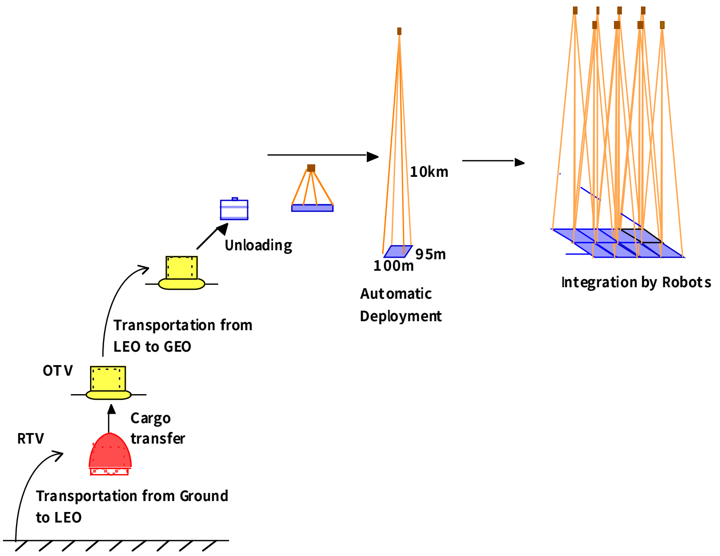

Fig.8 Construction scenario of Tethered-SPS.

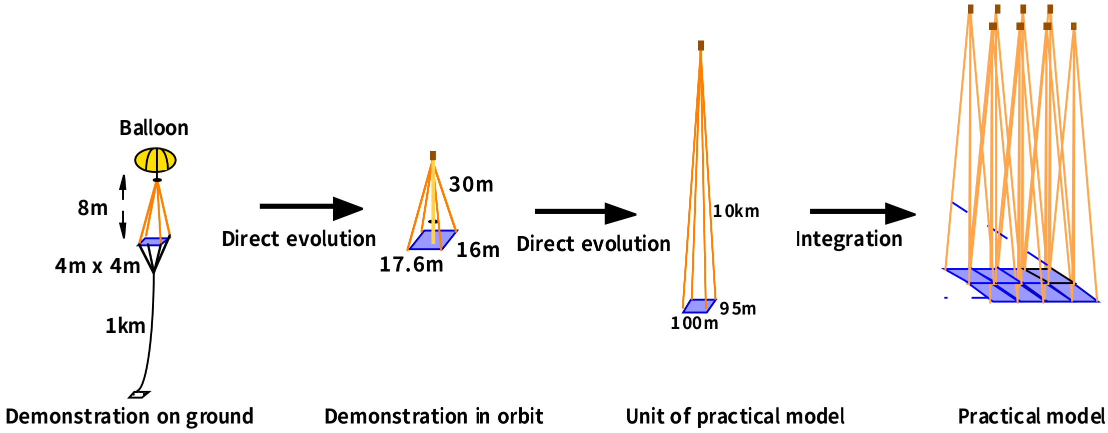

Fig.9 Evolutional development from the demonstration model to the commercial model.

the cargo is transferred to the geo-stationary orbit in 4 months. The unit of Tethered-SPS is deployed automatically in the orbit. The function of the unit is fully tested and then it is integrated to the SPS main body by latching the panels to each other. Docking assistant robots which are manipulated from the ground control center will be required for the integration. The SPS function of the main body can be verified intermittently during the construction phase from the low power to the full power. After completion of construction, any unit in trouble can be unlatched and removed from the main SPS for maintenance, and a new unit can be installed for that.

3.5 Evolutional Development

A scale model of the unit of Tethered-SPS can be used for the demonstration experiment both on the ground and in orbit. The technologies for the power generation/ transmission module and tether configuration which are essential for the Tethered-SPS are verified in the demonstration experiments. Evolutional relationship from the demonstration experiment to the practical SPS is shown in Fig.9

3.6 Investment

Construction of SPS requires a huge amount of investment more than 10 B$, which will be shared by different nations or companies. The unit structure of Tethered-SPS is highly beneficial to define the interface and responsibility of each party in

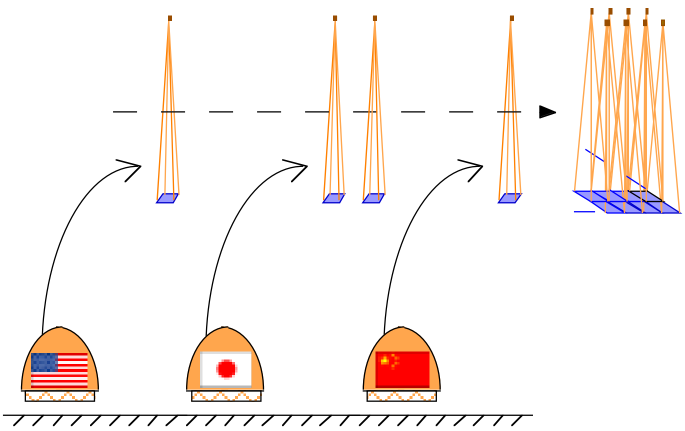

Fig.10 Construction of SPS invested jointly by different nations or companies.

the promotion of the joint venture. One unit of Tethered-SPS, 2 MW transmission capability, will cost 20 M$. Each party will invest resources in the SPS enterprise according to the demand and affordable resources. This system has an expansibility to increase the transmission power after completion of the construction if power demand is increased in the future.

3.7 Coexistence with Other Geo-stationary Satellites

The geo-stationary orbit is a valuable orbit for communication and earth observation, as well. The number of satellites in the geo-stationary orbit is limited to avoid mutual collision. One solution to the limited capacity is to build the geo-stationary satellites in the same shape of the unit of the Tethered-SPS. The communication and earth observation satellites can be connected to the Tethered-SPS, forming an information and energy complex in orbit. In this context, a concept of "Equatorial Space Belt" connecting various space facilities along the geo-stationary orbit is promising idea for a space infrastructure in the distant future. The world primary energy (currently 13,000 GW) can be supplied from the Space Belt 2 km wide with a length of 32,500 km （14 % of total length of the Equatorial Space Belt） .

4. SUMMARY AND CONCLUSION

A new model Tethered-SPS, consisting of perfectly equivalent units of a power generation/transmission panel suspended by four tether wires from a bus system, has been investigated. This concept has many advantages, as summarized below;

(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 system is composed of equivalent units, which enables the phased construction and leads to easy integration and maintenance.

(4) The unit consists of equivalent power generation/transmission modules, which enables low cost mass production.

(5) There is no wired signal/power interface between the modules, which leads to easy deployment of the unit.

(6) Active thermal control is not required because of uniform distribution of the transmitting power.

(7) A scale model of the unit of the Tethered-SPS can be used for the demonstration experiment on the ground

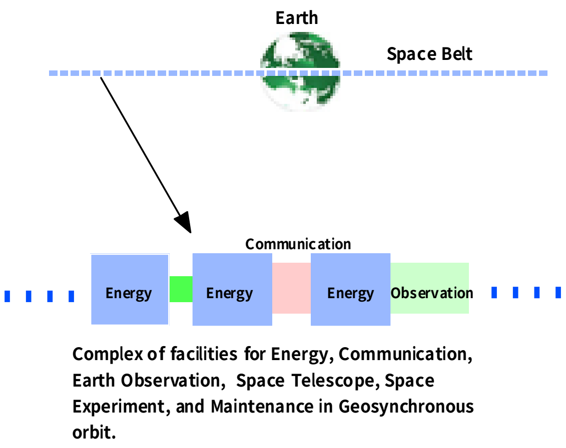

Fig.11 Conception of Equatorial Space Belt in the geo-stationary orbit.

and in orbit in the near future, which assures an evolutional scenario for the SPS development from the initial demonstration to the commercial SPS.

(8) The unit structure of Tethered-SPS is suited for joint promotion of the SPS enterprise because the work interface is clearly defined.

(9) There is a possible scenario to share the geo-stationary orbit together with other purpose satellites.

As a conclusion, the new model Tethered-SPS is a highly practical SPS concept, with a number of advantages in the production, integration, construction, operation, and maintenance as compared with the past SPS models. Since the technologies employed in the Tethered-SPS are essentially achievable, this model can be used as a realistic reference model to evaluate the cost and CO_2 load as a future energy system. However, our current study still remains an initial conceptual stage. Further investigations are required to confirm the technical feasibilities, especially for microwave control, integration of the units, and orbit maintenance of the large structure.

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