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# CONSTRACTION SCENARIO FOR TETHERED SOLAR POWER SATELLITE

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## Abstract

Tethered Solar Power Satellite (Tethered-SPS) has been proposed as a feasible and practical Solar Power Satellite. It consists of a power generation/transmission panel suspended by tether wires deployed from single or multiple bus satellite. Especially, the multi-bus Tethered-SPS, recently invented, is highly flexible and expandable. It can be constructed by integrating perfectly equivalent units of miniature Tethered-SPS connected to each other. Each unit folded up is transported from the ground to the geo-stationary orbit and deployed automatically. This concept enables phased construction approach, evolutional development scenario, and coexixtence with other geostationary satellites.

## 1.INTRODUCTION

There have been a number of SPS concepts more than fifty proposed since Peter Glaser first published the SPS concept in 1968 [1]. From a standpoint of power collection, they are categorized into 4 types as shown in Fig.1. 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 hardly realized because of its complicated configuration and also cannot avoid the over-heat problem of the solar

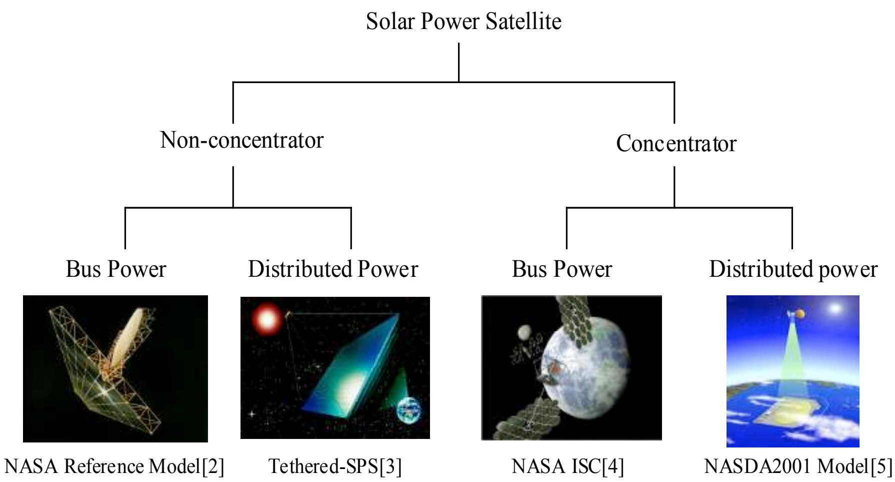


Fig. 1 Classification of SPS models and typical examples.

array panel. For the non-concentrator SPS, there are two types of configuration; bus power type or distributed power type. The typical examples of the bus-power SPS without the concentrator are the NASA reference system of 1979 [2] and the NEDO grand design of 1992 [6]. But the weight of the power collection cables for the bus power configuration is too large to be accepted as a practical SPS. Actually 1 GW power transmission for 1 km requires more than 10,000 MT cables even if a high voltage bus at 1 kV is used. Furthermore, there are no practical technologies for the rotary joint mechanism without a serious power loss. The distributed-power type without the concentrator is the only model that has no critical difficulties based on the existing technologies. Since this type SPS 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 to both sides of the panel. However, the simple, technically feasible, and practical configuration resolves almost all the technical problems in the other SPS models.

As a typical example of the distributed-power type SPS without the concentrator, we have investigated a Tethered-SPS in which a power generation/transmission panel or so-called sandwich panel is suspended by tether wires extended from the upper bus systems. The attitude of the system is stabilized by the gravity gradient force. 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 2~10 km tether wires extended from a bus system. The weight of the unit of the Tethered-SPS is 42.5 MT. The unit has the capability of microwave power transmission of 2.1 MW. The essential technologies required for the unit are deployment of the long tether of 2~10 km and the large panel of 100 m scale in orbit. The basic parts of these technologies have been already demonstrated in orbit.

In the original concept of the Tethered-SPS [3], the units are integrated to the commercial system of 1 GW level by connecting each bus system and unit panels to each other, having one panel and one bus system after integration. In the current Tethered-SPS concept, the power generation/transmission panels are connected, leaving groups of the bus systems unconnected, as shown in Fig.2. The number of grouping of the bus systems is selected so as to avoid the interference between the bus systems. In this paper, a grouping of 5x5 units into a sub-panel is considered. The configuration of the

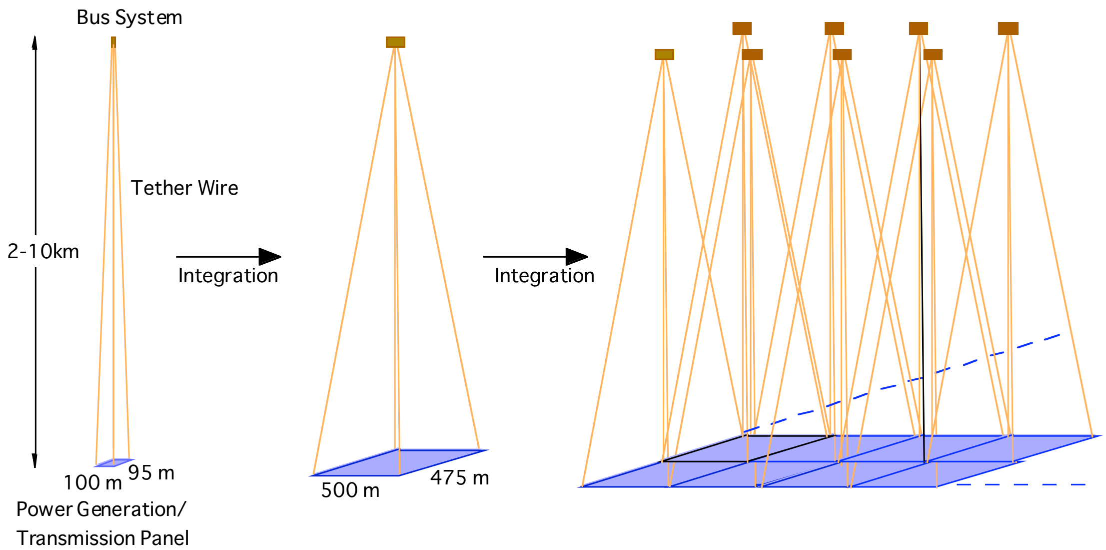


Fig.2 Unit of the Tethered-SPS and its integration to a large-scale SPS.

Fig.3 Fleet of Tethered-SPS.

separated bus system greatly enhances flexibility, expansibility, and maintenance performance of the Tethered-SPS. Figure 3 illustrates a conceptional image of Tethered-SPS. By connecting the fleet, the capability of the power plant grows without limitation.

## 2. TYPICAL CHARACTERITICS OF TETHERED-SPS

There are two versions of the Tethered-SPS. One is direct power supply from the solar power generator to the microwave power transmitter, which

Table 1 Summary of Tethered-SPS (1GW constant output)

| | |
|---|---|
| Configuration<br>Panel size<br>Tether wire length<br>Bus separation | Power generation/transmission panel suspended by 100 wires<br>2.5 km x 2.375 km x 0.02 m<br>2.5 km approx.<br>356 m (8° ) |
| Total weight<br>Panel weight<br>Bus weight | 26,600 MT<br>25,200 MT<br>1,400 MT |
| Sub-panel<br><br>Size & weight<br>Unit number/sub-panel<br>Tether tension | Power generation/transmission panel suspended by 4 wires<br>(internal 96 wires are slacked)<br>500 m x 475 m x 0.02 m, 1,010 MT<br>25 (5x5)<br>54 gw per wire |
| Unit panel<br>Size & weight<br>Module number/unit panel<br>Tether tension<br>Power transmission | Power generation/transmission panel suspended by 4 wires<br>10 m x 95 m x 0.02m , 40 MT<br>3,800 (20x190)<br>2 gw per wire<br>2.1 MW |
| Module<br>Module size & weight<br>Power generation<br>Power transmission | Power generation/transmission panel<br>5 m x 0.5 m x 0.02 m, 10.625 kg<br>1,181 W<br>555 W constant |
| Microwave Frequency<br>Output Power | 5.8 GHz<br>1 GW constant (rectenna DC output) |

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 can 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. G.A.Landis [7] has shown that the non-tracking, integrated solar/microwave SPS can be economically attractive, particularly configured to match peak power demand. Since this system can provide the electric power constantly regardless of the weather condition and seasonal variation, it can partially play a role of the base load power supply.

Another type of Tethered-SPS is power storage model equipped with batteries to provide a constant microwave power to the rectenna as the base load power supply. It has been considered unrealistic 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. The storage capability of the current batteries (Li-ion) is typically 100-200 Wh/kg. If the capacity exceeds 1,000 Wh/kg in the future, they can work for the commercial SPS. Table 1 shows an example of the design of 1 GW class Tethered-SPS with the power storage system. It is composed of 625 units of Tethered-SPS (2.1 MW each). The size of the power generation/transmission panel and weight are 2.5 km x 2.375 km and 26,600 MT, respectively. The size of each unit panel is 100 m x 95 with 0.02 m thickness. Each unit panel has 3,800 power generation/transmission modules of 5 m x 0.5 m size.

## 3. CONSTRUCTION SCENARIO

### 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 for the tether is 54 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 wires slightly deviate from the local vertical. 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 one degree in case of the former configuration (one-bus configuration). In order to keep the stationary orbit, about 50 N thrust is constantly required to the panel. If the thrust vector is adjusted precisely to the direction of the center of gravity, the attitude disturbance is within an allowable range less than several degrees.

### 3.2 Module Panel

In each power module, the electric power generated by the solar cells is converted to the microwave power and no power line interface is required between the modules. Figure 4 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

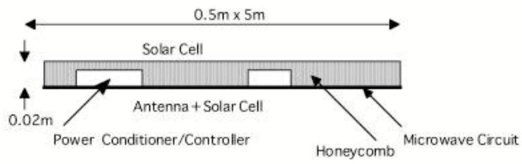

Fig.4 Module structure.

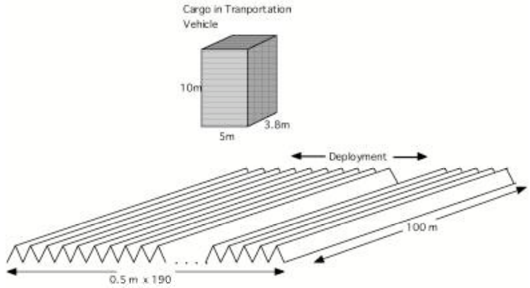

Fig.5 Two-dimensional deployment of module panels.

controller. Each module transmits a microwave power of 555 W constant (power storage type). The weight of the module is 10.6 kg. Since all modules are controlled by the wireless LAN system, there is no wired signal interface between the power modules. The 3,800 module panels are folded in a block cargo when it is transported in the transportation vehicle from the ground to the orbit. Figure 5 illustrates how to deploy the cargo to the flat panel. Since there need a huge number of actuators to deploy the module panels, the deployment mechanism must be simple and light-weight. The SMA (shape memory alloy) plate or coil that can be activated by heat is one of the potential candidates for the expedient actuator. A deployment experiment using the SMA coils has been conducted for the 4x8 miniature panels (23cm x 11cm each) as shown in Fig.6. It has been demonstrated that a combination of the SMA actuators and magnets works quite well for the panel deployment and latch.

Fig.6 Demonstration of deployment of 4x8 miniature panels using SMA coils.

## 3.3 Transportation and Construction

The over all construction scenario is illustrated in Fig.7. Each unit cargo (10mx5mx3.8m, 42.5MT) is 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 minimize the degradation of the solar cells by the trapped energetic particles in the radiation belt, the cargo will be contained in a

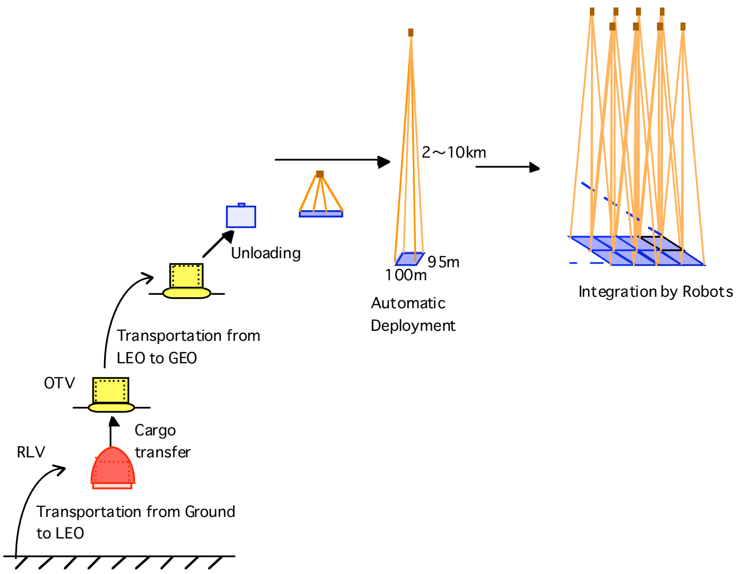


Fig.7 Transportation and construction scenario of Tethered-SPS.

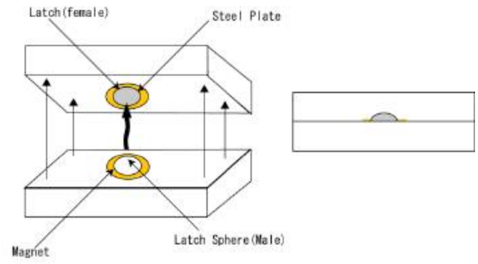


Fig.8 Connection of the unit panel using a sheet magnet and a steel plate.

radiation shield vessel. If we use a 200 MT OTV equipped with an electric propulsion of 80 N thrust, the cargo is transferred to the geo-stationary orbit rapidly in 3-4 months. The unit of Tethered-SPS is deployed automatically in the geo-stationary orbit. After the function test of the unit is completed, it is integrated to the sub-panel SPS by connecting the panels and bus systems. Once the sub-panel SPS consisting of 25 units of Tethered-SPS is constructed, it is integrated to the SPS main body by connecting the panels to each other. A combination of a sheet magnet and a steel plate together with a guide sphere as shown in Fig.8 is considered for the connecting and latching mechanism. Docking assistant robots which are manipulated from the ground control center will be used 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 unconnected and removed from the main SPS for maintenance, and a new unit can be installed for that.

## 4.DEVELOPMENT SCENARIO

### 4.1 Evolutional Development and Commercialization

A scale model of the unit of Tethered-SPS will be used for the demonstration experiment in the initial development phase. The technologies for the power generation/transmission module and tether configuration which are essential for the Tethered-SPS are fully verified in the demonstration phase. Evolutional and straightforward relationship from the demonstration experiment to the commercial SPS is shown in Fig.9

Construction of SPS requires a huge amount of investment more than 10 B$, which will be shared by different nations or companies. The unit structure of Tethered-SPS is highly beneficial to define the interface and responsibility of each party in the promotion of the joint venture. One unit of Tethered-SPS, 2.1 MW transmission capability, will cost 20 M$. Each party will invest resources in the SPS enterprise according to demand and affordable resources. This system has an expansibility to increase the transmission power after completion of the construction if power demand is increased

### 4.2 Coexistence with Other Space Infrastructure

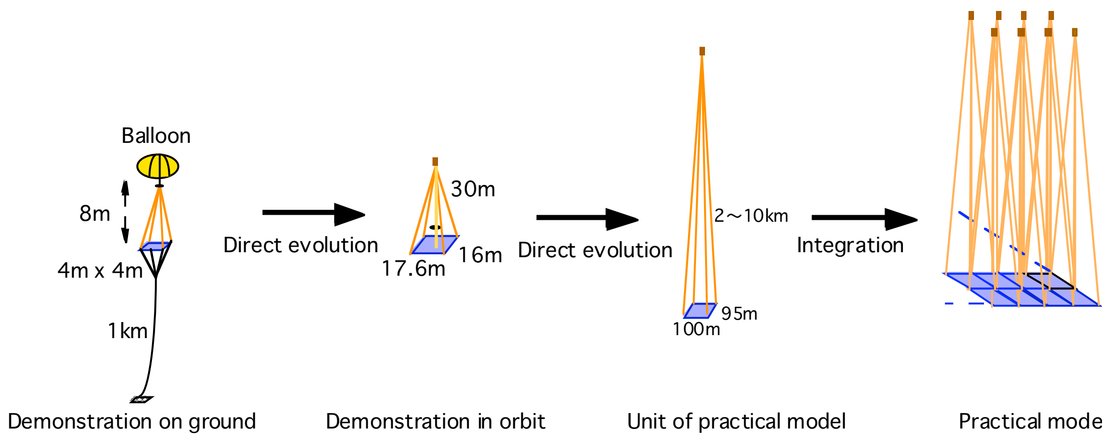


Fig.9 Evolution from the demonstration model to the commercial model.

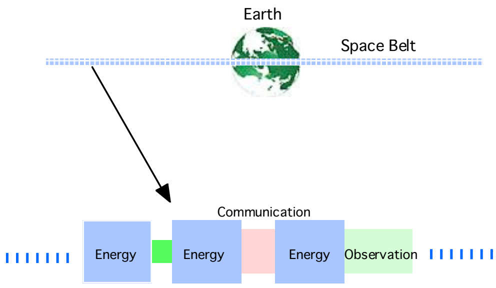


Fig.10 Conception of "Equatorial Space Belt" in the geo-stationary orbit.

The geo-stationary orbit is a valuable orbit for communication and earth observation, as well. The number of satellites in the orbit is limited to avoid mutual collision and interference. 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 as shown in Fig.10 is a promising scheme for an ultimate space infrastructure in the distant future. The world primary energy (currently 13,000 GW) can be all supplied from the Space Belt 2 km wide with a length of 32,500 km (14 % of total length of the equatorial Space Belt).

## 5. CONCLUSION

The Tethered-SPS, a distributed-power type SPS without the concentrator, is a highly practical SPS model. It is constructed in the geo-stationary orbit by integrating perfectly equivalent units of the Tethered-SPS. Each SPS unit is transported from the ground and deployed automatically in the orbit. This construction scenario has many innovative aspects; phased construction to guarantee sound development, easy integration and maintenance, and straightforward development strategy from the demonstration to commercial phase.

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