JAXA Activities for SSPS Research

By Susumu SASAKI[1,2], Koji TANAKA[1], and JAXA Advanced Mission Research Group[2]

[1] *The Institute of Space and Astronautical Science, Sagamihara, Japan*
[2] *Aerospace Research and Development Directorate, Tsukuba, Japan*

There are four major research activities associated with Space Solar Power Systems (SSPS) in JAXA. The first one is demonstration of wireless power transmission on ground both for microwave and laser. We will demonstrate the beam pointing technologies with kW-level at a range of 50-500 m. For laser, we also make research to establish the sun light-laser (1.06 μm) direct conversion technology for SSPS. The second one is to establish the technologies to construct 100 m scale structures both for a panel 0.1 m thick and a ultra-light mirror structure with a density of 300 g/m^2. Scale models will be used to demonstrate the construction technologies on ground. The third one is preparation for demonstration experiments of wireless power transmission in orbit. The small scientific satellite now under development in JAXA or JEM on the International Space Station is the possible platform to conduct a kW-level space-to-ground power transmission experiment. The fourth is to develop a realistic roadmap towards the commercial SSPS in 2030's, considering technical feasibilities. Following the roadmap, SSPS requirements to future space transportation systems are analyzed.

Key Words: Space Solar Power Systems, Microwave, Laser, Large Space Structure, Roadmap

1. Introduction

Construction of SSPS requires 6 major technologies; power generation, power management, wireless power transmission, large space structure, attitude/orbit control, and space transportation, each in an extremely large scale. All technologies except wireless power transmission have been already put into practical use in a certain scale. Wireless power transmission has been verified at the 10 kW level in laboratory and field experiments. This situation is completely different from the nuclear fusion, another revolutionary energy system, for which the principle technology "break-even" has not been verified yet. The major problem associated with SSPS is to apply the technologies to the larger system at GW level in power, km level in size, and several ten thousands of tons in weight. Also it is requested to make its power cost be competitive with that of existing power generation systems on the ground. Table 1 summarizes the existing technology level and target level for the SSPS primary technologies.

Table 1. SSPS technologies compared with existing technologies.

Technology for SSPS	Existing level	Target level	Factor
Solar power generation	100 kW (space)	1 GW	10,000
Microwave power transmission	10 kW (ground)	1 GW	100,000
Laser power transmission	100 W (ground)	1 GW	10,000,000
Heat rejection	100 kW (space)	100 MW	1,000
Large space structure	100 m (space)	1 km	10
Space transportation	10,000 $/kg	100 $/kg	1/100

Since 1998, JAXA has been investigating the SSPS system concepts and associated technologies, jointly with researchers from universities, research institutes, and companies. In the first 10 years, the efforts were mainly concentrated on creation of new SSPS concepts. During the conceptual design study, several key technologies were identified to be verified by experimental approach. They are listed in Table 2.

Table 2. SSPS key technologies required for near-term verification.

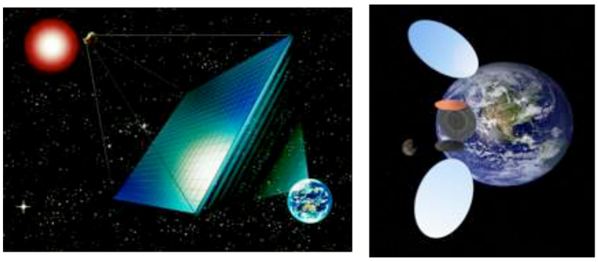
Technology field	Verification item
Microwave power transmission	Precise microwave beam pointing
	High efficiency power conversion between dc and rf
	Interaction between high-power beam and ionosphere
Laser power transmission	Direct laser generation from sunlight in a high efficiency
	Precise laser beam pointing
	High efficiency power conversion from laser to dc
	Transmission efficiency through atmosphere
Solar power collecting mirror	High magnification sun light collector
	Filter coatings for uv and ir light
Large space structure	Deployment of plate structure typically 0.1 m thick
	Deployment of thin film structure typically 100 g/m^2

From 2008, JAXA has been making experimental research for the 4 fields listed in Table 2. The research for the microwave power transmission has been conducted jointly with Institute for Unmanned Space Experiment Free Flyer (USEF). In addition to the verification type research, we have developed a detailed technology roadmap towards the commercial SSPS to be realized around mid-2030's.

2. Experimental Research

2.1. Microwave Power Transmission

There are two major microwave-type SSPS concepts recently studied in Japan; basic model and advanced model as shown in Fig.1. The basic model is the Tethered-SPS in which the power generation/transmission panel is suspended by tether wires and stabilized by the gravity gradient force, which has been studied by USEF. The configuration is just simple and the technologies for the model are conventional, but the power collection rate is relatively low as compared with the sun-pointing type SSPS. The advanced model is a combination of two reflective mirrors with two power generation solar array panels and a microwave transmitter panel. It utilizes the formation flight of the reflective mirrors and a power generation/transmission complex, which has been studied by JAXA. The sun-pointing configuration by the reflective mirrors leads to a good power collection rate, but the technologies for the model are quite challenging.



(a) Basic Model (b) Advanced Model

Fig. 1 Microwave type SSPS currently studied in Japan.

JAXA and USEF, in corporation with researchers of universities and several research institutes, are preparing a microwave power transmission experiment on the ground in the next several years 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 50 m apart from the transmitter. The configuration of the experiment is shown in Fig.2.

The transmitter consists of 4 panels of antenna array that are movable to each other to simulate dynamic motion of antenna in orbit. The power level from each panel will be several hundreds of watts, totally one kW level, at 5.8 GHz. Each panel, 0.6m x 0.6m, has an array consisting of hundreds of transmitting antennas, receiving antennas for the pilot signal, phase controllers, and power systems. The thickness of the panel will be less than 5 cm. The frequency of the local oscillator in each panel is synchronized by a master oscillator. A phase shifter just before each main amplifier is controlled so as that the microwave beam from the antenna array is directed to the rectenna by detecting the pilot signal. The phase of local oscillator in each panel is adjusted by a Rotating Element Electric Field Vector (REV) method so as that the power at the receiving site gets maximum. The technologies for the beam forming and beam direction control in the ground experiment are described in another paper[1]. In the demonstration experiment, the output dc power from the rectenna will be several hundreds of watts, which will be used to operate household electric appliances for public demonstration.

Fig.2 Microwave power transmission experiment on the ground.

2.2. Laser Power Transmission

Laser type SSPS has been regarded as an optional idea since the initial phase of research in 1970's. However, the recent technology on the direct laser excitation pumped by concentrated sunlight can give a high conversion efficiency more than 20 %, which can be applied to the laser-type SSPS. The laser of 1.06μm wavelength is excited by Nd/Cr-YAG ceramic when it is irradiated by strong sunlight, 500-1000 times solar intensity. The laser-type SSPS shown in Fig.3, which JAXA has been studying, is a combination of focusing mirrors, a crystal laser exciter, optics, and a heat radiator. The technologies required for the laser model are much more challenging than the microwave-type model.

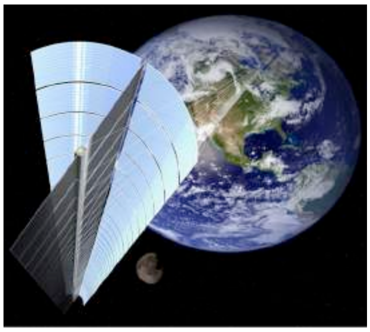


Fig. 3 Laser type SSPS currently studied in Japan.

We are planning to conduct a laser power transmission experiment using a laser transmission test facility in Kakuta of JAXA. The sunlight is concentrated up to 1000-2000 times solar intensity using a solar reflector with 10 m^2 area. The Nd/Cr-YAG ceramic cell will excite 1kW laser. The direction of the beam is controlled at an accuracy less than several μ-radian by the laser optics so as that the beam is transmitted precisely to the light receiver located at 500 m apart from the transmitter. The light receiver consists of laser optics, a homogenizer, and photovoltaic cells. The total output power at receiving site will be 0.3 kW. A precursor experiment to the 1 kW system, we are now developing 100 W model consisting of 2 m diameter sun light concentrator combined with a Nd/Cr-YAG laser exciter, as shown in Fig.4.

2.3. Construction of Large Space Structure

Fig.4 100 W class laser power generation model .

There are two kinds of structures for the three SSPS models shown in Figs.1 and 3. One is a panel with a thickness typically 10 cm or less, such as the sandwich panel of several square kilometers in the basic model, the solar array panel and the microwave antenna array panel of several square kilometers in the advanced model, and the radiator panel of several hundred square meters in the laser model. Another is a ultra-light structure typically less than 300 g/cm^2, such as the reflective mirror of several tens of square kilometer in the advanced model and the reflective mirror of several hundred meters square in the laser model.

As a near-term target, we aim at establishing technologies to construct 100 m scale structure in orbit using existing launch vehicles. After a series of trade-off study, we have started development of a panel builder for ground testing, in which panels with trusses are deployed, connected, and extended automatically, as shown in Fig.5. This system can be directly applied to deployment of the SSPS panel. For the mirror structure, a ultra-light truss consisting of rigidizable inflatable tubes is a potential candidate for the back-structure. An advanced type of vapor-inflatable tube which is rigidized by self-heating is now under development. The technologies for the automatic panel deployment and inflatable tube in the ground experiment are described in another paper[2)].

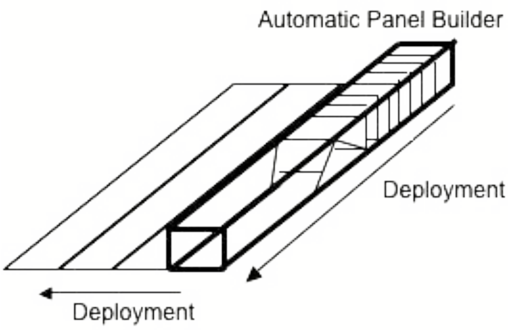


Fig.5 Configuration of automatic panel builder.

2.4. Demonstration Experiment in Space

Based on the design of the wireless power transmission experiments on the ground, a small scale microwave and laser power transmission experiments in orbit will be conducted in the near future as a logical step[3)].

The major objectives of the microwave power transmission experiment in space are to demonstrate the microwave beam control technology and to verify microwave power transmission (~kw/m^2) through the ionosphere. A small scientific satellite now under development in JAXA to be operational soon or JEM (Japanese Experiment Module) on the International Space Station is the possible platform for the demonstration experiments, as shown in Fig.6. The weight of payload instruments will be 200 kg for the small satellite and 500 kg for the Space Station, including diagnostic instruments such as plasma probes, particle energy analyzers and plasma wave receivers. For the small satellite experiment, a power transmission panel consisting of 4 modular panels, 1.6m x1.6m totally, will be used to transmit a 3.8 kW power beam. The experiment on the International Space Station will have 9 modular panels, which are capable of transmitting a 8.6 kW power beam from a 2.4 m x 2.4 m antenna. In order to study the nonlinear interaction of the microwave power beam with the ambient plasma, a power density more than 100 W/m^2 is required. In case of the JEM experiment, maximum beam intensity more than 1000 W/m^2 will be realized for 100 m from the antenna and that more than 100 W/m^2 for 400 m.

Fig.6 Microwave power transmission experiment in space on a small satellite (left) and on the International Space Station (right).

Figure 7 shows the experiment sequence near the ground station. The microwave beam at 10 % of the full power is transmitted to the ground for the first and last 2 minutes in the experiment sequence. The onboard computer controls the beam direction without the pilot signal from the ground during the low power mode. When the experiment system passes over the ground station, the microwave beam at the full power is transmitted to the ground for 16 sec guided by the pilot signal from the observation site. The beam direction is changed in ± 10 degrees from the normal line of the panel to target the receiving site. The power

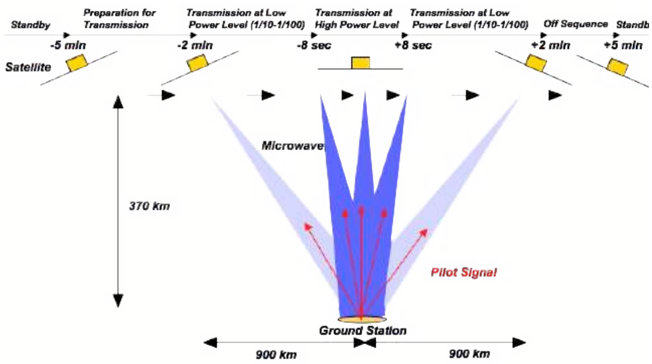


Fig.7 Experiment sequence of microwave transmission experiment.

density on the ground is 26 μW/m^2 at maximum. Although the effective electric power cannot be obtained for such a low power level, we will be able to measure the beam pattern by distributed antennas on the ground and fully evaluate the performance of the beam control capability.

For the laser power transmission, a power transmission experiment at 1 kW level from the low earth orbit to the ground is considered using the JEM on the International Space Station. The small satellite is not suitable platform for the laser beam transmission experiment because of the constraints of attitude stability. The experimental objectives are to demonstrate the laser beam control precisely to the target on the ground from the transmitter in orbit and to verify the laser power transmission efficiency through the atmosphere,

The pointing accuracy is required less than 1 μrad in a closed loop system, which is one of the most challenging technologies. The on-orbit experiment will give a good opportunity to verify the high-accuracy feed-back system and also to study the scattering effect of the laser beam in the atmosphere in the real configuration. It is believed the scattering is mainly caused by the aerosol near or less than 1 μm size existing below 10 km. Figure 8 shows a proposed configuration for the laser power transmission experiment from JEM. A 1 kW laser beam at 1.06 μm is transmitted through a 20 cm diameter optical system to a ground station guided by a pilot signal. The deviation of the beam center from the receiver center is detected and uplinked to correct the beam direction by controlling the beam mirror. If we use a 10 m diameter receiver consisting of photovoltaic cells, totally 200 W DC power will be obtained at the receiving site.

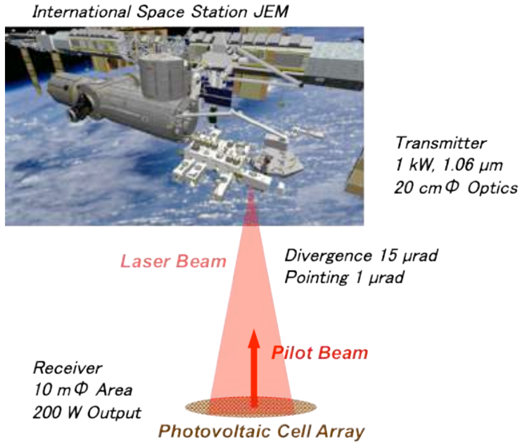


Fig.8 Laser power transmission experiment on the International Space Station.

3. Development Roadmap

JAXA is working on a detailed technology roadmap towards the commercial SSPS to be realized in 2030's. The guidline plan we are referring to for generation of detailed roadmap is shown in Fig.9. We just started development of the wireless power transmission demonstration systems on the ground at 1 kW level both for microwave and laser. The major part of the ground demonstrations will be completed by the end of 2013. Based on the design of the ground demonstration system, a small scale microwave power transmission experiment in orbit will be conducted around 2015. If the technologies for the laser power transmission are ready for the space experiment, they will be also demonstrated in the same time frame. After completion of the demonstration experiments on the ground and in space, we will select the transmission media, microwave or laser. After selection, we will start 100 kW class demonstration in space. All basic technologies required for the commercial SSPS will be verified at this stage. Following the demonstration experiment, the initial

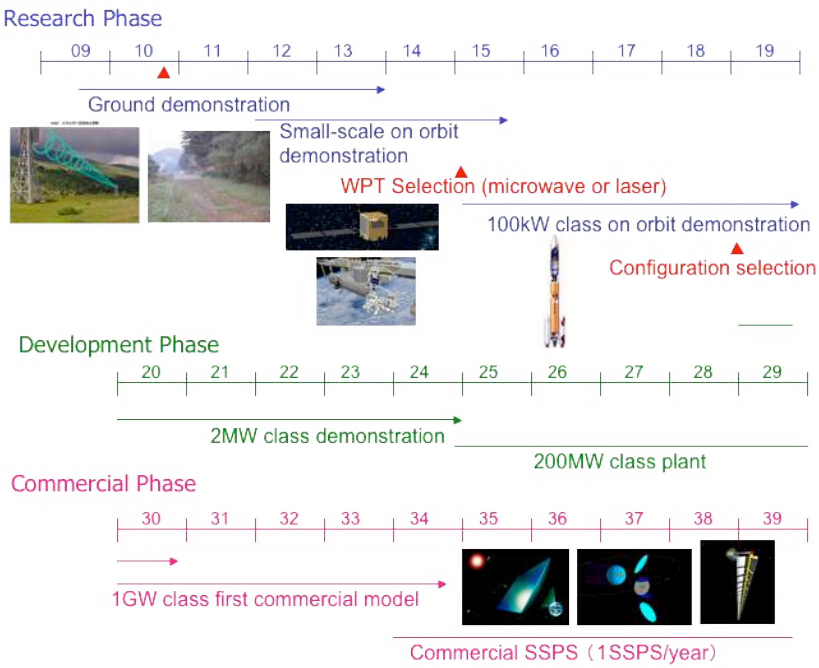


Fig.9 Guideline plan towards commercial SSPS.

target for the configuration of the commercial SSPS will be selected. The expected power cost and public acceptance will be the major trade off factors for selection. The demonstration for the commercial SSPS will be conducted using 2MW and 200 MW class SSPS plants before 2030. This scenario guaranties the start of construction of the 1 GW class commercial SSPS in 2030's. Corresponding to the SSPS roadmap, we have analyzed SSPS requirements to the space transportation systems, as shown in Table 3. Reusable launch vehicle (RLV) will be necessary before the small plant demonstration (2MW class) around 2020, and orbit transfer vehicle (OTV) is required before the large plant demonstration (200 MW class) around 2025. The requirements are undoubtedly very tough, but are not impossible if the space transportation communities seriously challenge their realization.

4. Summary

JAXA is conducting ground-based demonstrations for microwave power transmission, laser power transmission, and construction of large space structure. After these ground demonstration projects, we will start space-based experiments for the wireless power transmission at several kW using small satellite or International Space Station. Based on the results from the ground/space experiments, together with analytical studies and road-mapping, we will clarify the prospects for the commercial SSPS. This approach is in accordance with the basic plan on space development by the government's space development strategy headquarter in Japan.

References

1) Miyakawa, T., Yajima,M., Fukumuro,Y., Sasaki,S., Sasaki,S., Homma,Y., and Namura,K.: Research of Beam Steering Control Subsystem for Microwave Wireless Power Transmission Ground Experiment, 28th ISTS, 2011.
2) Joudoi, D., Fujita,T., Sasaki,S. : Status of Studies on Large Structure Assembly of Space Solar Power Systems (SSPS), 28th ISTS, 2011.
3) Sasaki,S., Tanaka, K., and Advanced Mission Research Group: On-orbit Demonstration for SPS Wireless Power Transmission, Proc. of the IAA 50th Anniversary Celebration Symposium on Climate Change/Green Systems, 2011, pp.103-107.

Table 3. SSPS requirements to space transportation system.

Phase	Small scale demonstration	Large scale demonstration	Small plant	Large plant	First commercial model	Commercial
Target year	2015	2020	2025	2030	2035	2035～
Orbit	LEO	LEO	1000 km	GEO	GEO	GEO
Power level	1～5kW	100 kW	2 MW	200 MW	1 GW	1 GW
System weight	500 kg	15 tons	50 tons	3000 tons	10000 tons	10000 tons
Construction period	NA	NA	1 year	2 years	5 years	1 year
Payload weight	500 kg	15 tons	10 tons	50 tons	50 tons	50 tons
Launch vehicle	1 ELV LEO	1 ELV LEO	1 RLV 1000km 5 Round trips launch/2.4 months	4 RLV 500 km 24 Round Trips 2 launch/month	8 RLV 500 km 40 Round Trips 5 launch/month	8 RLV 500 km 40 Round Trips launch every day
Orbit transfer vehicle	NA	NA	NA	15 RLV 500 km-GEO 4 Round Trips *	20 RLV 500 km-GEO 10 Round Trips*	100 RLV 500 km-GEO 2 Round Trips*

* 6 months round trip, fuel 30 tons