On-orbit Demonstration for SSPS Wireless Power Transmission

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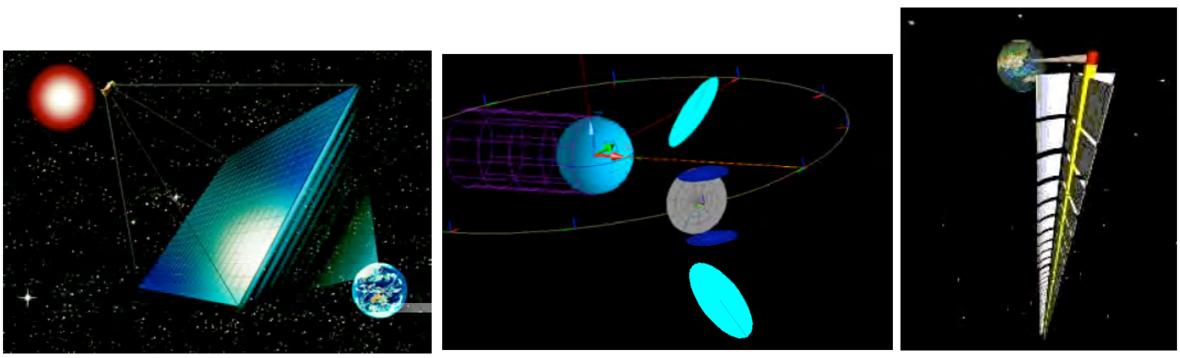
After completion of ground wireless power transmission experiments at the kW class both for microwave and laser, which are in progress in Japan, we plan to conduct small-scale demonstration experiments in orbit. There are two candidates for the experiment platform in space; a small satellite or the JEM (Japanese Experiment Module) on the International Space Station. For the microwave, power transmission at 4-9 kW level from the low earth orbit to the ground will be performed to verify the microwave beam control and to study the microwave-ionospheric plasma interaction. For the laser, 1 kW level demonstration experiment is considered on the Space Station JEM to verify the laser beam control technologies and to study the scattering effect in the atmosphere. Based on the results from the small-scale demonstration experiments in space and also from laboratory experiments, we will make a decision on the option of transmission medium, microwave or laser, for the next phase demonstration at the 100 kW class in orbit.

Key Words: SSPS, Wireless Power Transmission, On-orbit Demonstration

1. Introduction

We have three types of commercial SSPS (Space Solar Power Systems) model currently studied in Japan; microwave-type basic model, microwave-type advanced model, and laser-type model, as illustrated in Fig.1 The basic model is the "Tethered-SPS" in which power generation/transmission panels are suspended by tether wires and stabilized by the gravity gradient force[1)], which has been studied by USEF (Institute for Unmanned Space Experiment Free Flyer). The configuration is highly modularized and the required technologies are conventional, but the power collection rate is relatively low (64%) as compared with the sun-pointing type SSPS. The advanced model is a combination of reflective mirrors with solar array panels and microwave transmitter[2)]. It utilizes the formation flight of reflection mirrors and power generation /transmission complex, which has been studied by JAXA. The sun-pointing configuration provides almost 100 % power collection rate, but the technologies for the model are quite challenging. The laser-type model is a combination of focusing mirrors, a crystal laser exciter, optics, and a heat radiator[2)], which has been studied by JAXA. The technologies required for the laser model are much more challenging than the microwave-type models.

Our target is to realize the commercial SSPS in mid-2030's. The roadmap towards the commercial model we are proposing is shown in Fig.2. We just started developing demonstration systems for the wireless power transmission on the ground. The ground demonstration experiments will be completed by the end of 2013. Based on the design of the ground demonstration systems, small scale



(a) Microwave-type Basic Model (USEF) (b) Microwave-type Advanced Model (JAXA) (c) Laser-type Model (JAXA)

Fig.1 Typical SSPS models currently studied in Japan.

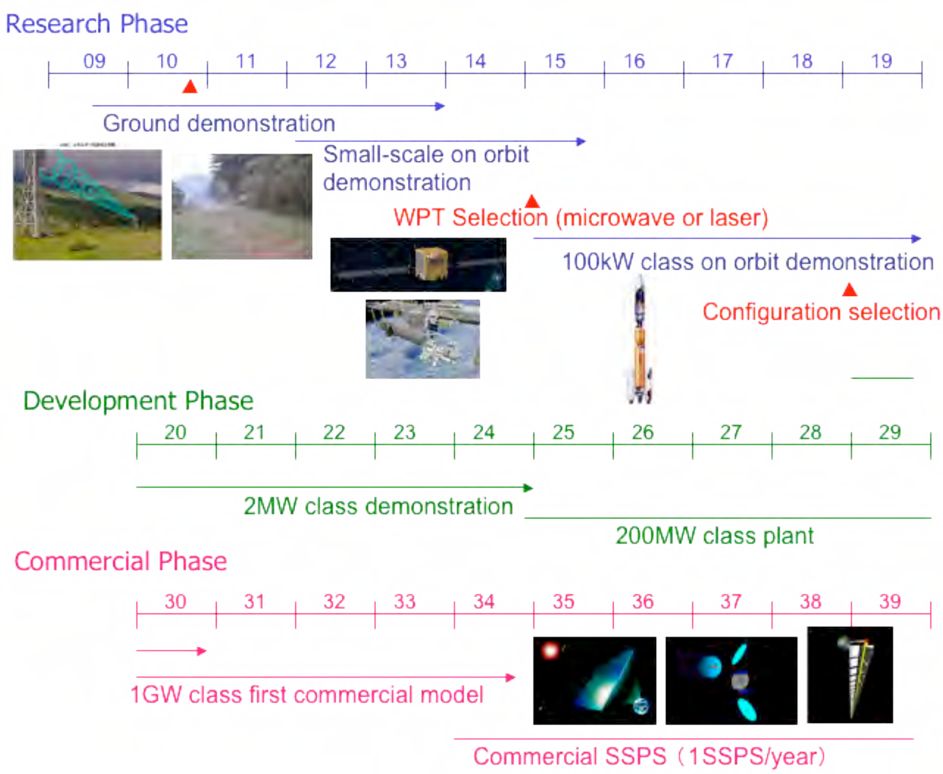


Fig.2 Roadmap towards commercial SSPS.

wireless power transmission experiments in orbit will be conducted around 2015. If the technologies for other SSPS technologies such as large-scale panel deployment get ready for the on-orbit experiment, they will be also demonstrated in the same time frame. A small satellite or JEM on the Space Station is the possible platform for the SSPS demonstration experiments. After completion of the demonstration experiments on ground and in space, we will be ready to select the transmission medium, microwave or laser. For the selected medium, we will demonstrate a 100 kW class SSPS in space by the end of 2010's. All basic technologies required for the commercial SSPS will be verified at this stage. After the 100 kW class demonstration, the system configuration for the commercial model; the basic model, the advanced model, the laser model, or other model, will be selected. The expected power cost ($/kWh) and public acceptance will be the major trade off factors for selection. For the selected configuration, the plant-level demonstration at the 2-200 MW class will be conducted in 2020's.

2. Wireless Power Transmission Demonstration

We are now in the phase of ground demonstration experiment for the wireless power transmission technologies both for microwave or laser. In the microwave power transmission experiment, a microwave beam at 2.8 kW will be transmitted from a 1.6 m x 1.6 m array antenna to a rectenna located at around 100 m apart from the transmitter. The microwave beam will be precisely guided by the

Fig.3 Microwave power transmission experiment on ground.

Fig.4 Laser power transmission experiment on ground.

retro-directive beaming technology using a pilot signal from the rectenna site (Fig.3). In the laser power transmission experiment, a laser beam at around 1 kW directly generated by a Cr/Nd:YAG crystal from concentrated solar light will be transmitted to a photovoltaic receiver located at 500 m apart from the laser transmitter as shown in Fig.4. After completion of the ground wireless power transmission experiments, we will be ready to conduct the wireless power transmission experiment in space both for microwave and laser.

2.1 Microwave Power Transmission Experiment in Space

The major objectives of the microwave power transmission experiment in space are;

1) demonstration of the microwave beam control precisely to the target on the ground from the antenna in orbit,

2) verification of microwave power transmission (~kw/m^2) through the ionosphere,

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

4) demonstration of the electromagnetic compatibility with the existing communication infrastructure.

Especially, item 2), the interaction between the intense microwave and the ionospheric plasma as shown in Fig.5, is important because it can be studied only in the space environment. Either a small satellite or JEM on the Space Station can be used for the demonstration experiment. The weight of payload instruments will be 200 kg for the small satellite and 500 kg for the Space Station.

The satellite configuration for the microwave power transmission experiment from the small satellite is shown in Fig.6. A power generation/transmission panel, 1.6m x 1.6 m consisting of 4 modular panels similar to those on the ground demonstration experiment, will be used to transmit 3.8 KW power. The system characteristics are summarized in Table 1.

There are two configurations in the experiment; transmission to the ground perpendicularly to the spacecraft

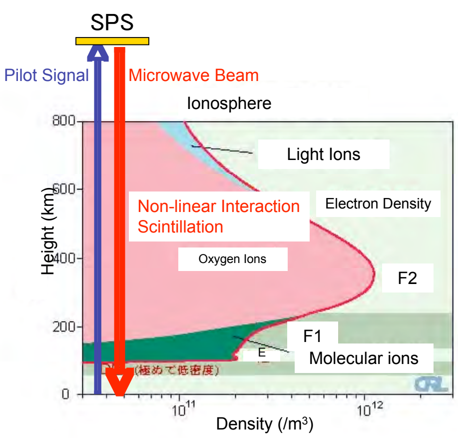


Fig.5 Study of interaction of microwave and ionospheric plasma.

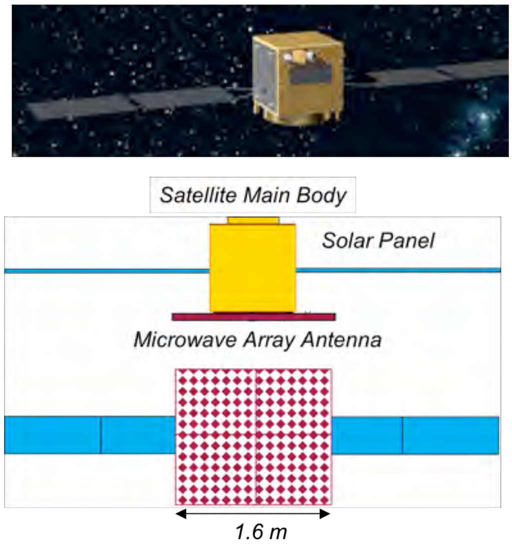


Fig.6 Configuration of the demonstration experiment using the small satellite.

Table 1 Specification of the demonstration experiment on the small satellite.

Mission	Period	1 year
System	Configuration	Power generation/transmission panel suspended by satellite main body
	Panel size	1.6 m x 1.6 m x 0.02 m
	Total weight	200 kg
	Attitude stability	±1°
Power transmission	Frequency	5.8 GHz
	Phase control	5 bit
	Number of module	4
	Beam control	Retro-directive/Computer control, ±10°
	Output power	950 W/module, 3.8 kW(total)
	Power density	1500,1000, 500, 100 W/m² (at antenna) 24 μW/m²(max, on ground)
Ground stations		JAXA ground stations International experiment sites

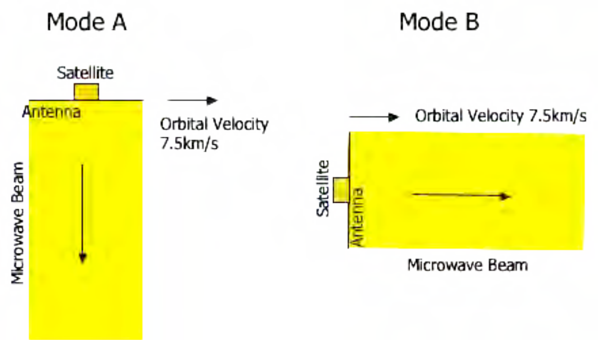


Fig.7 Two configurations of the demonstration experiment using the small satellite. The microwave beam is transmitted to the ground in mode A, while it is transmitted parallel to the orbiter velocity vector in mode B.

velocity vector (Mode A) and transmission parallel to the velocity vector (Mode B), as shown in Fig.7. In mode A, the microwave is transmitted to the ground guided by a pilot signal from the ground station. Mode B is a favorable

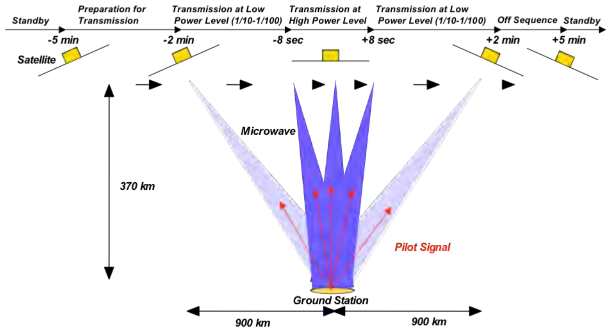


Fig.8 Experiment sequence in case of Mode A. The full power at 3.8 kW is transmitted to the ground for 16 sec guided by the pilot signal when the satellite is flying over the ground station. .

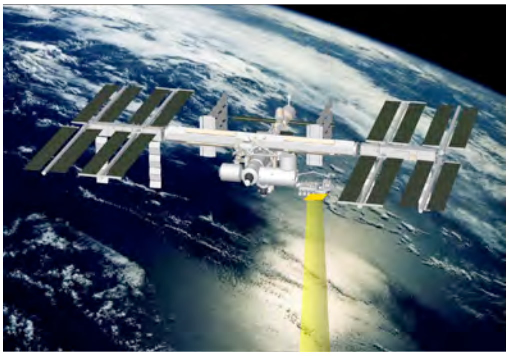


Fig.9 Microwave power transmission experiment at 8.64 kW from the Space Station JEM.

configuration to study the microwave/plasma interaction because the segment of the ionospheric plasma is irradiated longer time than that in Mode A. Figure 8 shows a typical experimental sequence in Mode A. At 2 min before flying over the ground station, the microwave transmission starts in a low power mode less than 100W. The high power transmission experiment at 3.8 kW is planned only for about 16 sec when the satellite passes just above the ground station. If we use the JEM on the Space Station as illustrated in Fig.9, we will have 9 modular panels, which are capable of transmitting a 8.64 kW power beam from a 2.4 m x 2.4 m antenna to the ground.

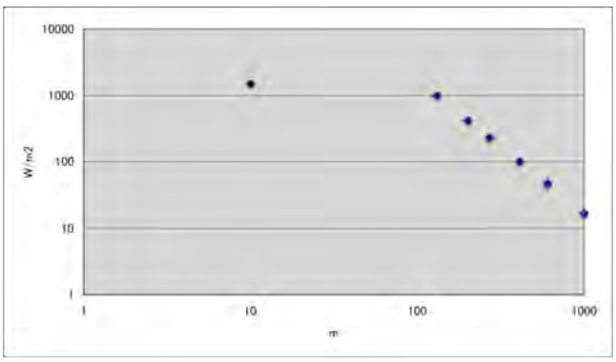


Fig.10 Microwave power intensity vs the distance from the transmitter in case of JEM experiment.

Table 2 Verification items in Mode A and B.

Verification items			Mode A	Mode B
Direction of microwave power beam			Ground	Orbit parallel
Ionospheric plasma irradiation time			0.2ms	10ms
Research subject			Observation	
Ionosphere interaction	Heating	F-layer electrons heating	partially	yes
		F-layer plasma density reduction	no	yes
		Lower ionosphere electrons heating and plasma density increase	no	no
	Thermal self-focusing	Electrons heating	partially	yes
		Plasma density reduction	no	yes
	Beam gradient self-focusing	Electrons heating and density reduction	yes	yes
		Plasma reduction	no	yes
	3-wave interaction	Back-scatter waves, plasma waves, electrons heating	yes	yes
Beam control	Transmission to ground station		yes	no

In order to study the nonlinear interaction of the microwave power beam with the ambient plasma, 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 130 m from spacecraft and that more than 100 W/m^2 for 410 m, as shown in Fig.10.

The verification items in mode A and B are summarized in Table 2. Because the orbital velocity is larger than the ion acoustic velocity, the ionospheric effects in which ions motion plays an important role can not be induced. But the electrons effects will be studied in the small scale experiment, especially in Mode B configuration. The beam direction control by the pilot signal from the ground station is verified only in mode A configuration.

2.2. Laser Power Transmission Experiment in Space

For the laser, a power transmission experiment at 1 kW level from the low earth orbit to the ground is considered using the JEM on the Space Station. The small

Fig.11 Possible laser scattering by aerosol below 10 km.

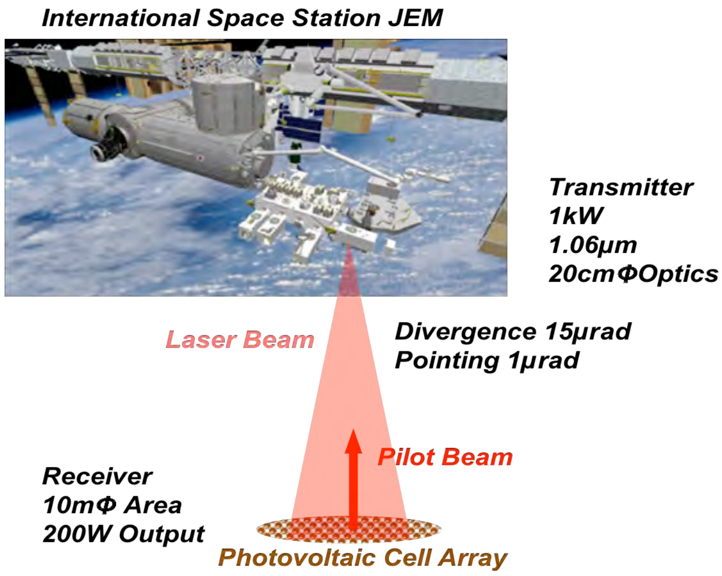


Fig.12 An example of laser power transmission experiment from the Space Station JEM.

satellite is not suitable platform for the laser beam transmission experiment because of the constraints of attitude stability. The experimental objectives are;

1) demonstration of the laser beam control precisely to the target on the ground from the transmitter in orbit,

2) verification of laser power transmission through the atmosphere,

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

4) demonstration of laser safety for public acceptance.

Especially, items 1) and 2) are important, because the pointing technology is especially challenging and on-orbit experiment is the real configuration to study the scattering of the laser beam in the atmosphere. It is believed the scattering is mainly caused by the aerosol near or less than 1 μm size existing below 10 km as shown in Fig.11. Figure 12 shows a preliminary idea 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 according to the pilot signal. If we use a 10 m diameter receiver consisting of photovoltaic cells, totally 200 W DC power will be obtained at the receiving site.

3. Summary and Conclusion

The ground demonstration projects both for microwave and laser power transmission are now in progress as the initial step towards the commercial SSPS. They will demonstrate the technologies for the wireless power transmission at kW level in the range of 100-500 m. The technologies verified in the ground experiments will be used to conduct the kW class demonstration experiments from the low earth orbit to the ground. A small satellite or the JEM on the Space Station will be used for the experiments. This approach is in accordance with the basic plan on space development by the government's space development strategy headquarter in Japan. Based on the results from the small-scale demonstration experiments in space, together with the results from the ground experiments, we will make a decision on the technology option, microwave or laser, for the following phase development. In the next step, we will make a 100 kW-class SSPS demonstration experiment in orbit by the end of 2010's, and then scale up to a 2-200 MW class pilot plant before 2030.

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