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SSPS TECHNOLOGIES DEMONSTRATION IN SPACE

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The basic plan for space policy in Japan, stating the government's commitment to SSPS (Space Solar Power Systems) research, has opened up a new prospect for SSPS demonstration experiments in space. There are a lot of SSPS technologies to be verified on orbit, but the most fundamental and urgent issue at this stage is the "wireless power transmission from space to ground". This paper presents plausible plans for microwave and laser power transmission experiment to be conducted in the initial phase of space experiment.

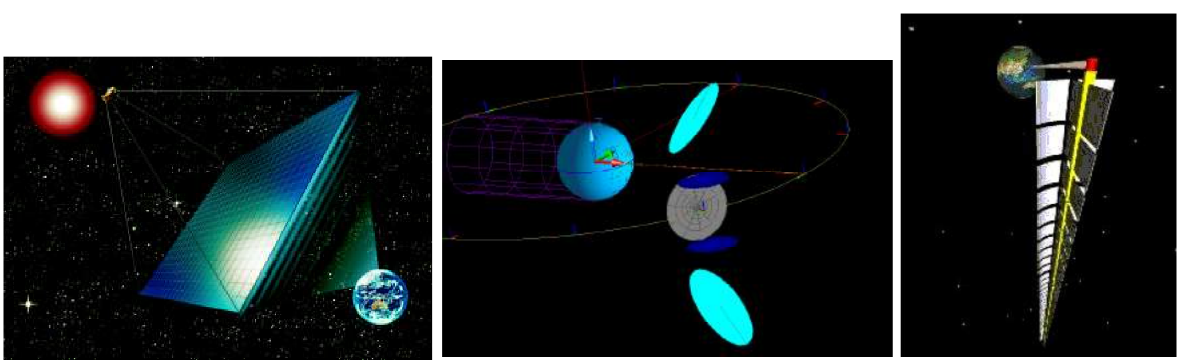
I. INTRODUCTION

The concept of the SSPS has long been attracting researcher's interests in the United States, Europe, the former Soviet Union, Canada, and Japan since Peter Glaser's first proposal in 1968 [1]. However, the governments and industries have not seriously committed themselves to conducting a full-scale SSPS research, quite different from the fusion research. Many people are still suspicious of its technical feasibility and cost-effectiveness. Like a which-came-first-the-chicken-or-the-egg question, the low level studies so far have not provided the convincing data to the questions to the SSPS promising features.

Recently, responding to the researchers appeals, new movements have been initiated in the world. One of the new reactions is the Japanese government's commitment to the new policy of the Strategic Headquarters for Space Policy. It says "Government will examine the system for the development of space solar power program from a comprehensive point of view in collaboration with related institutions, and also conduct demonstration of technologies for the energy transmission technology in parallel. Based on the result, Government will conduct ample studies, then start technology demonstration project on orbit utilizing "Kibo" or small sized satellites within the next 3 years to confirm the influence in the atmosphere and system check".

The important message in the new policy is that the government is now considering on-orbit experiments for SSPS technologies demonstration. In Japan, the microwave power transmission experiment was conducted by the sounding rocket twice in 1983 [2] and 1993 [3], providing important knowledge on the nonlinear interaction of the microwave with the ionospheric plasma, but they were short-time and short–range experiments during the parabolic flight. Now, we are able to plan more sophisticated and long-duration experiments using satellites or the Space Station for verification of SSPS technologies.

In the initial stage of space demonstration, the most fundamental technology that decisively affects the system-level concept needs to be verified. The first issue is regarding to the wireless power transmission medium, microwave and laser. For the microwave transmission, the beaming technology to the pilot signal station on the ground and possible interaction with the



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

Fig.1 Typical SSPS models currently studied in Japan.

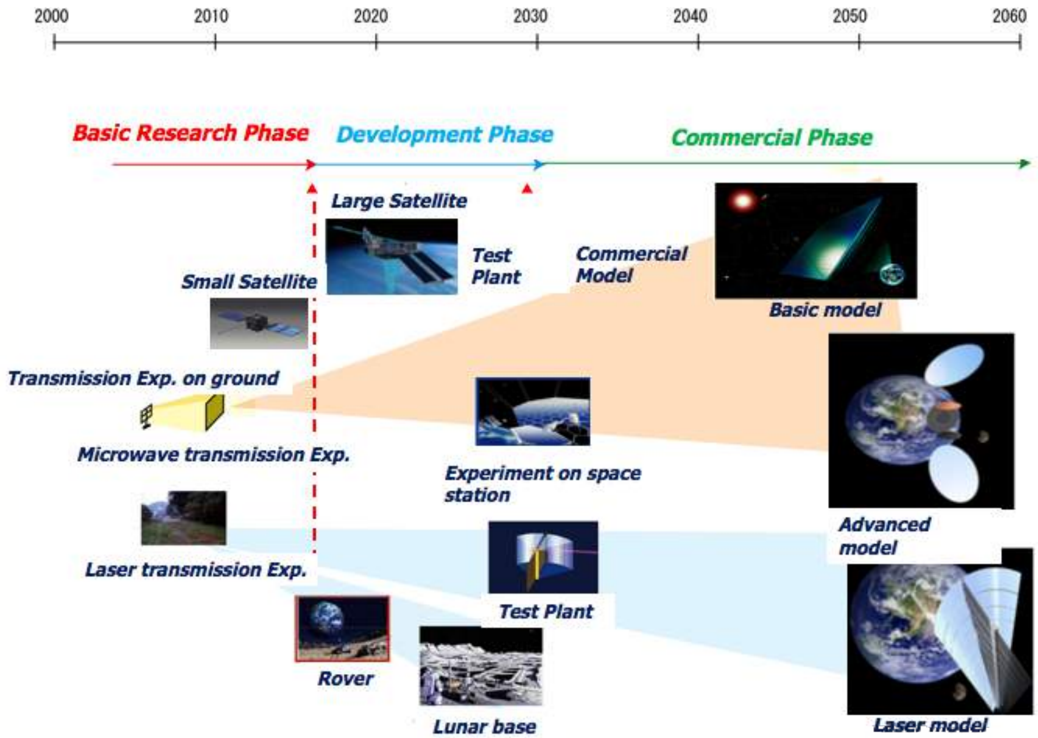


Fig.2 Road map for commercial SSPS.

ionospheric plasma are to be studied. For the laser transmission, the beam-pointing technology to the ground power receiving site and transmission through the atmosphere are to be studied. The data for the over-all transmission efficiency and electromagnetic/optical contamination outside the beam, together with the results of laboratory supporting experiments, will give a definite answer to the question which medium, microwave or laser, is more suitable for the wireless power transmission from space to ground.

II. ROADMAP TOWARDS COMMERCIAL SSPS

We have three types of commercial model currently studied in Japan; microwave-type basic model, microwave-type advanced model, and laser-type model, as shown in Fig.1 The basic model is the Tethered-SPS [4] in which the power generation/transmission panel is suspended by tether wires and stabilized by gravity gradient force, which has been studied by USEF (Institute for Unmanned Space Experiment Free Flyer). The advanced model is a combination of reflective mirrors with power generation solar array and microwave transmitter [5]. It utilizes the formation flight of reflective mirrors and power generation/transmission complex, which has been studied by JAXA. The laser-type model is a combination of focusing mirrors, a crystal laser exciter, optics, and a heat radiator, which has been studied by JAXA. The technologies required for the laser model are much more challenging than the microwave model.

One of the three models is expected to be realized in mid-2030's. The road map we are considering is shown in Fig.2. We just started development of the wireless power transmission demonstration systems at 1 kW level on the ground. For the microwave power transmission experiment, a power beam at 2.8 kW is transmitted precisely to a rectenna located at 100 m apart from the transmitter, as shown in Fig.3. For the laser power transmission experiment, a 1 kW laser beam excited directly from the sunlight is transmitted to an optical receiver located at 500 m from the transmitter as

Fig.3 Microwave power transmission experiment on the ground.

Fig.4 Laser power transmission experiment on ground.

shown in Fig.4. These demonstration experiments on ground will be completed by the end of 2013. Based on the technologies verified by the ground demonstration experiments, a small scale microwave power transmission experiment in orbit will be conducted around 2016. If the technologies for the laser power transmission are matured and ready for the space experiment, they will be also demonstrated in the same time frame. Small satellites and/or JEM (Japanese Experiment Module) on the International Space Station are the possible platforms for the demonstration experiments. After the small scale experiments are completed, the transmission medium is selected and the design of the current SSPS model will be updated. Then the associated technologies to be verified in space are identified. The technologies to be verified will be; construction of the large structure in orbit, the attitude control, and power management system. Also in this phase, 100 kW class demonstration experiment using the selected transmission medium, an end-end SSPS demonstration in which effective power is obtained on ground, will be conducted. After completion of the demonstration experiments on the ground and in space, we will select the target configuration for the commercial SSPS; microwave-type basic model, microwave-type advanced model, laser-type model, or others. The expected power cost and public acceptance will be the major trade off factors for the selection. Based on the space-verified technologies, we will be able to develop the pilot plant of 2 MW and 50 MW class SSPS, the initial practical model towards the commercial SSPS, in 2020's. This scenario guarantees the start of construction of the 1 GW class commercial SSPS in 2030's.

III. MICROWAVE POWE TRANSMISSION EXPERIMENT IN SPACE

After completion of the microwave power transmission experiment at 2.8 kW on the ground, we will be ready for a small-scale demonstration

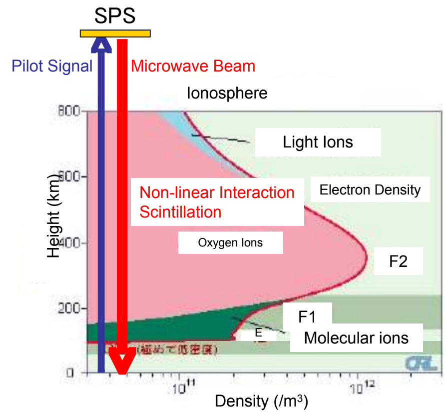


Fig.5 Possible interaction of the main beam and pilot signal with the ionospheric plasma.

experiment at the same power level from the low earth orbit to the ground. The experimental objectives will be;
(1) demonstration of the microwave beam control precisely to the target on the ground from the microwave 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, the 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 initial demonstration experiment. The weight of payload instruments will be 200 kg for the small satellite and 500 kg for the Space Station. An example of the microwave power transmission experiment from the small satellite is shown in Fig.6. There are two configurations in the experiment; transmission to the

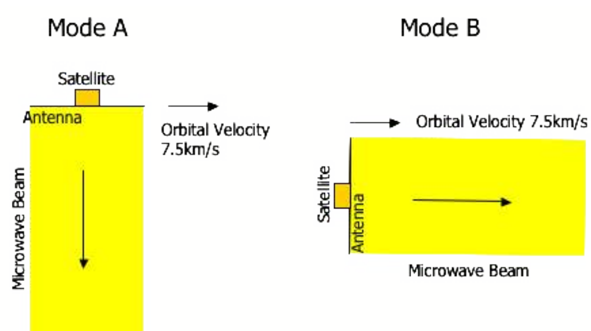


Fig.6 Two configurations of the demonstration experiment using a small satellite. The microwave beam is transmitted to the ground in mode A, while it is transmitted parallel to the orbiter velocity vector in mode B.

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

Mission	Period	1 year
System	Configuration	Power generation/transmission panel suspended by 4 wires
	Panel size	1.6m x 1.6 m x 0.02m
	Tether wire length	30 - 100 m
	Total weight	200 kg
	Attitude stability	±1°
Power generation	Thin film solar cell array	350 W (85 W/module)
Power transmission	Frequency	5.8 GHz
	Phase control	5 bit
	Number of module	4
	Beam control	Retro-directive/Computer control, ±10°
	Output power	950W/module, 3.8kW(total)
	Power density	1500,1000, 500, 100W/m² (at antenna) 1.9μW/m²(max, on ground)
Ground stations		JAXA ground stations International experiment sites

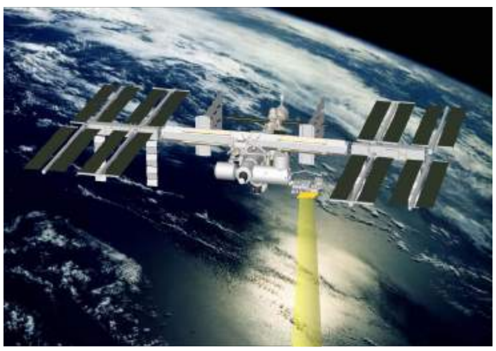


Fig.7 Microwave transmission experiment at 6.3 kW using the Space Station JEM.

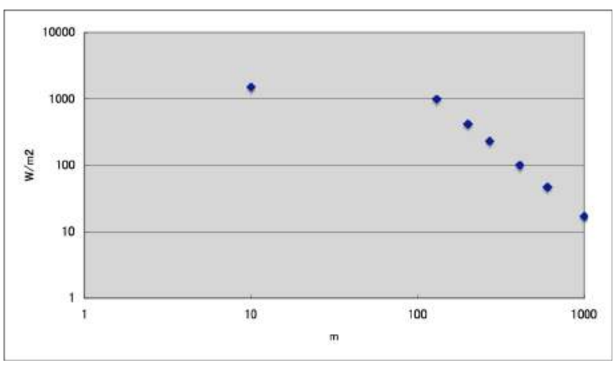


Fig.8 Microwave Power density in case of JEM experiment.

ground perpendicularly to the spacecraft velocity vector (Mode A) and transmission parallel to the velocity vector (Mode B). A power generation/transmission panel consisting of 4 modular panels, 1.6m x1.6m totally, similar to those on the ground demonstration

Table 2 Observable plasma effects in the two configurations.

			Mode A	Mode B
Direction of microwave injection			Ground	Orbital direction
Irradiation time on the same plasma segment			0.2 ms	10 ms
Research subject			Observation or experiment	
Ionospheric interaction	Plasma heating	F-layer electrons heating	Partially	Yes
		F-layer plasma depletion	No	Yes
		Lower ionosphere electrons heating Plasma density enhancement	No	No
	Thermal self-focusing	Electrons heating	Partially	Yes
		Plasma density depletion	No	Yes
	Self-focusing by microwave beam density gradient	Electrons heating, electrons density depletion	Yes	Yes
		Plasma depletion	No	Yes
	3-wave coupling	Back-scattering waves, plasma waves, electrons heating	Yes	Yes
Beaming technology	Beam direction control to a ground pilot station		Yes	No

experiment will be used to transmit a 3.8 KW power beam. The specification of the experiment for the small satellite experiment is summarized in Table 1. The experiment on the International Space Station as shown in Fig.7 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.

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.8.

The observable plasma effects 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 roll 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 is verified only in mode A configuration.

IV. LASER POWE TRANSMISSION EXPERIMENT IN SPACE

For the laser, a power transmission experiment at 10 kW level from the low earth orbit to the ground will be conducted. The experimental objectives will be;

(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,

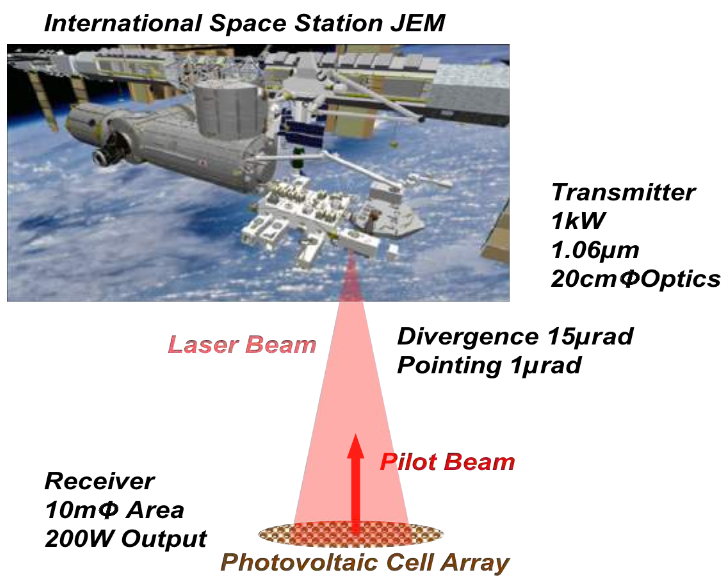


Fig.9 Laser power transmission experiment from the Space Station JEM.

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

(4) demonstration of laser safety for public acceptance.

Especially, item (2) is important, because on-orbit experiment is the best configuration to study the scattering of the laser beam in the atmosphere as shown in Fig.8. It is believed the scattering is mainly caused by the aerosol near or less than 1 μm existing below 10 km. Figure 9 shows a preliminary idea for the laser power transmission experiment from JEM. A 1000 W laser beam at 1.06 μm is transmitted 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.

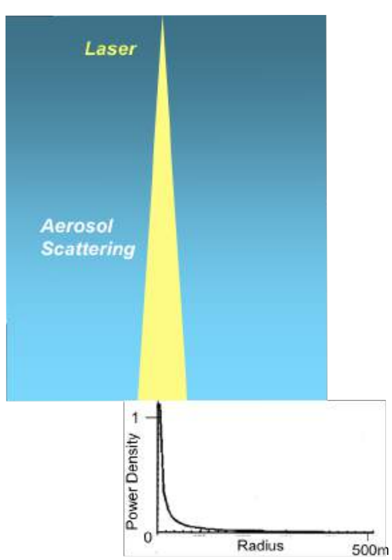


Fig.8 Expected laser scattering by aerosol below 10 km.

V. SUMMARY

As the first step towards the commercial SSPS, the ground demonstration projects both for microwave and laser started already. They will demonstrate the technologies for the wireless power transmission at kW level in the range 100-500 m. The technologies verified in the ground experiment will be used to conduct the next-step kW class demonstration experiments from the low earth orbit to the ground. A small satellite or the JEM/Space Station will be used for the experiments. Based on the results from the small-scale demonstration experiments in space, we will make a decision on the technology option, 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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