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Feasibility Study of a Large-scale WPT System Formed by a Modular Structure

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Abstract

This project is performing on the feasibility study of a large-scale wireless power transmission (WPT) system formed by a modular structure. Tethered solar power satellite (SPS) has been proposed in Japan 15 years ago. Since this proposal, many R&D activities regarding WPT have been performed on. This paper summarizes the original concept of the Tethered SPS and recent R&D activities in Japan. From these studies, the current unsolved issues of the Tethered SPS were identified. As one of the solutions for these unsolved issues, this paper introduces Digital retro-directive method, which is a new method explored in ISAS/JAXA. A phased array system was preliminary configured for demonstration experiment of this Digital retro-directive method. A basic test to control microwave obtained radiation patterns of this phased array system. Results of this test were nearly equal to numerical simulation results by CST studio. As a future work, unsolved issues of Digital retro-directive method should be confirmed or be solved by applying the latest technologies. Finally, this project will perform on demonstration experiment to verify the developed method and will promote the R&D for the large-scale WPT system formed by a modular structure.

Keywords: Solar Power Satellite, Wireless Power Transmission, Retro directive

Acronyms/Abbreviations

SPS	: Solar Power Satellite
WPT	: Wireless Power Transmission
RF	: Radio Frequency
GEO	: Geosynchronous Equatorial Orbit
LAN	: Local Area Network
MUSIC	: Multiple Signal Classification
ESPRIT	: Estimation of Signal Parameter via Rotational Invariance Techniques
REV	: Rotating Element Electric Field Vector
PAC	: Position and Angle method
DSP	: Digital Signal Processing
MSLL	: Maximum Side Lobe Level
HPBW	: Half Power Beam Width

1. Introduction

Recently, renewable energy being focused on as a solution for global issues such as global warming, energy, climate change. First concept of SPS was proposed as a huge renewable energy plant in 1968 [1]. This satellite is to generate a huge electricity from numerous photovoltaic cells and to transmit this energy continuously and stably to earth via microwave beam. The transmitted microwaves are converted back into the DC energy on the ground and supplied to the power grid. It is expected that SPS will become a huge clean energy source alternative to the traditional ones depend on fossil fuel energy and nuclear electric power in the near future.

Tethered SPS as shown in **Fig. 1** has proposed around 15 years ago. Tethered SPS is envisioned to have a modular structure to ensure the robustness, economical cost, and easy assembly. However, in the last 15 years, the R&D has progressed, and the related technologies have grown rapidly. The original tethered SPS needs to be revisited accordance with the latest developments and R&D progresses for SPS. Tethered SPS promising in Japan still has many issues to be solved for practical use such as WPT, ultra-light structure and economical cost. If the latest technology is applied to this SPS model, it may help clear up these unsolved issues and move development situation forward. Therefore, we are working on revising the requirements and design of the original model and rearranging the solved and unsolved issues. We are also challenging to summarize the latest technology such as communication field and to consider applying these technologies. These feasibility studies will promote the development of WPT system consisting of a modular structure such as Tethered SPS.

This paper describes an outline of a feasibility study to promote research and development of WPT systems with large-scale modular structures. The feasibility study is taking several steps as follows:

1. Summarizing the requirements and designs of WPT system for the tethered SPS,
2. Review of the recent WPT demonstration experiments and R&D activities in Japan,
3. Evaluation of issues solved and unsolved for large-scale WPT system,
4. Research on the latest technologies in communication field,
5. Promoting study and development of new WPT methods conducted at ISAS/JAXA.

Additionally, a basic WPT experiment was conducted in anechoic chamber. This experiment is a preliminary demonstration to challenge the unsolved issues identified in our feasibility study.

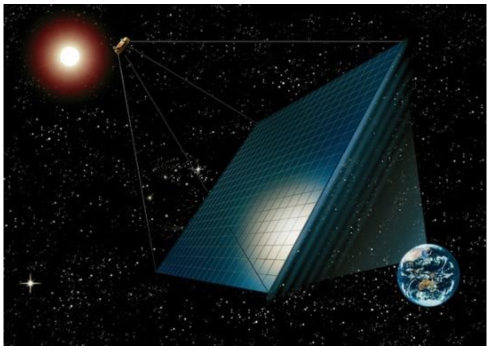


Fig. 1 Tethered SPS [J-spacesystems]

2. Summary of the original tethered SPS

The original concept of tethered SPS is summarized in this section. This concept was studied by a team organized by Institute for Unmanned Space Experiment Free Flyer (USEF) (current J-spacesystems).

In this model, a tethered SPS unit consists of 38,000 panels which have functions both power generation and power transmission (power generation/transmission panel) (see **Fig. 2**). A tethered SPS unit is suspended by four tethers from the bus system. These power generation/transmission panels have same specification and each panel is electrically independent. A huge WPT system about 2.5 square km consists of 625 tethered SPS units (see **Fig. 3**). This model has a relatively simple and robust structure, which contribute to the low-cost production and high reliability [2,3].

For the WPT system, the phased array antenna will control the microwave beam precisely. It is essential issue that numerous panels must synchronize the reference signal each other to achieve the highly accurate and efficient microwave control. Tethered SPS is envisioned to broadcast the reference signal with wireless LAN system from each bus system.

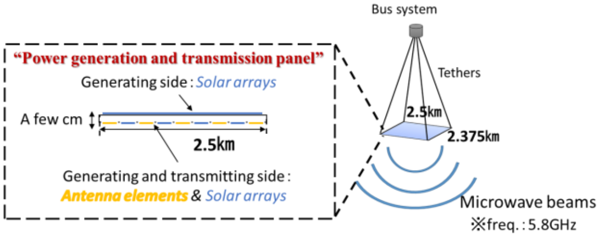


Fig. 2 Power generation and transmission panel

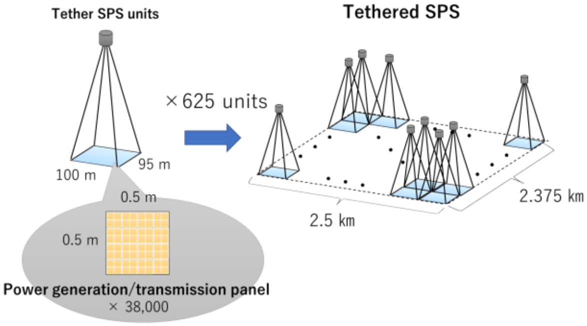


Fig. 3 Sketch of Tethered SPS model

3. Recent R&D activities in Japan

Various R&D activities regarding WPT have been performed on in Japan during the 15 years period since the birth of first Tethered SPS concept. Some demonstration experiments verified the effectiveness of recent technologies such as the retro-directive system, the direction-finding method, and phase-correction method. This section summarizes these recent and mainstream technologies with some demonstration experiments.

3.1. Retro-directive system

Generally, SPS needs to control accurately the microwave beam toward the receiving site on the ground. Especially, the transmitting efficiency of SPS depends highly on this accuracy to control the microwave beam. Therefore, the WPT system must have abilities to precisely estimate the direction of the target and to steer the microwave beam toward that target direction. Retro-directive system was developed to achieve these requirements. Retro-directive has possible to estimates the direction of the target using the pilot signal delivered from the target. The direction of the target is calculated by comparation between the reference signal and the phase values of the pilot signal.

Retro-directive system is roughly divided into two categories of the Hardware retro-directive method (see **Fig. 4**) and Software retro-directive method (see **Fig. 5**). The Hardware retro-directive makes phase-conjugation waves from the pilot signal by using circuits. These phase-conjugation waves are radiated from transmitting antennas and form the main beam to the angle of arrival of the pilot signal. Because of hardware processing, the Hardware retro-directive achieves fast beam control. However, functions such as security, safety, flexibility of frequency, and amplitude taper of radiation are poor. Amplitude taper can supress the sidelobe level and grating lobe level. On the other hand, the Software retro-directive detects the phase or amplitude of the pilot signal by computational algorithms alternative to the hardware circuits. Afterward, it turns the microwave beam toward the target direction by using phase shifters. This method has the separated functions such as the direction-finding and the beam forming. Because of these functions, the Software retro-directive method resolves the issues of the Hardware retro-directive.

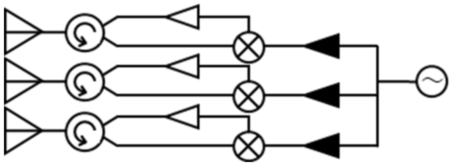
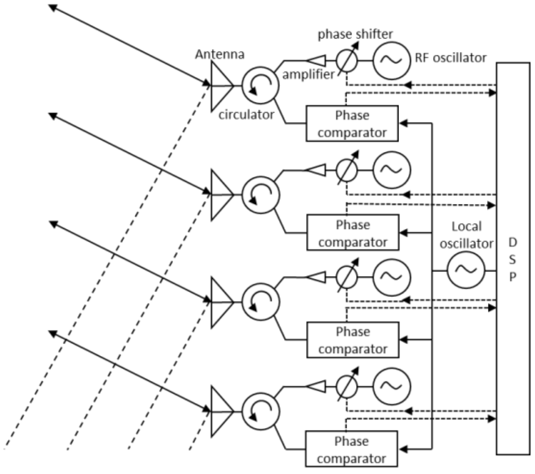


Fig. 4 Block diagram of a Hardware retro-directive [4]



*DSP：Digital signal processor

Fig. 5 Block diagram of a Software-retrodirective [4]

3.2. *Direction-finding methods and phase-correction methods.*

Table 1 shows the recent direction-finding methods being studied in Japan. Mono-pulse method is well known as direction finding method. This method has two types of methods such as the phase mono-pulse type and the amplitude mono-pulse type. They are often used in defence and space field [4].

The MUSIC [5] and ESPRIT [6] have potential to used for the software retro-directive method as an algorithm to estimate the angle of arrival of the pilot signal. It is also being studied as more accurate direction-finding methods as the traditional methods [4].

Regarding the SPS of very large structure in the crucial thermal environment, phase errors are occurred due to displacements of the antennas or the variation of RF characteristics. As refer to the precise controlling of the beam, correction of these phase errors among antenna elements must be required not only the direction-finding methods.

Table 1 presents some recent phase-correction methods in Japan. The REV method measures the amplitude of microwave by rotating 360 degrees of the phase. From obtained amplitude, it calculates the phase error. The PAC method estimates the position and angle of each transmitter panels via the pilot signal from the receiver site. Each transmitter panels correct own phase error from the reference panel. The parallel method transmits phase modulated microwave beam to receiver site. The receiver calculates phase errors between a reference panel and other panels from the modulated downlink. The receiver transmits back calculation result to each transmitter via pilot signal.

Table 1 Direction-finding methods and phase-correction methods.

Direction-finding method	Phase-correction method
Mono-pulse (phase/amplitude)	REV
MUSIC	PAC
ESPRIT	Parallel

3.3. *Demonstration experiments in Japan*

For demonstration experiments regarding the WPT, some Japanese institutes and organizations have performed on the experiments which verify the principle of such as retro-directive systems, the beam forming technologies and the phase-correction methods (see **Table 2**). The phase-correction method such as the PAC method and the Parallel method has been demonstrated in 2010 simultaneously. This demonstrations in 2010 achieved the accuracy to detect phase errors of pilot signals within 1 degree [7].

The horizontal WPT demonstration in 2015 [8] transmitted the power of 340 W to the receiver 55 m away from the transmitter. This experiment has proved the principle of the horizontal directional WPT using the amplitude mono-pulse method and the REV method. The frequency of the power signal and the pilot signal were 5.8 GHz and 2.45 GHz, respectively.

The WPT demonstration in 2019 [9] performed on vertical directional WPT toward an airborne drone with fully automated control of the microwave beam. This experiment has successful to transmit the power of 105 W and 42 W to 19 m and 30 m above the ground, respectively. For the retro-directive system, amplitude mono-pulse method and the REV method was used. The frequency of the power signal and the pilot signal were 5.8 GHz and 2.45 GHz, respectively.

For the next demonstration, WPT of long distance around 1 km to 5 km is currently being designed by J-spacesytems. This demonstration will verify beamform and power transmission toward the flying receiver [10].

Table 2 The past feasibility experiments of the WPT in Japan.

Ref.	Years	Description
[7]	2010	-PAC method
[7]	2010	-Parallel method
[8]	2015	-The horizontal WPT experiment -The software retro-directive -The amplitude mono-pulse method -REV method -76 subarrays (one subarray has 4 patch antennas) -Power signal frequency:5.8 GHz -Pilot signal frequency:2.45 GHz -Transmission power: 340 W (@ 55 m)
[9]	2019	-The vertical WPT experiment using the drone in outdoor -The amplitude mono-pulse method -The REV method -Power signal frequency:5.8GHz -Pilot signal frequency:2.45 GHz -Transmission power: 105 W (@19 m), 42 W (@30 m)

4. Unsolved issues

As shown in **Table 2**, the amplitude mono-pulse method and the REV method has been demonstrated its effectiveness for the WPT. However, these methods still have 2 essential issues should be resolved. These unsolved issues that our project focused on are phase and frequency synchronization and processing time.

With large-scale modular structure deforming its structure and rising its temperature, these factors will cause phase errors. These phase errors can lead to undesirable radiations and power losses of the phased array antenna. Therefore, the modular structure must adjust phases in a same value among electrically and physically independent modules. Additionally, the modular structure must have same frequency among the modules, not only the phase.

With large-scale structure as Tethered SPS, the phase synchronization should be done quickly among all equivalent modules. On the other hand, the REV method, and other methods in Table 1 requires the long processing time until it corrects phase errors of all modules. Due to this problem, the WPT system cannot track the target.

For one of the solutions of these unsolved issues, applications of the latest technology such as the communication field can be effective. As another solution, next section introduces the new WPT method installing on the digital signal processing in JAXA/ISAS.

5. New WPT method in ISAS/JAXA

This section introduces a new WPT method, Digital retro-directive method alternative to the Software and Hardware retro-directive [11]. For the SPS installed on the GEO, the required angle accuracy of the beam pointing is .0001°. However, the space environmental conditions will deform the structure of the WPT system and vary the characteristics of the devises mounted on. These causes can lead to the fatal phase errors. To correct these phase errors, the Software and Hardware retrodirective being focused on, while these methods have the issues such as no flexibility about frequency, long processing time and phase synchronization. The Digital retro-directive method can resolve these traditional issues.

5.1. The concept of the Digital retro-directive

Fig. 6 shows the concept of the Digital retro-directive method. This method generates a phase conjugation of the pilot signal by using DSP. Each set of pilot signal receiving antenna and power transmitting antenna work independently. Thanks to this, this new method does not need the phase synchronization among a huge number of antennas such as the Software retro-directive. However, the reference signal in a group consists of sets of a Rx and a Tx is required. There are flexibilities such as selection of frequency and control of the beam shape in this method.

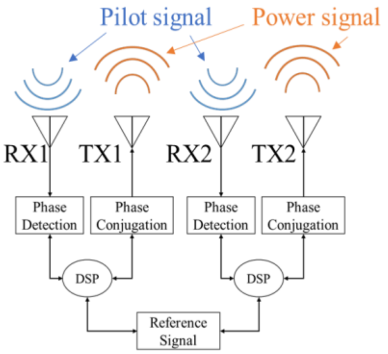


Fig. 6 Concept diagram of the Digital retro-directive

5.2. Demonstration of the new method and comparison of the past method

An experiment of the Digital retro-directive method [11] confirmed its accuracy of the beam pointing. In this experiment, 4 pilot receiving antennas using dipole antennas and 4 elements subarrays using microstrip patch antennas were used as shown in **Fig. 7**. Result showed that the beam pointing error of this WPT system was the 0.21° rms. This result achieved the goal of 0.98° which is 10 % of beam width [11]. Then, comparison was performed between the Digital retro-directive and the REV method. At the past experiment as described in chapter 3, the beam pointing error of the REV method was 0.15° rms [8]. Therefore, the new method is as accurate as the REV method is. However, the Digital retro-directive method has processed its calculation earlier than the REV method [11].

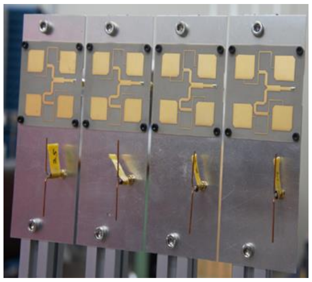


Fig. 7 Pilot receiving antennas and power transmitting antennas

5.3. Future works of the Digital retro-directive method

In the past demonstration experiment of the Digital retro-directive method, phase correction was performed on with antennas deformed forward and backward direction up to 0.8λ. This past experiment has not performed the angular deformation case yet. Therefore, the angular deformation case should be verified. Methods to provide the reference signal between groups of the Rx/Tx sets has been explored but are not enough yet. Therefore, our project is aimed at exploration, development, and demonstration of these issues by using the latest technologies in the communication field such as the GPS, MIMO, and wireless LAN.

6. Progress in demonstration of Digital retro-directive.

As a preliminary experiment for the demonstration of the new phase detection and phase conjugation method, the experiment to control beam by using high power amplifiers and phased array antenna. was conducted. This basic WPT experiment showed that this experimental setup can perform basic beam controls.

6.1. Experimental setup and conditions

This experiment was performed in the anechoic chamber in AMETLAB at Kyoto university. The power transmitting section was put on the turn table to measure the azimuth pattern of the range from -90° to 90° (see **Fig. 8**). The transmitting section consists of a 25 dB boost amplifier, power divider, RF controller board, and array antenna board (see **Fig. 9**). The power divider divides input power to 8 RF boards. A RF board consists of 4 groups of a power amplifier and a phase shifter. The array antenna board consists of 32 subarrays. One subarray has 4 microstrip patch antennas. Between antenna elements and RF boards, a 30 dB attenuator is inserted. The output power of a power amplifier is around 3 W. For the phase synchronization among 32 elements, all feeding networks were setup in same length. The horn antenna received the radiation from the transmitting section with the distance 7.2 m away (see **Fig. 10**). The azimuth direction of far-field radiation pattern was acquired with NSI 2000.

The main beam direction was steered to 0, 5, and 10° by controlling the phase sifters via SPI serial bus communication. The input power to the transmitting section was 12.7 dBm. For the phase synchronization among 32 elements, manual phase calibration by vector network analyser (VNA) was done. The signal frequency was 5.8 GHz.

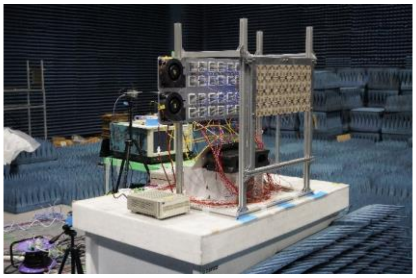


Fig. 8 Power transmitting section

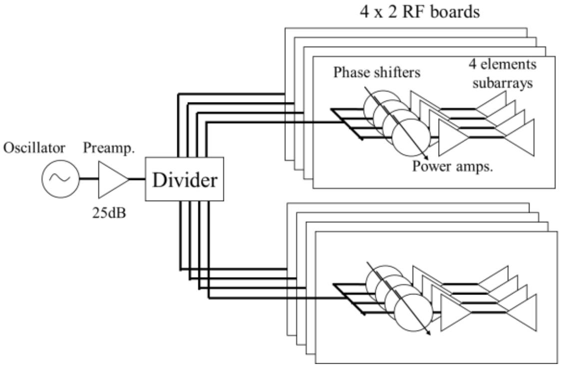


Fig. 9 Block diagram of the phased array system

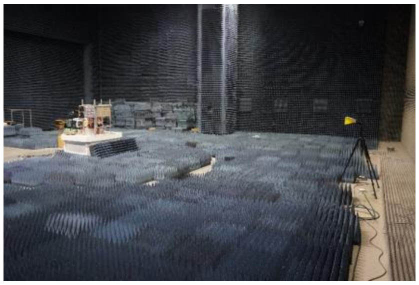


Fig. 10 Measurement system

6.2. Results, numerical simulations, and discussions

Figures 12, 13, and 14 presents the results of measured radiation pattern with the beam steered toward 0°, 5°, 10° By using the software of the CST studio, numerical electromagnetic field simulations are presented. The numerical analytical model of the phased array system is shown in **Fig. 11**. These results are shown in **Fig. 12,13, and 14**. Comparation between the experimental results and numerical results were performed. This simulation ignored the mutual couplings among antenna elements. **Table 3, 4, and 5** presents main lobe direction, MSLL, and HPBW of each result of the test and the CST, respectively. According to these comparation, these simulation results was nearly equal to the actual measurement radiation pattern. Therefore, this experiment has confirmed the ability to control the microwave beam.

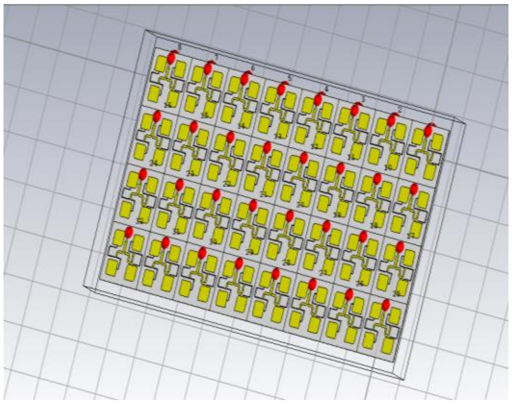


Fig. 11 Numerical simulation model

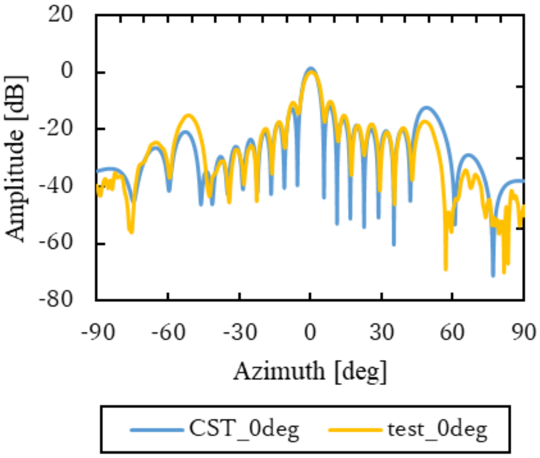


Fig. 12 0° beam steering

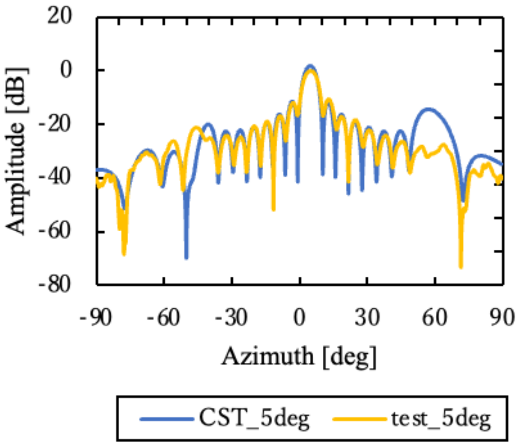


Fig. 13 5° beam steering

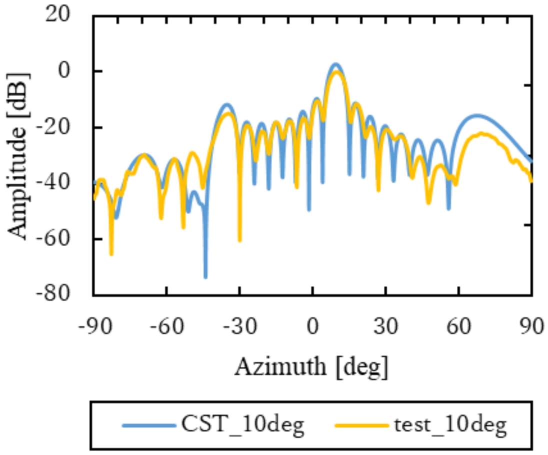


Fig. 14 10° beam steering

Table 3 Comparation for actual and analytical values for 0° beam steering

	Test	CST	unit
Main lobe direction	0.30	0	deg.
MSLL	-10.38	-14.2	dB
HPBW	5.704	5.1	deg.

Table 4 Comparation for actual and analytical values for 5° beam steering

	Test	CST	unit
Main lobe direction	5.0	5.0	deg.
MSLL	-10.58	-13.6	dB
HPBW	5.701	5.1	deg.

Table 5 Comparation for actual and analytical values for 10° beam steering

	Test	CST	unit
Main lobe direction	9.80	10.0	deg.
MSLL	-10.39	-12.6	dB
HPBW	5.75	4.9	deg.

6.3. Future works

This experiment showed that the setup of the phased array antenna has ability to control the microwave beam. This setup is available for the demonstration experiment for the Digital retro-directive method. For one of the future works, the influences on the beam pointing of angular deformation case of the Digital retro-directive should be confirmed. As another future works, this project investigates and develops a new method to synchronize the reference signal between retro-directive system by using the latest technology such as GPS. After that, demonstration of a new method will be done.

7. Conclusion

This paper presented an overview and progress of the feasibility study of a large-scale WPT system with modular structure conducted by our project. Chapter 2 summarized the original concept of Tethered SPS explored in Japan. Chapter 3 reviewed the recent technologies and R&D activities in Japan. This review confirmed Software retro-directive, REV method, and amplitude mono-pulse method are focusing on. Chapter 4 clarified the unsolved issues of the WPT system formed by a modular structure. The current retro-directive system has two big issues such as phase synchronization and ling time processing. For one of the solutions, this paper introduced Digital retro-directive method as a new system being developed in ISAS/JAXA. This new method achieved the accurate control of microwave beam in the past demonstration. With the processing time shorter than the REV method, its accuracy is nearly equal to that of the REV method. For moving this new method forward, the WPT system toward demonstration experiment was setup in this project. This WPT system preliminary performed the basic experiment to beam and control the microwave. By comparation between the obtained radiation pattern and numerical simulation, the nominal operation of this WPT system was confirmed. As future works, this project will explore the issue of the Digital retro-directive. Then, solution for these issues will be developed. Finally, the demonstration experiment of this new method will be performed on and promote the R&D for Tethered SPS.

Acknowledgements

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