Solar Power Satellite and its EMC Issues

Kozo Hashimoto[#1] and Naoki Shinohara[*2]

Research Institute for Sustainable Humanosphere, Kyoto University
Gokasho, Uji, Kyoto 611-0011, Japan

[1]kozo@rish.kyoto-u.ac.jp

[2]shino@ rish.kyoto-u.ac.jp

Abstract— **The solar power satellite (SPS) which attracts attention as CO_2 free clean energy is introduced and the examination of interference by SPS are discussed**.
Key words: Solar Power Satellite, Microwave power transmission, Electromagnetic interference, Clean energy.

I. Introduction

Solar power satellite (SPS) attracts attention as clean energy which does not take out CO_2 and can solve an environmental problem and the energy problem of drain of a fossil fuel. Efficiency is much higher than the solar power placed on the ground as a base power supply which can be supplied for 24 hours. An essential technology for SPS is microwave power transmission (MPT). The outline of SPS, MPT, and the interference issues by the SPS are introduced.

II. Microwave Power Transmission and Solar Power Satellite

Table I shows CO_2 emissions per unit electric power from various plants [1]. Although the emission from SPS are calculated based on below-mentioned NASA/DOE Reference Model, it is as few as that from a nuclear power plant. In breeder scenario which builds SPS with the electric power made from SPS, it becomes half of that.

TABLE I
CO_2 Emissions per Power from Plants [2]

CO_2 Emissions From Alternative Electric Power Generating Systems (G CO_2/kWh)

Generating system	Operations	Construction	Total
SPS (baseline scenario)	0	20	20
SPS (breeder scenario)	0	11	11
Coal[b]	1,222	3	1,225
Oil[b]	844	2	846
Liquefied Natural Gas (LNG)[b]	629	2	631
Nuclear power[b]	19	3	22

Notes: the SPS-breeder scenario is discussed in Section V; and estimates for these power generation methods are given in [13].

Brown wrote the history of MPT in 1984 [3]. Tesla has tried and failed in wireless power transmission by a 150 kHz radio wave in the 1900s. It became full-scale after high power microwave tubes were available at the postwar period and Brown made a large contribution to MPT. He succeeded in the first demonstration of MPT to drive a dc motor attached to a fan by 100 W of dc power retrieved from 400W CW power generated by a magnetron in 1963. He invented rectenna (= rectifier+antenna) which changes microwave into a direct current directly and made a microwave-powered helicopter flight in 1964. He also demonstrated a system where the overall efficiency from dc power into a magnetron generator to dc power output of the rectenna was 54%. The conversion efficiency of rectenna could reach up to 90% [3]. Over 30 kW of dc power was transferred over one mile (1.6 km) from a parabolic antenna for the satellite tracking of the JPL (Jet Propulsion Laboratory) Goldstone Facility.

Matsumoto [4] introduced in 1995 early history, Japanese experiments of microwave power transmission, the rocket experiment on an interaction with the microwave in the ionosphere, its theoretical analysis and computer simulations, a microwave driven airplane, and some other Japanese microwave power transmission experiments.

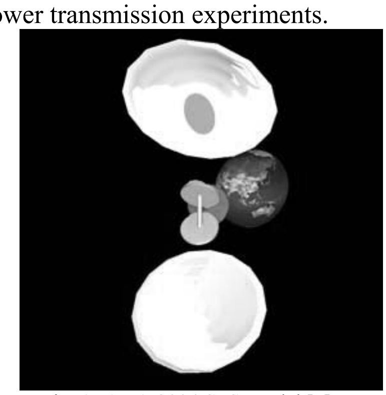


Fig. 1 JAXA 2004 SPS Model [7]

The SPS concept was proposed by Glaser in 1968 [5] based on the result of the microwave power transmission (MPT). Then, NASA performed examination about SPS in collaboration with the U.S. Department of Energy (DOE), and made the famous reference model [6]. A satellite with solar cells (10 km x 5 km) is launched to a geostationary orbit and 7GW microwave of 2.45GHz is transmitted from an antenna with a diameter of 1 km. On the ground, 5-GW direct current power is obtained by a rectenna site with 10 km in diameter. Although it was planned to provide all the U.S. electric power by 60 SPS's, it was too huge to realize this. Recent typical SPS model are 1 GW output at a frequency of 5.8 GHz band with transmission and reception antennas of about 2 km in diameter as an example shown in Fig. 1 [7].

URSI (international union of radio science) published White Paper on Solar Power Satellite (SPS) Systems in 2007, which is the first white paper of URSI. It consists of the text summarized by Board and Report of the URSI ICWG (Inter-commission working group) on SPS which describe details, and opens to the public in the URSI homepage [8]. Activities on MPT and SPS in Japan, US, and Europe are reviewed. Typical SPS parameters are shown in Table II.

TABLE II
TYPICAL SPS PARAMETERS

Frequency	5.8 GHz	2.45 GHz
Output Power	1.3 GW	6.72 GW
TX antenna diameter	1.93kmϕ	1.0 kmϕ
Amplitude taper	10 dB Gaussian	
Max TX power density	114 mW/cm^2	2.2 W/cm^2
Min TX power density	11.4 mW/cm^2	0.22 W/cm^2
Antenna spacing	0.75 λ (3.9cm)	0.75 λ (9.2cm)
Power per one antenna	Max 6.1W	Max 185 W
Number of elements	540 million	97million
Rectenna diameter	2.45 kmϕ	10 kmϕ
Max power density	100 mW/cm^2	23 mW/cm^2
Max electric field	614 V/m	294 V/m
Collection efficiency	96.2 %	89 %

III. INFORMATION ON MICROWAVE POWER TRANSMISSION

In microwave power transmission, the collection efficiency, that is, the ratio of received power to transmitted power, is important. Fig. 2 shows the collection efficiency, η as a function of τ, where the square root of the product of the areas of transmitter and receiver antennas is divided by the product of the wave length and propagation distance [2]. The square of τ can be represented as follows:

$$\tau^2 = \frac{A_t A_r}{\lambda^2 D^2} = \frac{P_r}{P_t}$$

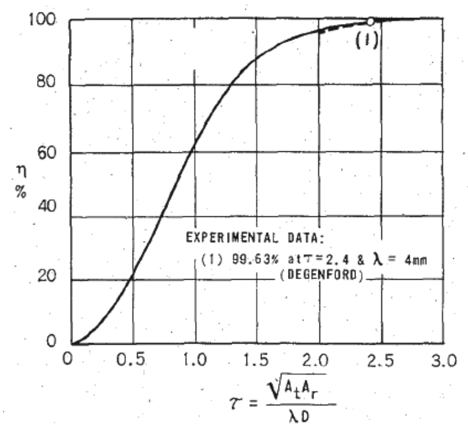


Fig. 2 Collection efficiency as a function of τ [2]

Although the right equation is the ratio of the received power to the transmitted power according to Friis transmission formula, the former should never exceed the latter. This inconsistency occurs since the formula is valid only in small τ. High efficiency is obtained in large τ though.

Such high efficiency is not obtained by uniformly excited antenna elements. The optimal power density distribution across the antenna aperture is approximated by Gaussian distribution in many cases. An example of the power distribution in the receiving point in one dimension at the time of Gaussian distribution is shown in Fig. 3. As a beam width is wider, the first sidelobe level is lower than -13dBc at the time of uniform excitation and the electric power concentrates on the main lobe.

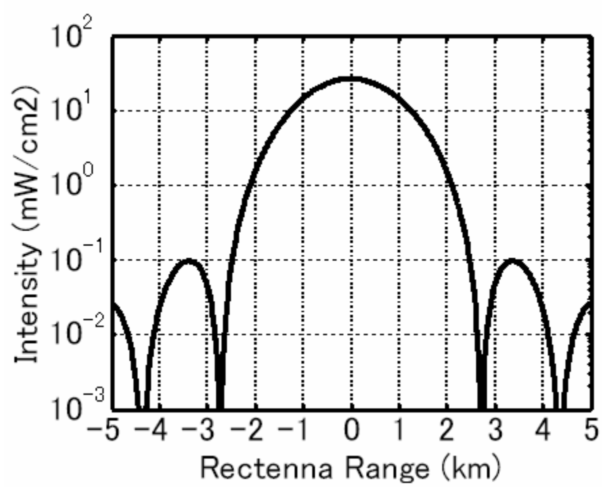


Fig. 3 Example of power distribution in a receiving point [8]

The interference problem committee under the JAXA (Japan Aerospace Exploration Agency) SSPS (Space Solar Power Systems) committee examined interference issues of SPS [10]. Although the contribution document which asks for the extension of Question ITU-R210 / 1 (Wireless Power Transmission) which was due to end in 2005 was submitted to ITU (International Telecommunications Union)-R WP (Working Party) 1A through JAXA as a sector member in 2004, then it did not discussed as premature. The contribution document which includes the summary of interference examination by the committee was submitted to ITU-R WP 1A as a contribution document 1A/81-E which asks for the extension of the Question in 2005, and we succeeded in the extension [9].

The characteristics of MPT based on the response to the Question are as follows.

1) *What are the technical characteristics of the signal employed in wireless power transmission?*

It is fundamentally CW (carrier wave) with no modulation and is changed into a direct current in the power receiving site. A demonstration satellite will transmit rather weak power to the ground and evaluate the beam steering. Modulation might be necessary in order to increase the bandwidth if the PFD (power flux density) regulation exists.

2) *Under what category of spectrum use should administrations consider wireless power transmission: ISM, or other?*

Although the 2.45 GHz and 5.8 GHz ISM (industry, science, and medical) bands have been usually used for MPT experiments so far, no bands have yet been assigned to MPT and these experiments were licensed as experimental stations to our knowledge. Although the ISM bands are fundamentally suitable, the 2.45 GHz band (2400 to 2500 MHz) are allocated and widely used for IEEE 802.11 wireless LAN, and 5775 to 5845 MHz among the 5.8 GHz band (5725 to 5875 MHz) is allocated to DSRC (dedicated Short Range Communications)/ ETC (electronic toll collection system) and frequencies above 5850 MHz are assigned to relay broadcasting (FPU: Field Pick-up Unit).

3) *What radio frequency bands are most suitable for this type of operation?*

SPS system transmits the microwave to the earth from a geostationary orbit. Since its efficiency is essential, frequencies must be in the radio window (1 to 10 GHz). Although higher frequency is better for smaller antennas, rain attenuation must be taken into consideration at frequencies higher than about 6 GHz. Although the ISM bands are basically suitable frequencies for SPS, frequency bands other than the ISM bands should be included as suitable bands since they are used worldwide as shown above. Frequencies higher than 10 GHz are also suitable for MPT applications other than SPS.

4) *What steps are required to ensure that radio services are protected from power transmission operations?*

Although frequency interference issues are discussed in the next section, it is necessary to continue and extend such discussions.

5) *What effects would wireless power transmission have on radio propagation?*

From the safety to biological objects, power density is limited to less than 100 mW/cm^2 at the center of the receiving site, where the density is maximum. No effect on radio propagation is not known at this level although further experimental evaluation is required.

IV. Frequency Interference Issues

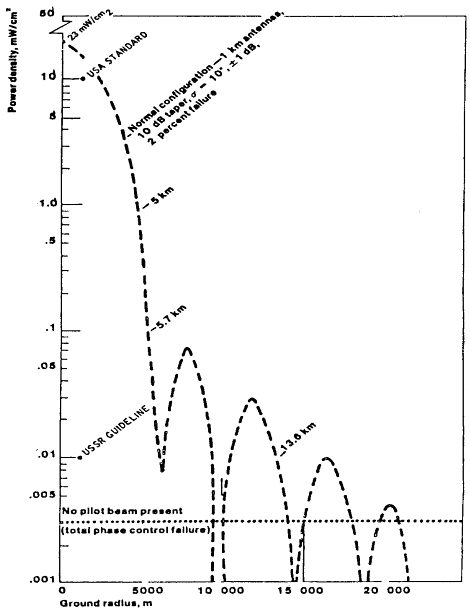


Fig. 4 Power flux density characteristics on the ground in the NASA/DOE reference model.

Fig. 4 shows the power-flux-density characteristics in the ground in a NASA/DOE reference model. Since 10 dB Gaussian type power density distribution is applied to the elements of a power transmission antenna for improvement in collection efficiency, the maximum power flux density at the center is 23mW/cm^2 and the first sidelobe level is as low as 0.1 mW/cm^2 (-25dB**c).** The power density at the edge of the receiving site with a distance of 5 km from the center is 1 mW/cm^2 (61.4 V/m) which is the safe level and the area inside the edge is restricted.

The contribution document [9] submitted to ITU-R includes interference examination by JAXA [10]. The transmitting frequencies are assumed to be the 2.45 GHz and 5.8 GHz ISM bands. A stabilized magnetron is one of dominant candidates of SPS power sources because of its high efficiency. Spurious noises and harmonics generated from a DC-powered magnetron are reported to be less than -75 dBc if its filament is turned off [11] as shown in the thick line of Fig. 5. The measured values of harmonics of the magnetron are used for the evaluation; 2nd harmonic: -55dBc, 3rd: -80dBc, 4th: -70dBc, 5th: -75dBc. Bandwidth is assumed to be 1 MHz at the fundamental frequency. Phased array antenna is assumed.

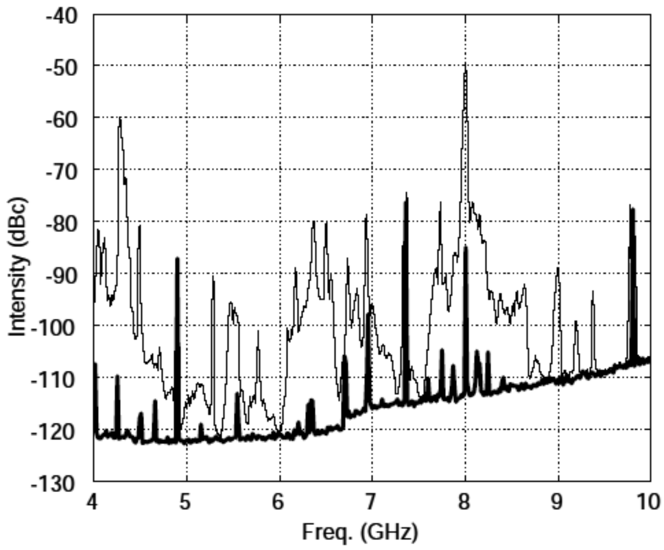


Fig. 5 High frequency spurious spectra of a stabilized magnetron. Thin line: filament on and thick line: filament off. [6]

Interferences with other radiocommunication services are examined.

1) 5 GHz and 11 GHz microwave relay system

When phases are controlled in the same manner as the fundamental frequency, interfere could occur. It can however be compatible when phases become random and directivity is omni-directional. Filters or phase shifters must be devised.

2) Allowable levels of in-band interference for radar

ARSR (air route surveillance radar, 1.3-1.35 GHz), ASR (airport surveillance radar, 2.7-2.9GHz) and MR (meteorological radar, 5.25 ～ 5.35GHz) are covered. Compatibility conditions are input power of 100 mW in which the TR limiter (high electric power input prevention) operates and an allowable interference level in a band; -112 dBm, -108 dBm, and -116 dBm for ARSR, ASR, and MR, respectively. Coexistence is possible at the distance of several kilometers from a radar.

3) The PFD limit of communication between space and ground

10.7-11.7 GHz and 11.7-12.5 GHz bands overlap the 5th harmonic of 2.45 GHz (12.25 GHz) and the second harmonic (11.6 GHz) of 5.8 GHz. The power flux density (PFD) is limited at these frequencies. It can be compatible when phases become random and directivity is omni-directional.

4) Comparison between radio astronomy bands and harmonics of the ISM bands

If the SPS frequencies are allocated to the 2.45 GHz ISM band, the second and the ninth harmonics may overlap with radio astronomy bands (4.8-5.0 GHz and 22.1-22.5 GHz). It is expected that the interference level at around 4.9 GHz is higher than the harmful interference threshold (Rec. ITU-R RA. 769). If SPS uses the 5.8GHz band, radio astronomy bands lower than 76 GHz are not affected by its harmonics. Harmonics of the 2.45 GHz and the 5.8 GHz bands, however, overlap the 76-116 GHz radio astronomy band [9]. Experimental evaluations would be necessary in such high frequencies.

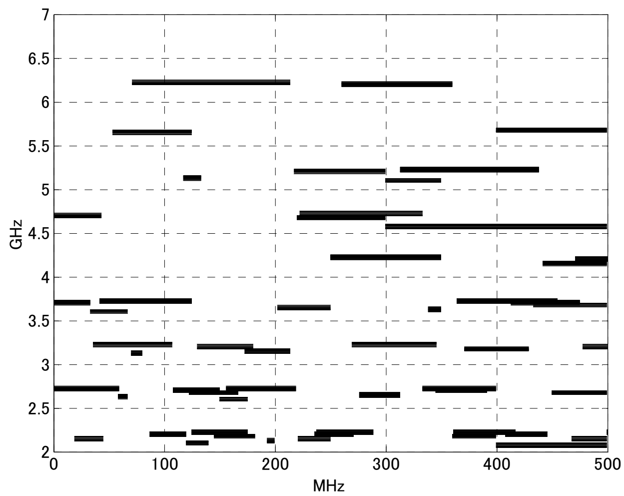
5) Radio LAN (IEEE802.11b, 2400-2483.5 MHz)

If frequency difference is more than 20 MHz, a D/U ratio is higher than 60dB. This is valid however only if the intensity of the interference is lower than the allowable level of a receiver and not valid if it is much higher than IP3 of a RF stage.

6) Broadcast relay, FPU: Field Pick-up Unit

Coexistence with B band FPU is impossible in the same area.

Fig. 6 Frequencies whose harmonics are in radio astronomy bands.



Interference to microwave radio astronomy bands (4.8-5.0, 10.6-10.7, 15.35-15.4, 22.21-22.5, 23.6-24.0, 31.3-31.8, 42.5-43.5, 76-116 GHz) is examined for SPS frequencies of 2-7 GHz as shown in Fig. 6. It is found that frequencies whose harmonics are not in the radio astronomy bands are 4543-4720, 5000-5117, 5133-5217, 5438-5525, and 5625-5900 MHz. Since the band of 76 to 116 GHz is too wide, harmonics of frequencies lower than 40 GHz overlap.

The maximum power density of 100 mW/cm^2 shown in Table II is a lowered result based on comments of biomedical specialists. This value is (happens to be) equivalent to the power flux density of the sunlight on the ground.

V. Conclusion

EMC problems cannot be bypassed towards realization of SPS. The outline of SPS is explained and its characteristics and present state of the examination on interference issues with other communications and radio astronomy were examined.

Acknowledgments

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