Technology developments relevant to Solar Power Satellite System (SSPS) design

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Roles of radio waves in communication and energy systems in comparison with wired systems. Also, the concerned companies in Japan are listed to show the territories.

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1. Introduction

• A Space Solar Power System (SSPS) is a green and everlasting power station, and could be cost-competitive with atomic power generations.

• A solar power satellite (SPS) generates the electric power using huge solar cell panels.

• Transmitted from a transmitting antenna, a spacetenna, via a beam of microwave to the rectenna.

• The system is connected to a commercial power grid, as is like a power plant in space.
Space solar power system and connection to a power grid.

Solar power satellite (SPS) - Sapcetenna - Microwave beam - Rectenna - Interfacer - Power grid - Customer
• An SPSS needs component technologies to enable its long and steady operation in a harsh environment of space.

• The technologies of launching to, and assembling in space are inevitable. Those factors are relevant to the field of Wireless for Space and Extreme Environments.
2. **The System Configuration of Space Solar Power System (SSPS)**

- The satellite in the final stage: in the geo-synchronous earth orbit (GEO). 36000 km above the equator.
- The satellite revolution is synchronous to the earth's rotation. seen at the fixed angle from the rectenna.
- Great advantage as a basic power source.
- The satellite in the technology verification stage: in a low earth orbit (LEO). at the altitude of 600 to 1000 km and is not restricted over the equator.
- The satellite moves fast over the rectenna in 20 minutes at longest.
- The advantage: the microwave beam on the ground is small. the satellite can be much smaller than GEO case.
Geo-synchronous earth orbit (GEO) and a low earth orbit (LEO)

Unit: km

Sun light
SPS Reference System (NASA illustration)
Receiving station on the earth (rectenna).

5km diameter : GEO SPS with the 1km spacetenna, 1km diameter : LEO SPS with the 50m spacetenna.
• Various system models have been proposed.
• NASA's Reference System, a constellation model, and a tethered model are GEO satellites.
• SPS 2000 model is a LEO satellite.
Constellation model
3. Necessary technologies for SSPS and their maturity

1. An SSPS is huge in size and weight.
2. The microwave beam should be extremely narrow in order to put most part of the transmitted power into a receiving antenna (rectenna). $8.0 \times 10^{-3}$ degree.
3. Attitude control is needed: At least, the spacetenna should point to a rectenna on the earth. Preferably, the solar panels face to the sun to obtain the highest solar power generation.
4. High power at microwave frequency should be rectified. Several GW.
5. The generated power should be poured into the grid.
6. Launch cost should be greatly reduced. Presently, 10,000 USD / kg.
Size relation between a radiated beam and a receiving antenna

(a) SSPS

(b) Communication and radar

Solutions for narrow beam

• A large antenna is needed.: $\lambda$/diameter
  
  In the reference system of NASA, 1km diameter, 200 million radiating elements in an array.
  
  cf. World-largest antenna: Puerto Rico, 305m diameter.

• To overcome the limitation due to mechanical structure.

• Antenna construction procedure:
  
  launch $\rightarrow$ deploy $\rightarrow$ assemble
• Component technologies of an SPS:
  - solar cells to generate electric power from sun light,
  - conductor bus from solar cells to an inverter,
  - converts the generated DC power to microwave,
  - transmitting antenna (spacetenna),
  - pointing of the spacetenna,
  - attitude and direction control of the satellite,
  - communications between the satellite and the ground,
  - mechanical structure and assembling,
  - launching of the space segments.
• Component technologies of a rectenna:
  - receiving antenna,
  - rectifying devices and combiners,
  - converter of the microwave power to DC or AC power,
  - interface circuit between SSPS and commercial grid.
Maturity of technologies

The evaluation of **maturity** may be defined by the following factors.

- Factor #1: Basic physics of a technology.
- Factor #2: Application to existing systems.
- Factor #3: Application to SPS.

And expressed as its reversed expression, **difficulty**.
#1: Incompleteness of physics verification
#2: Difficulty of application in other easy systems
#3: Difficulty of application to SPS

(a) Transmit antenna

(b) Formation flight
Explanation for the meanings of judgement

(a) Transmit antenna
• Principle of antenna behavior is well known so that Difficulty #1 is low.
• Difficulty of application #2 is low as small antennas are widely used in the fields of communications or radars.

(b) Formation flight
• Physics verification of two body system to keep Sun- and earth-pointing is not complete yet (#1).
• Difficulty of application #2 is low as asynchronous formation flights of small satellites are used in Global Positioning System.
#1: Incompleteness of physics verification
#2: Difficulty of application in other easy systems
#3: Difficulty of application to SPS

#3: Environment should be kept clean against much fuel consumption.

(e) High power amplifier

(f) Cheap and harmless rocket
4. Example technology - Antennas

NASA's reference system needs 200 million dipoles. Each dipole is \( \lambda/2 \) in length, and \( \lambda/4 \) in height. It is impossible to fabricate.

Solutions for simplification and mass-production of antennas

1. Radiating element
   - ULPD
2. Feeding
   - Partial drive
   - Uniform excitation
3. Folding structure
4. Antennas by the other institutions
5. Measures against emergency
The array antenna adopted in the reference system of NASA (half wavelength dipoles in an array).
1. Radiating element
- Ultra Low Profile Dipole (ULPD)


- Formerly, most antenna researchers told that a dipole antenna in a proximity of a reflector does not radiate a radio wave.
- Common sense: The radiations from a real dipole and the image dipole with opposite phase cancel each other.
- ULPD in Fig.1. Studied the electromagnetic field distribution around the antenna and antenna characteristics by simulation and experiment.
Fig. 1 Model of a horizontal dipole placed a distance $h$ above a perfect electric conductor (PEC) plane.

Fig. 4 ULPD configuration and the experimental setup for its measurement.
Practical ULPD with one port
A quarter wavelength branch was replaced by a parasite.

Fig. 6 Measured and computed radiation patterns of a constructed antenna. The maximum gain is 8.4dBi (measured) and 8.9dBi (calculated).

- This is against common sense.
- Confirms the prediction by John Kraus.
Fig. 10 Formation of electric field lines for a dipole antenna and its image corresponding to the quadruple mode

- The field distribution around the dipole behaves as a quadruple mode instead of two dipole modes.
- Two dipole modes persistent to a real and image dipoles do not make radiation in total.
  - (a) $t = 0$
  - (b) $T=4 > t > 0$. 
2. Feeding
- Partial drive

• Formerly, side-by-side coupling between elements was considered wrong, and to be avoided. - Common sense!

• Proposal: to excite some elements and leave the remaining parasitic.

• This design takes advantage of the inter-coupling among elements to simplify feeding, and has potential for a new class of antenna arrays.

• Moreover, trial is being pursued to make the antenna in a flat configuration using printing technology.

Figure 1 Antenna model with configuration parameters 2S and d

Fig. 3 Configuration of a unit array antenna with one driven and two parasitic elements.
Fig. 6 Computed radiation patterns of the unit array antenna \((h = 0.63\lambda, d = 0.60\lambda)\) with measured patterns.
2. Feeding
- Uniform excitation

- Conventionally, antenna elements were excited to generate a desired beam adjusting each element’s amplitude or the gain of an attached amplifier.
- However, this approach is expensive and cumbersome.
- Instead, the element spacing can be used to realize the equivalent field distribution to the conventional one.
- The benefit is uniform gain of amplifiers and extreme reduction in power requirements, making the realization of large arrays practical and more suitable for mass-production.
Fig. 2 Realization of an arbitrary field distribution on an aperture in an array antenna

(a) Conventional design: Uniform separation and field-dependent excitation.
(b) Proposed design: Uniform excitation and field-dependent separation

Amplifier gain should be adjusted. This work is a heavy task, and raises the antenna cost.
Non-linearity of an amplifier and its operation range.

- The generation of harmonics and power loss.
- An edge taper causes low element excitation in the central part and back-off in the periphery.
- Power loss and eventual generation of electric heating.
3. Folding structure
- Multiple folding and phase compensation
Traditionally, antenna designers endeavored to make a flat plane in the deployed state in using array panels. For this purpose, special hinges with large spatial margin and special rotational operation were required to address the panel thicknesses. This is due to the lack of collaboration between antenna and mechanical engineers.

Proposed: phase compensation. By this technique, the folded volume can be made very small and the number of panels is not limited. A large deployable antenna, 10 m diameter, can be fabricated as part of 1km diameter antenna for microwave power transmission.
Fig. 1 Configuration of a deployable phased array antenna with nine panels.

(a) Deployed state (plane view)

(b) Folded state (side view)
Fig. 2 Outlook and the deployment procedure of the proposed antenna.

This novel scheme allows steps between panels using vertical plates and usual hinges.

Fig. 5 Phase compensation principle for the level difference between two panels.

- The steps must be compensated electrically. The phase of each element is adjusted according to step sizes as well as the desired beam direction.
Fig. 4 Computed radiation pattern

4. Antennas by the other institutions

CASSIOPeiA Phased Array Antenna

Talk given by Ian Cash for the CASSIOPeia Power Beaming Phased Array,
presented at the 2017 Wireless for Space and Extreme Environments conference (http://sites.ieee.org/wisee-2017) -
Concordia University, Montreal, October 2017.
Comments : Merits

• The radiating unit has an excellent radiation characteristics of horizontal uniformity.
• The array with the radiating units of horizontal uniformity can shift the beam to any horizontal direction.
• At any direction, some of the rows can be seen due to various setting angles.

Comments : Demerits

• Three radiating elements form a radiating unit, and the separation between the elements is not $\lambda/2$ but $\lambda/4$.
• Therefore, the element number is 2 x 3 times larger than the normal array antenna.
5. Strategy for R&D and commercialization

5.1 Technology

- Maturity of key technologies is important, and determines a system concept.
- System-peculiar or difficult technologies should be studied at the first stage.
  e.g. Antennas, constellation accuracy, tether handling.

5.2 Finance

- Final commercial satellite may be quite expensive.
- Initial cost for R&D and halfway verifications can be quite small amount.
- Stepwise financing and judgement.
- Collaboration between space agencies and electric power companies.
Fig. 9 Gantt chart (personal plan)

- Basic research
- Technology proof on the ground
- Verification of a narrow beam management in orbit
- Operation
- Verification of power transfer in orbit
- Operation
- Commercial SPS
- Operation

△: Judgement
• Before proceeding to the next step, solutions of technology issues are judged.
• If the issues are not solved, promotion to the next step is prohibited. The outreach of technologies developed in the former step should be considered.
• In general, the money in the next step is several to several 100 times more than that in the former step.
• In the initial stage, it is not necessary to demand an extraordinary amount of budget.
• Technology proof on the ground and in-orbit test #1 should be carried out mainly by space agencies.
• In-orbit test #2 should be carried out mainly by electric power companies.
7. Conclusions

- Necessary technologies for Space Solar Power System (SSPS) were clarified with the indices of difficulty (maturity).
- Several technologies have severe difficulty, and may affect system design of particular SSPS models.
- The accomplishments of antenna research were explained at the present stage.
- Surprisingly, antennas had not been deeply studied in spite of common needs by all SSPS models.
- Strategy for R&D and commercialization should be determined on the basis of solving difficulties and financing procedure.
- The international collaboration is inevitable.
Thank you for your kind attention!
REFERENCES


REFERENCES


