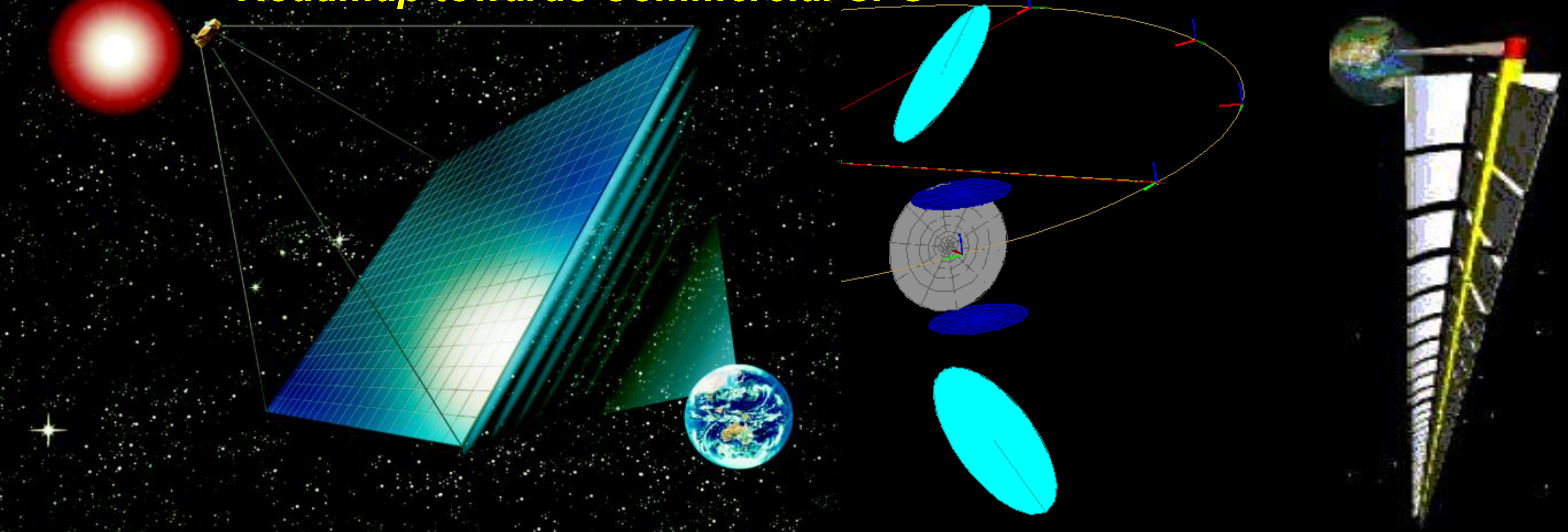
# *Wireless Power Transmission Technologies for Solar Power Satellite*

- *Concept of Solar Power Satellite (SPS)*
- *Microwave Power Transmission for SPS*
- *Demonstration Experiment of Microwave Power Transmission*
- *Roadmap towards Commercial SPS*

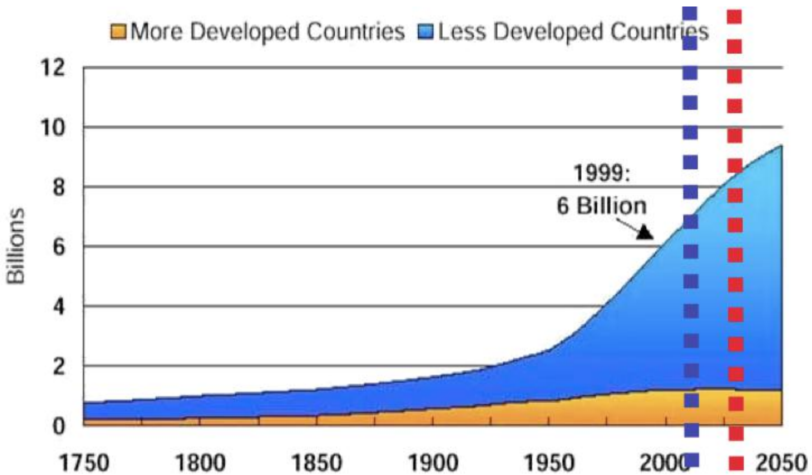


*May 2011*

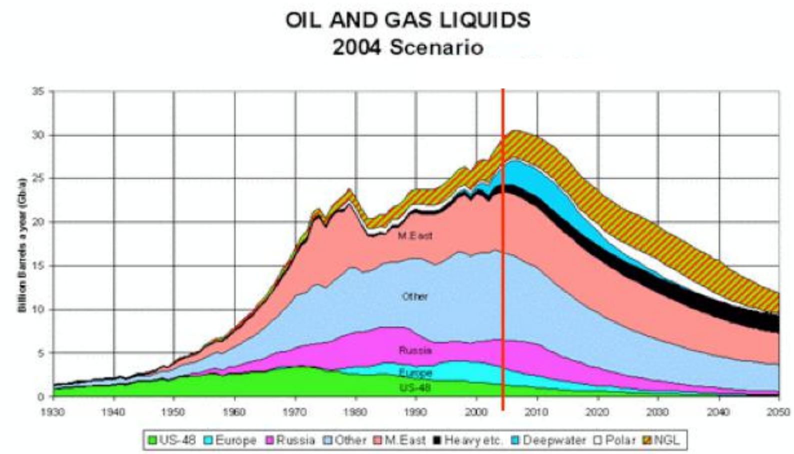
# Concept of Solar Power Satellite (SPS)

Why new energy system required?
Why SPS promising?
SPS configuration
SPS research history
Typical SPS models
Japanese SPS concepts

# *Why New Energy System Required?*

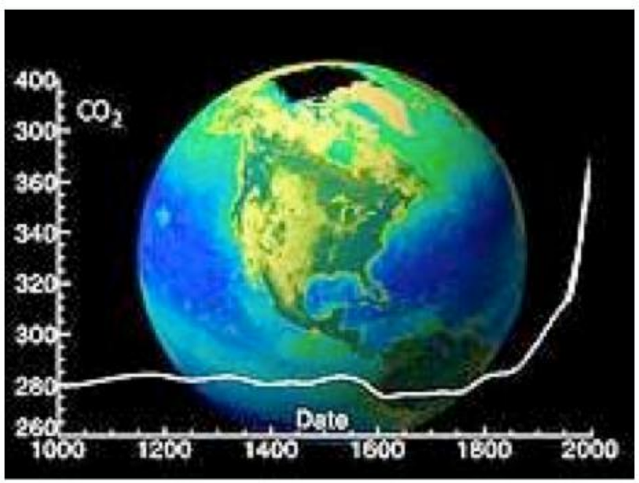



***Population***




***Fossil Fuel***

*Ref:*Abundant & Affordable Space-Based Solar Power Realizing the Opportunity*John C.Mankins(2007)*




***$CO_2$ Emission***

*New Energy System Required*

*Clean*

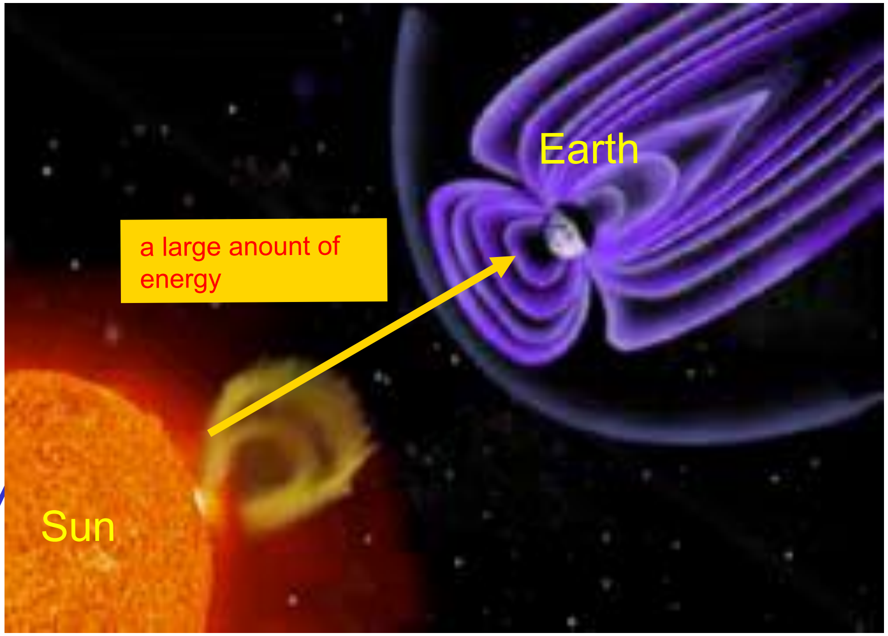
*Safe*

*Large-scale*

*Permanent*

# Space Solar Power -A Potential Solution

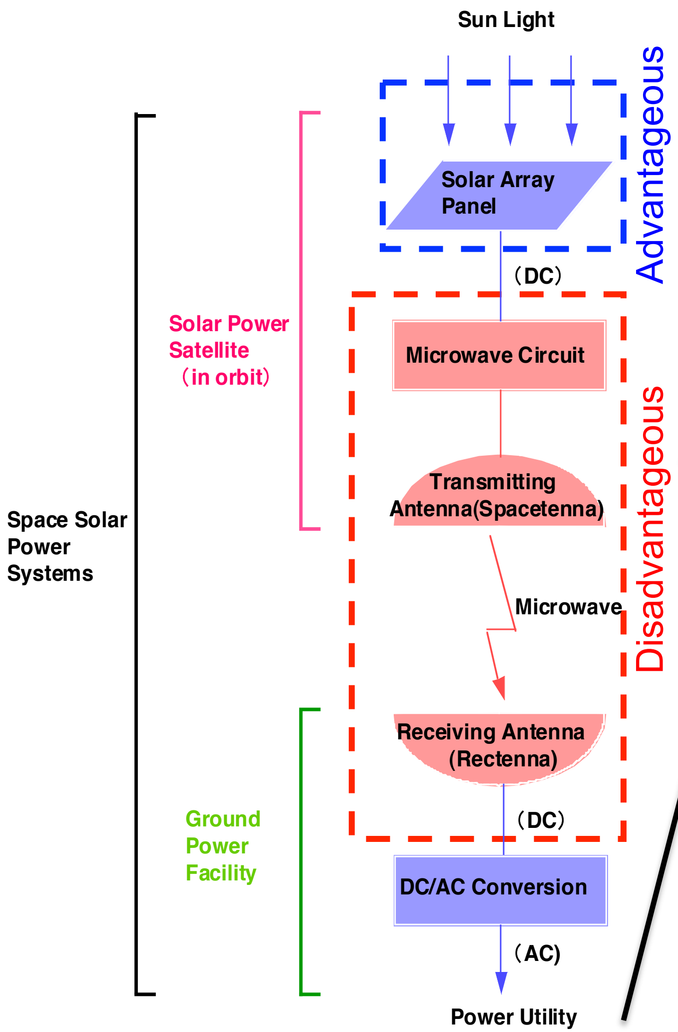
**Why Solar Power?**
**Power from Sun to Earth:**
**$1.77x10^{17}$Watt**
**10,000 times more than total power consumption**
**⇒large potential for power source for human activities**




**Why Space?**
**Power density in space: 1,350W/$m^2$**
**Power density on ground: 100〜200W/$m^2$**
**due to night, whether dependence, atmospheric loss**
**⇒"Space" is preferable to obtain solar power, if we have an efficient method to transfer the energy from space to ground (wireless power transmission).**

⇨ **Solar Power Satellite (SPS)**

# *What's SPS Advantage?*




***Solar power density 10 times larger than ground on average***

***Wireless power transmission efficiency more than 0.5***

***Totally, 5 times better than ground solar power plant.***

*Possibility of a large-scale clean energy system*

- *Stable, independent on local time and whether conditions*
- *Practically unlimited amount of energy*
- *Energy payback time could be less than one year*
- *Power cost could be 10–30 ¢/kWh*
- *$CO_2$ emission could be less than one-several tenth of fossil power plant*

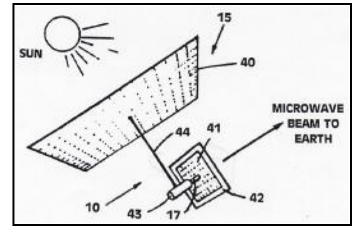
# SPS Major History

| | | |
|---|---|---|
| 1968 | First Concept by Peter Glaser "Power from the Sun: its Future" in Science | |
| 1970' | NASA/DOE (Department of Energy) Study | |
| | 1977-1980 | NASA Conceptual Design (20 M$) |
| | 1978 | DOE's SPS Concept Development and Evaluation Program(CDEP) |
| 1980 | Study in US terminated by President Reagan | |
| 1983 | First Sounding Rocket Experiment in Japan to Study Microwave/Plasma Interaction | |
| 1990 | ISAS Study "Demonstration Model SPS 2000" in Japan | |
| 1995 | NASA Fresh-look Study （−2004） | |
| 1998 − | NASDA(now JAXA/MEXT*) SSPS Study, USEF/METI ** SSPS Study in Japan | |
| 2002-2004 | ESA SPS Study | |
| 2009 | SPS research included in Government Basic Plan for Space Policy in Japan | |

***JAXA/MEXT:Japan Aerospace Exploration Agency/ Ministry of Education, Culture, Sports, Science and Technology***
*****USEF/METI:Unmanned Space Experiment Free Flyer/ Ministry of Economy, Trade and Industry.***

# Typical SPS Models

*Concept of SPS*



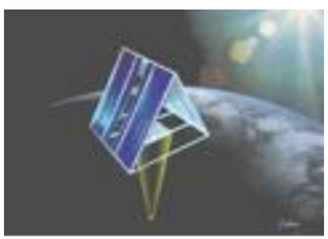

Solar Power Satellite

- Non-concentrator
  - Bus Power
  - Separated Power
- Concentrator
  - Bus Power
  - Separated Power
  - Laser Direct Excitation

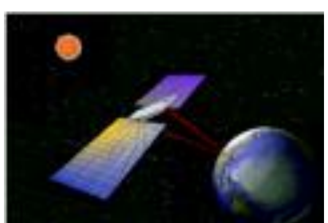
***Microwave type***

## Non-concentrator – Bus Power

NASA Reference Model

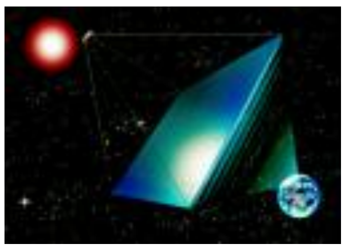


SPS2000



NEDO Grand Design

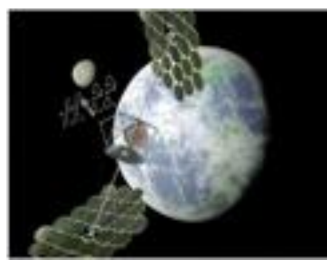
## Non-concentrator – Separated Power



USEF Tether SSPS

## Concentrator – Bus Power

NASA Sun Tower

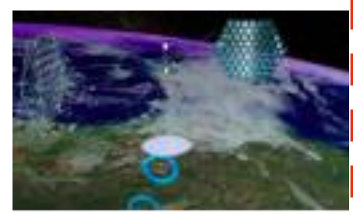


NASA ISC

JAXA M-SSPS

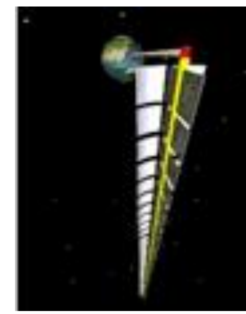
## Concentrator – Separated Power

NASDA 2001



IAA Study Model

## Laser Direct Excitation



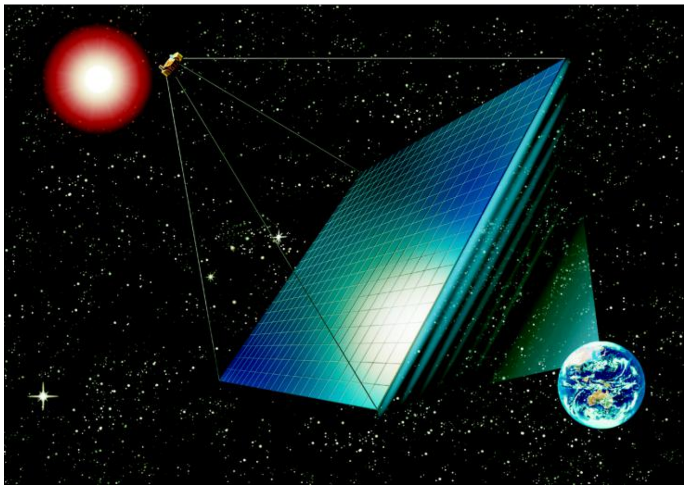
JAXA L-SSPS

# Comparison of Microwave and Laser Power Transmission

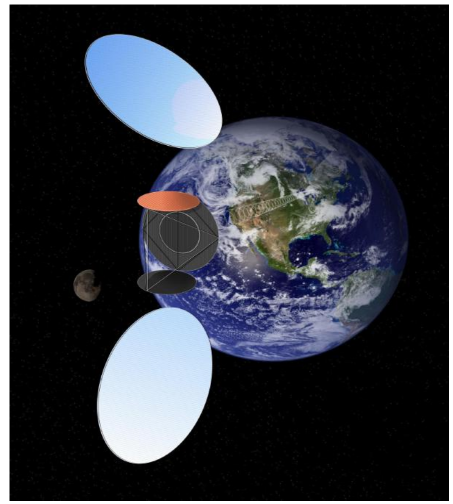
| | Microwave | Laser |
|---|---|---|
| Frequency/Wave Length | ~several GHz | ~1 μm |
| Power Conversion | Solar-DC-RF・・・DC | Solar-Laser・・・DC |
| Conversion Efficiency | Higher | Lower |
| System Size | Larger | Smaller |
| Beam Energy Density | Lower(Safer) | Higher |
| Electromagnetic Compatibility | Lower | Higher |
| Weather Dependence | Smaller(typically 97% transmission) | Larger (typically 35-40 % transmission) |
| Technology Maturity | Higher | Lower |
| Comment | Near term demonstration | Space-Space |

# Examples of Commercial SPS Models Currently Studied in Japan

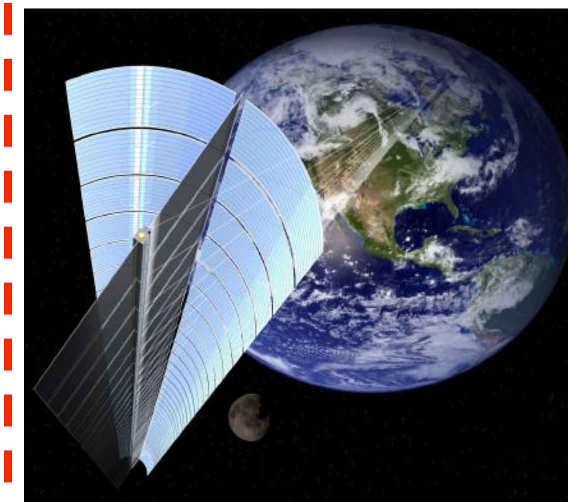
**Microwave type**



Basic Microwave-type Model (USEF/METI)



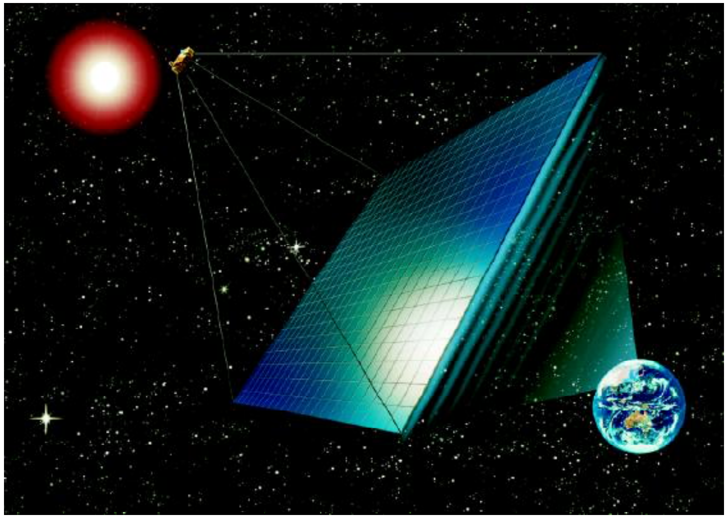
Advanced Microwave-type Model (JAXA/MEXT)



Laser Model (JAXA/MEXT)

*USEF/METI:Unmanned Space Experiment Free Flyer/ Ministry of Economy, Trade and Industry*
*JAXA/MEXT:Japan Aerospace Exploration Agency/ Ministry of Education, Culture, Sports, Science and Technology*

# *Basic Type (Earth-pointing)*



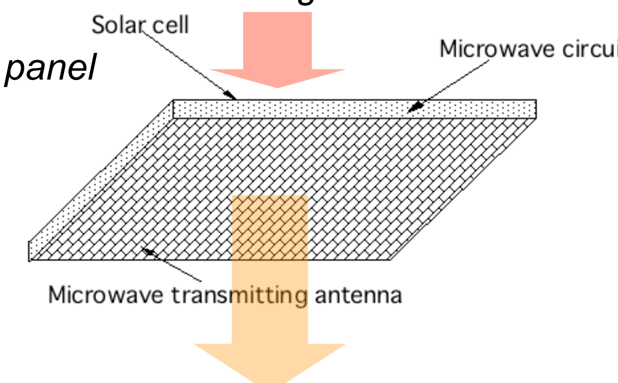
***Single-Bus Model***

***Multi-Bus Model***

***Earth pointing 1 GW-SPS***
***(1GW=$10^9$W, equivalent one nuclear plant)***
***Power generation/transmission panel(sandwich panel) 2km x 1.9km x(2-10)cm$^t$***

*solar light*

*sandwich panel*

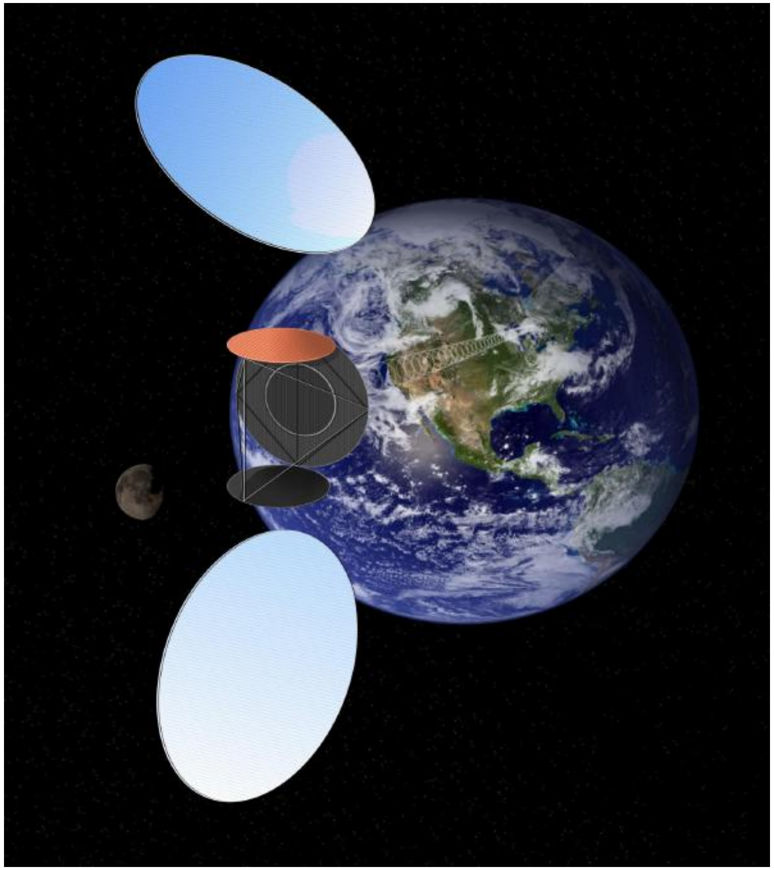



*microwave*

***Suspended by tether wires of 5-10 km, stabilized by gravity gradient force***
***Unit panel 100m x 100m size***
***Total weight 20,000 tons***

***Simple but low rate power collection (64%)***

# Advanced Type (Sun-pointing)



Sun pointing 1GW-SPS
Reflection mirrors (free flying) :2.5 km x 3.5 km

1000 tons x 2sets、
100~300g/m$^2$

Power generation:
1.25 kmΦx2 sets
Power transmission:
1.8 km Φ
Total weight：
10,000 tons(target)

Complicated but high rate power collection

# *Microwave Power Transmission for SPS*

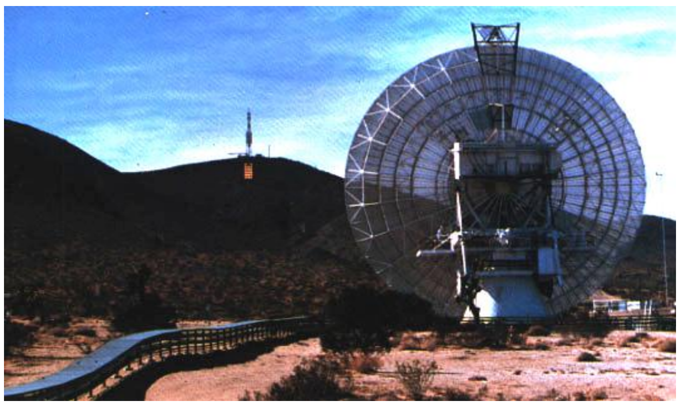
***Major historical milestones***

***Issues for SPS application***

- ***Technologies***
- ***Frequency allocation***
- ***Transmission through ionosphere***
- ***Public acceptance***

# *Historical Epochs of Microwave Power Transmission for SPS*

*Tesla tower intended for wireless power transmission experiment (1905)*

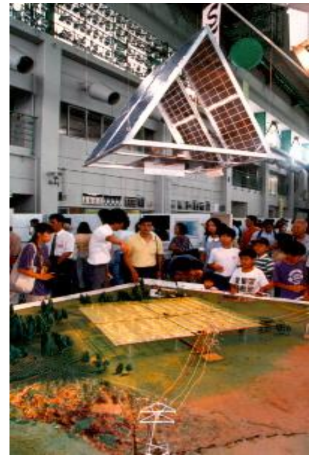


*Microwave power transmission demonstration experiment at NASA JPL Goldstone, transmitted 34kW, 1 mile, the world record (1975)*


*Microwave transmission experiment near kW in space by Kyoto Univ., Kobe Univ., and ISAS(1983,1993)*

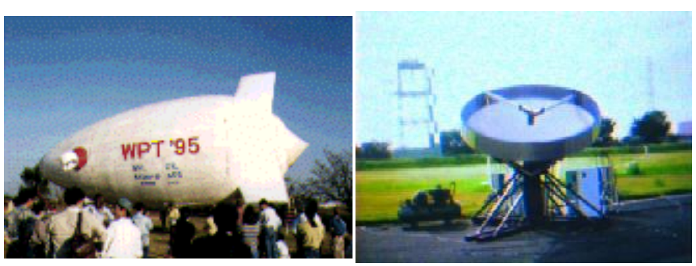
# Recent Microwave Transmission Experiments

*Small Airplane Experiment (1992、Kobe Univ., Kyoto Univ.)*

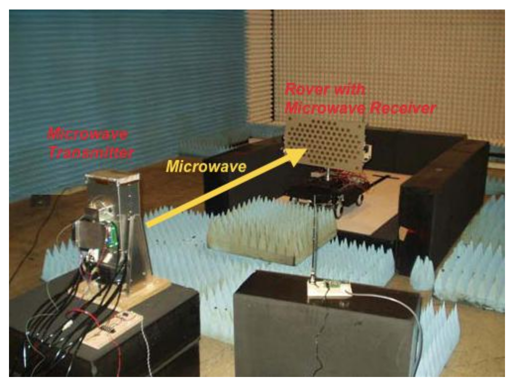


*SPS2000 demonstration experiment(1994、ISAS)*

*Yamasaki 50 m transmission (1994、Kyoto Univ. Kobe Univ.)*




*Transmission to Balloon (1995、Kobe Univ.)*




*Transmission to rover experiment(2006、USEF)*

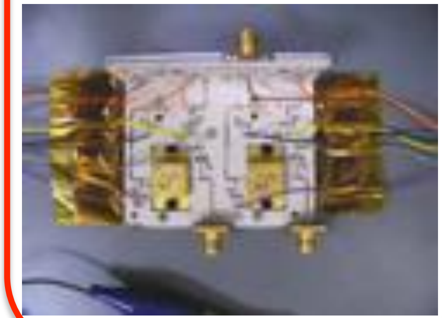
*Hawaii long-range transmission (2008, Kobe Univ. & US team)*

# Issues for Microwave Power Transmission for SPS

Public Acceptance

YES

Transmission Technologies



YES

**Microwave Power Transmission for SPS**

YES

Transmission through Ionosphere

YES

Frequency Allocation

ITU International Telecommunication Union

# *Microwave Power Transmission Technologies for SPS*

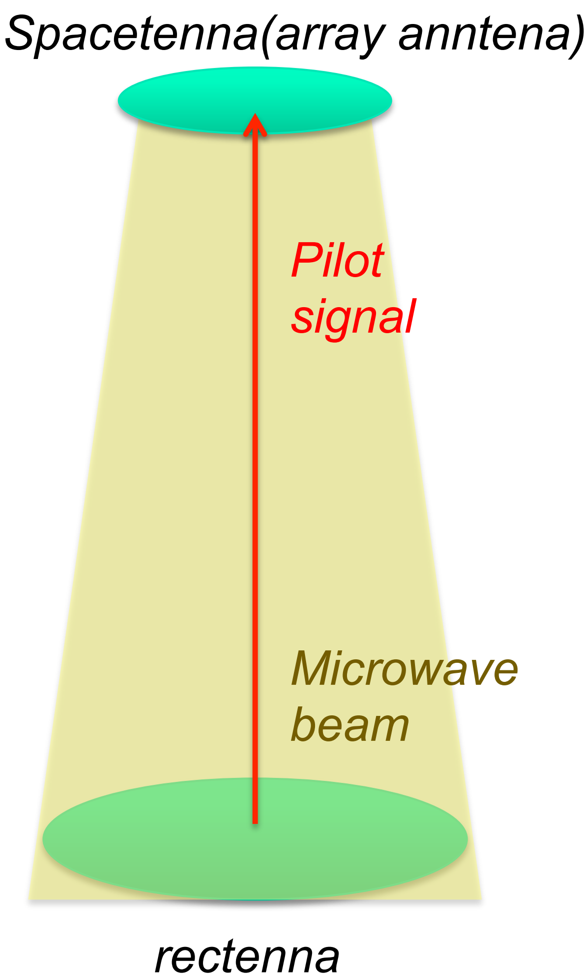
*DC power from solar array panel* → *Microwave transmitter* → *Microwave Receiver* → *Electric power grid for commercial use*

1. *High efficiency microwave circuit*
   - *transmission efficiency > 80%*
   - *rectenna efficiency > 80%*
2. *Low cost microwave elements*
   - *transmitter < 1 $/Watt*
   - *receiver < 0.5 $/Watt*
3. *Precise microwave beam forming and pointing*
   *(2 km diameter transmitter in geosynchronous orbit to 3.5 km rectenna on ground)*
   - *beam forming < 100 μradian*
   - *pointing accuracy < 10 μradian*

# Current Performance of Microwave Elements

| Subsystem | Type | Efficiency /Loss | Power | Tasks required |
|---|---|---|---|---|
| Microwave generator/ amplifier | Electronic tube（Magnetron , TWT, Clystron） | 70-80% | Several hundreds W~ Several MW | Phased array configuration<br>Weight (g/w) reduction |
| | Semiconductor | 50-60% | Less than 100W | Efficiency improvement<br>Weight (g/w) reduction<br>Cost reduction |
| Microwave beam controller | Phase shifter | -1dB/bit | Less than 10 W | Loss reduction<br>Life improvement (MEMS) |
| Microwave receiver | Rectenna | 80-90% | More than 100 mW | Efficiency improvement for array and low-power input |

# Technologies for Microwave Beam Control




Required Technologies

1. Determination of rectenna position by detecting and processing pilot signal from the rectenna site.
2. Controling the phase of microwave from each antenna (or sub-array) so that the microwave beam as a whole directs to the rectenna center precisely.

Requirements

| Item | Target |
|---|---|
| Beam forming | 100 μrad |
| Beam control accuracy | 10 μrad |
| Beam control range | ± 10 degrees(tentative) |
| Power concentration | 90 % inside the rectenna |
| Response (phase control) | sec scale for small antenna area(m) |
| | hour scale for large antenna area(100m) |

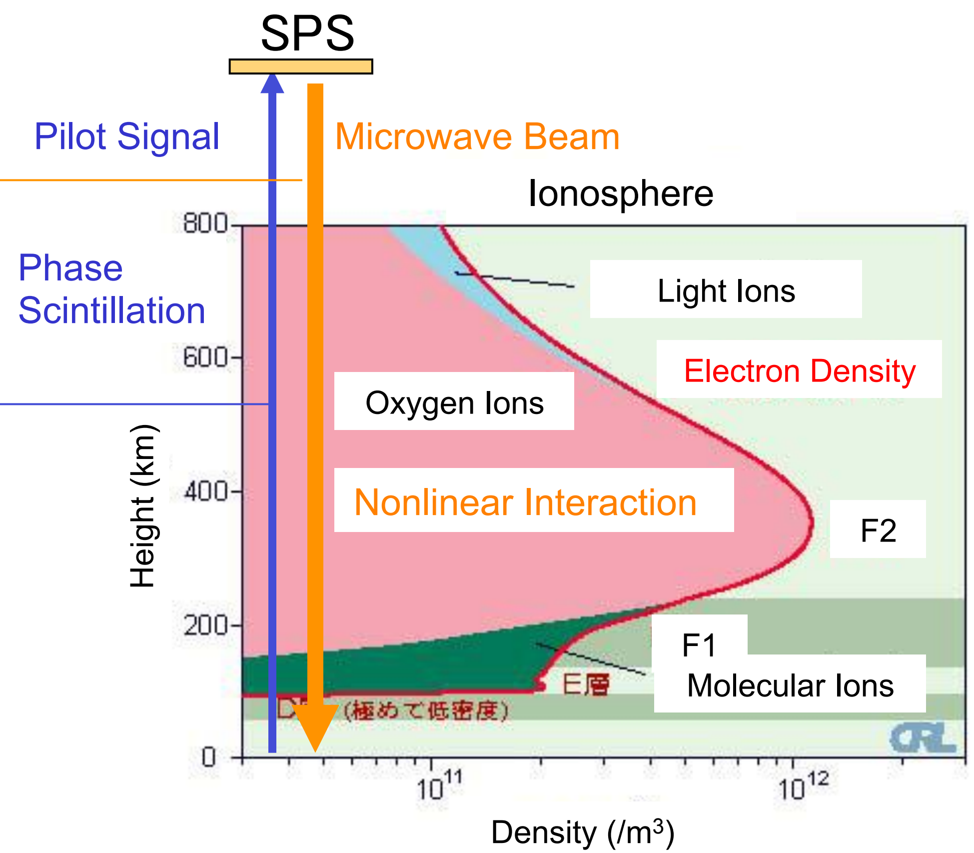
# *Frequency Allocation*

| Step | Current status & prospects |
|---|---|
| *Selection of candidate frequencies* | *Candidates selected just for experiments (preliminary). Not yet for commercial use (less than 10 GHz).* |
| ↓ | |
| *Interference analysis* | *Preliminary discussion just for experiments* |
| ↓ | |
| *Agreement in domestic level* | *Several years* |
| ↓ | |
| *Agreement in international level(ITU)* | *International collaboration required*<br>*Usually more than 10 years* |

# *Ionospheric Interaction*

***High power density microwave typically more than 100W/m² could excite non-linear interaction with the ionosphere.***
***Threshold power density～1/f² or 1/f³***

***Pilot signal could be subject to ionospheric scintillation effect when strongly disturbed.***

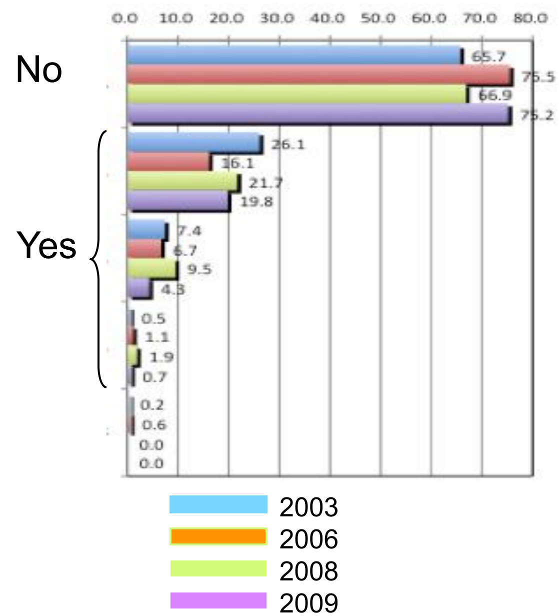


# Public Acceptance

| Radiation Safety for Human | Field Experiment | SPS Consciousness |
|---|---|---|

*System Design Guidelines*
*Inside the beam(rectenna): controlled as an evacuation area*
*Outside the beam(rectenna): Less than international regulation level (1mW/cm²) with a margin*

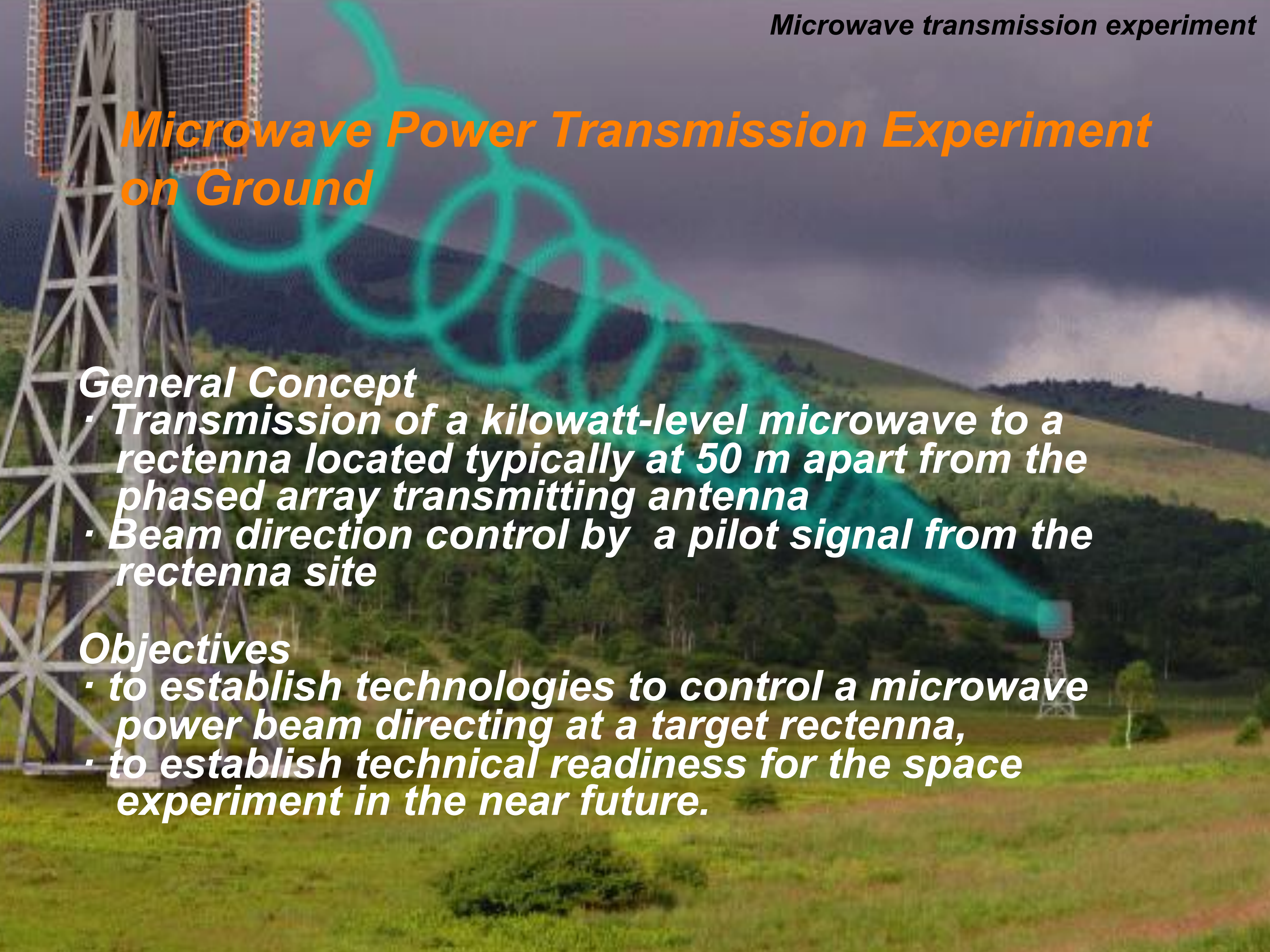
*Long-duration microwave exposure facility to study microwave biological effects at National Institute of Advanced Industrial Science and Technology (AIST)*




*Almost 75 % of people don't know what SPS is. More publicity work is required.*

## *Microwave transmission experiment for SPS*

*1 kW class experiment on ground*
*1 kW class experiment in space*
*100 kW class experiment in space*



# Microwave Power Transmission Experiment on Ground

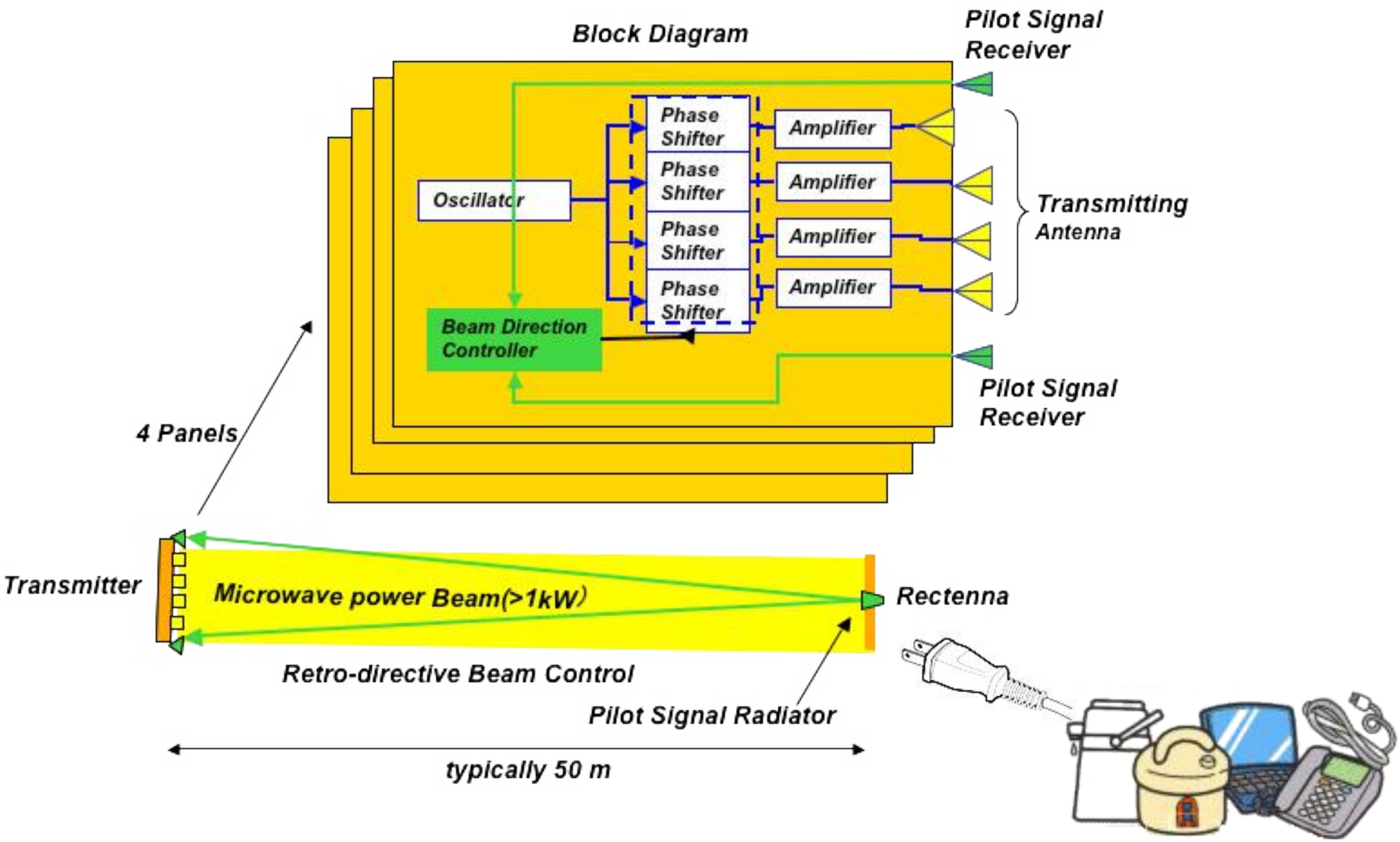
**General Concept**

- Transmission of a kilowatt-level microwave to a rectenna located typically at 50 m apart from the phased array transmitting antenna
- Beam direction control by a pilot signal from the rectenna site

**Objectives**

- to establish technologies to control a microwave power beam directing at a target rectenna,
- to establish technical readiness for the space experiment in the near future.

# Microwave Power Transmission Demonstration

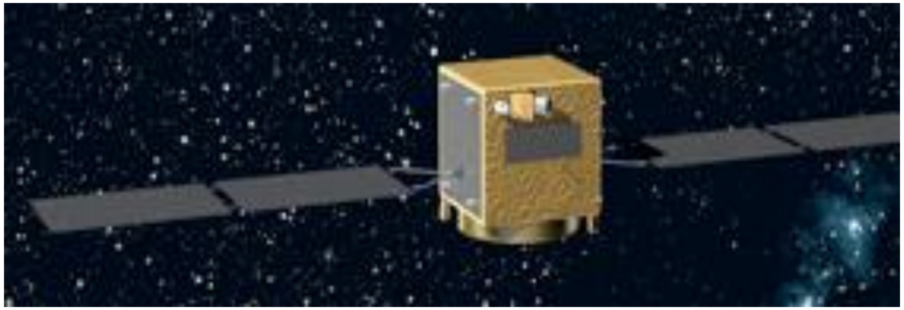



***Rectenna output power will be used to operate household electric appliances for public demonstration.***

# Characteristics of Microwave Transmission Experiment on Ground

| | |
|---|---|
| Transmitter configuration | 4 panels movable to each other.<br>400 W/panel(typical), 20 kg/panel (typical) |
| Microwave transmission panel | 76 sub-array/panel,<br>4 antennas/sub-array,<br>60 cm x 60 cm, less than 4 cm thick<br>conversion efficiency 35 %(typical) |
| Microwave amplifier | 5.8 GHz, 5 W, efficiency 60 %(typical) |
| Antenna configuration | 0.65 $\lambda$ spacing |
| Microwave beam control | retro-directive control using a pilot signal from rectenna site |
| Phase control accuracy | 5 bits |
| Rectenna | rectenna panel 2.5m$^{\phi}$ (typical)<br>Array conversion efficiency to DC more than 50% (typical)<br>Output power 350W (typical) |
| Transmission range | 50 m (typical) |

# Two Possible Platforms for SPS Wireless Power Transmission Experiment in the Near Future



***JAXA small scientific satellite to be launched by next-generation solid propellant rocket, Epsilon launch vehicle. 500 kg class satellite. Payload weight 200 kg typical. First flight will be in 2013.***

***Japanese Experiment Module Kibo on the International Space Station (ISS), for science and technology research. Payload weight 500 kg typical.***

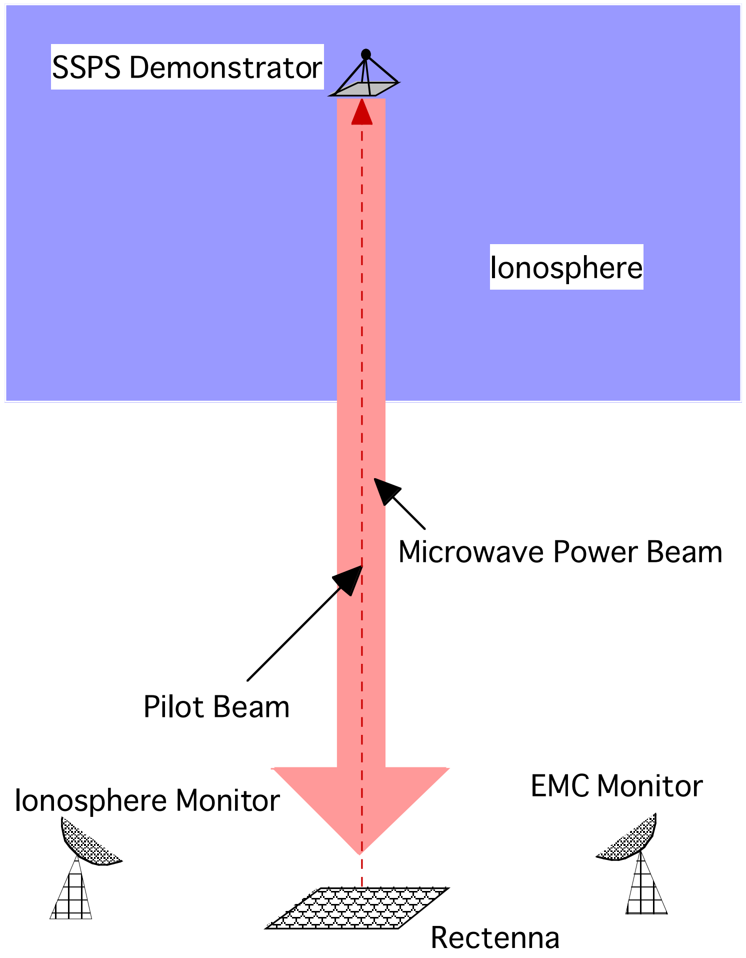
# Objectives of Microwave Power Transmission Experiment in Space

(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,

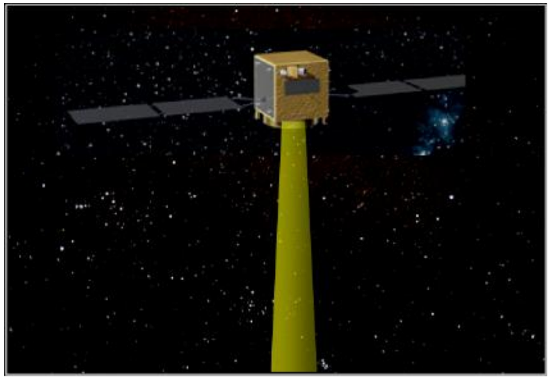
(3) evaluation of the over-all power efficiency as an energy system,

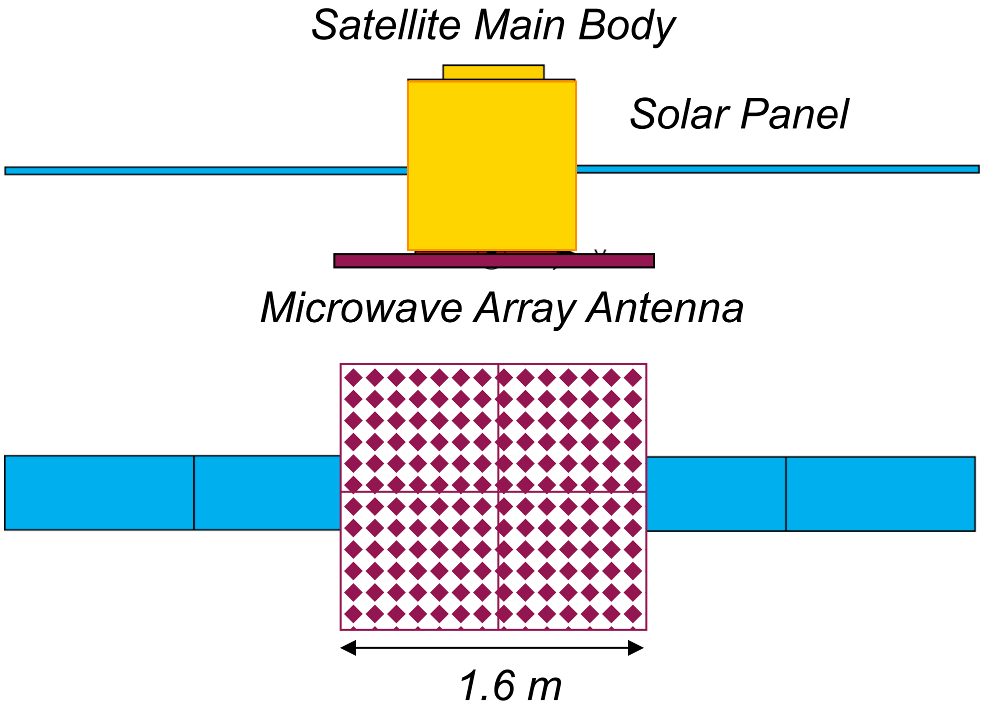
(4) demonstration of the electromagnetic compatibility with the existing communication infrastructure.



# Experiment on Small Satellite

*Orbit: Low Earth Orbit (370 km)*
*Satellite Weight: 400 kg*
*Mission Weight: 200 kg*
*Attitude Control: 3-axis Stabilization*
*Transmission Power: 3.8 kW*

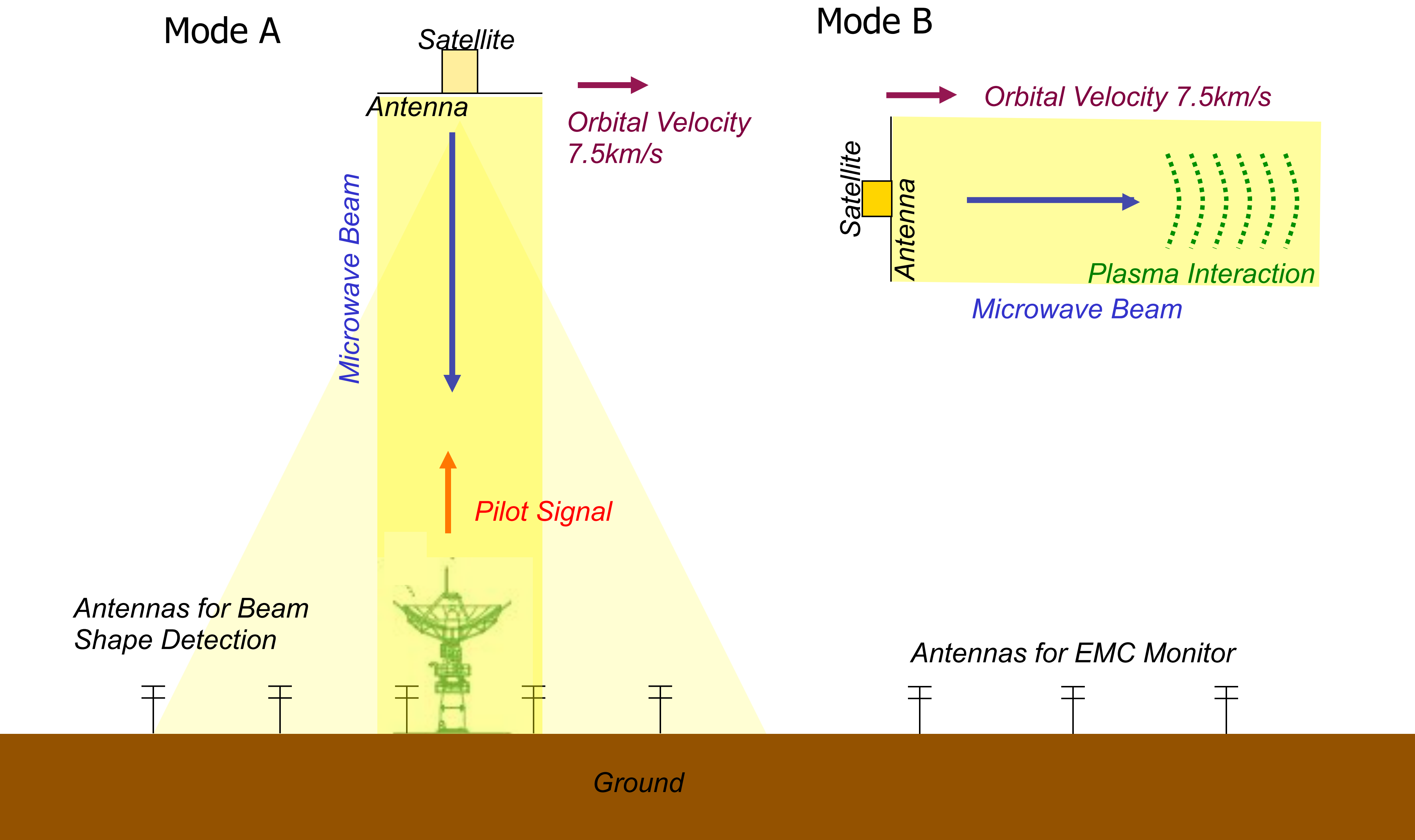




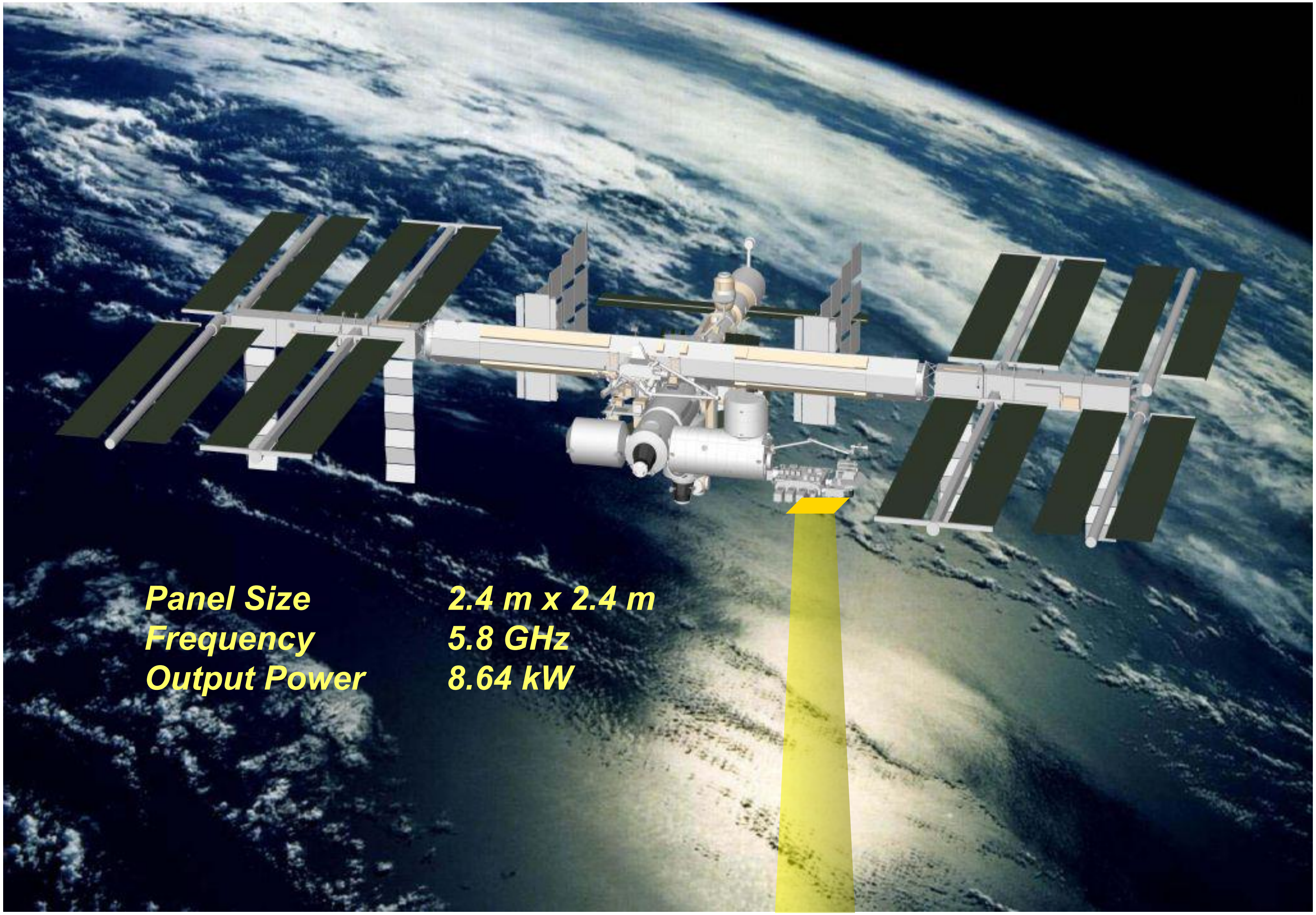
# System Characteristics of Demonstration Model (Typical Example)

| Mission | Period | 1 year |
|---|---|---|
| System | Configuration | Power transmission panel attached to 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 $W/m^2$ (at antenna)<br>24 $\mu W/m^2$(max, on ground) |
| Ground stations | | JAXA ground stations<br>International experiment sites |

# Experiment Configuration

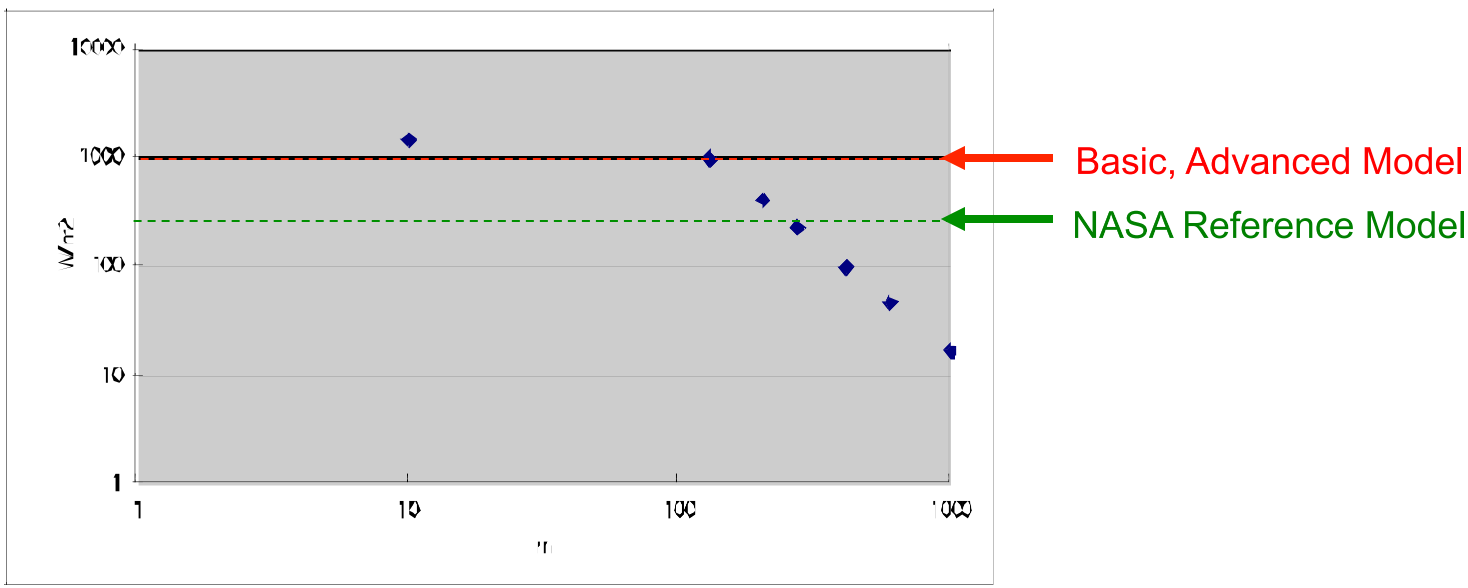


# *Microwave Power Transmission Experiment from JEM*

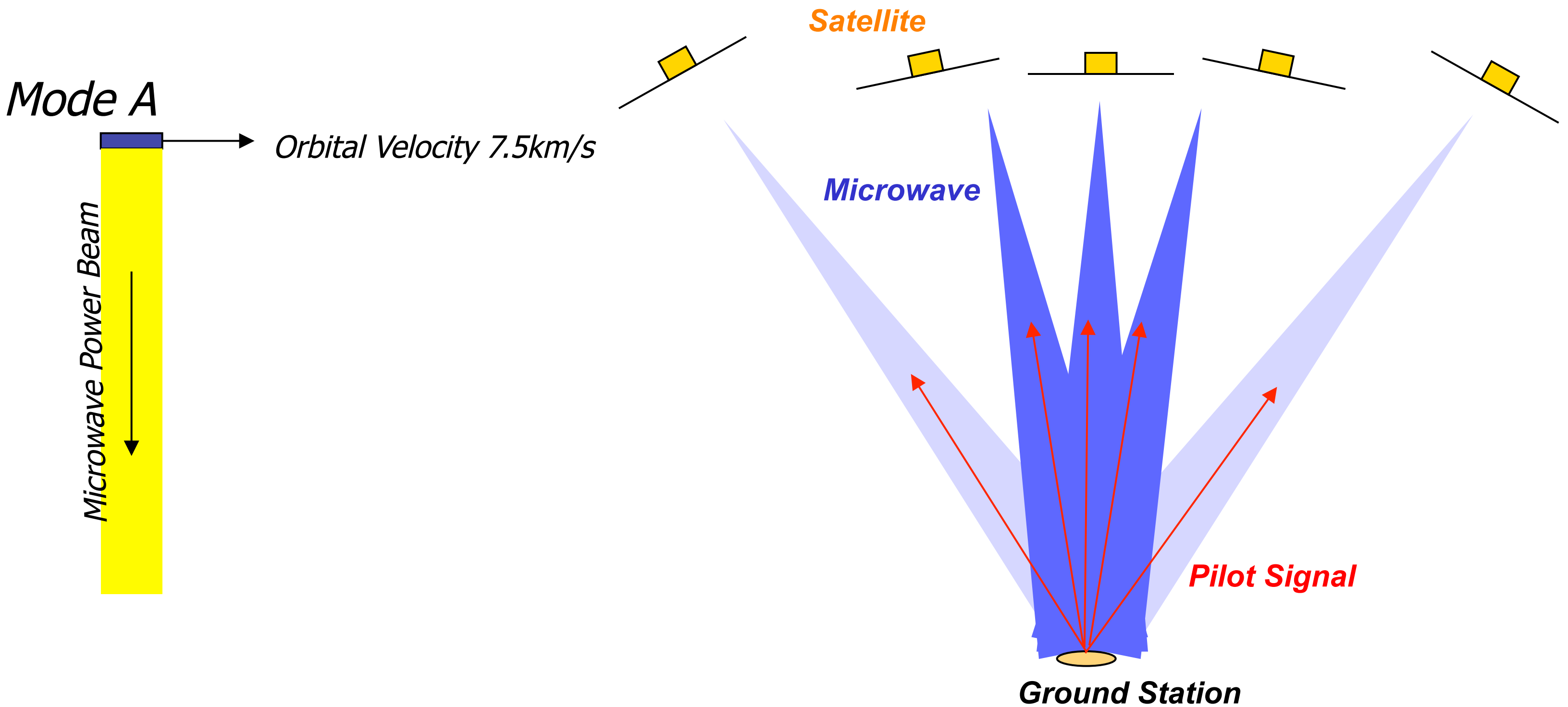


# Microwave Power Density

| | |
|---|---|
| *Panel Size（9 panels）* | *2.4 m x 2.4 m* |
| *Frequency* | *5.8 GHz* |
| *Output Power* | *8.64 kW、1.5kW/m²* |
| *Power Density（>1000W/m²）* | *130 m* |
| *Power Density（>230W/m²）* | *270 m* |
| *Power Density(>100W/m²)* | *410 m* |
| *Power Density(on ground)* | *136μW/m²* |



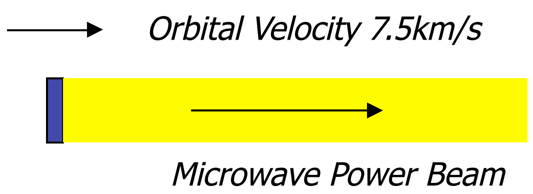
# *Verification of Beam Forming and Control*




- *Beam forming according to array antenna theory (diffraction limit, beam width 3 degrees (null-to-null)) will be verified.*
- *Beam control accuracy according to retro-directive control theory (0.5 degrees accuracy (TBD) ) will be verified.*
- *With experimental results, beam forming and beam control from geo-stationary orbit to ground can be evaluated quantitatively.*

# Verification of Microwave/Plasma Interaction

*Mode B*




**Observation**

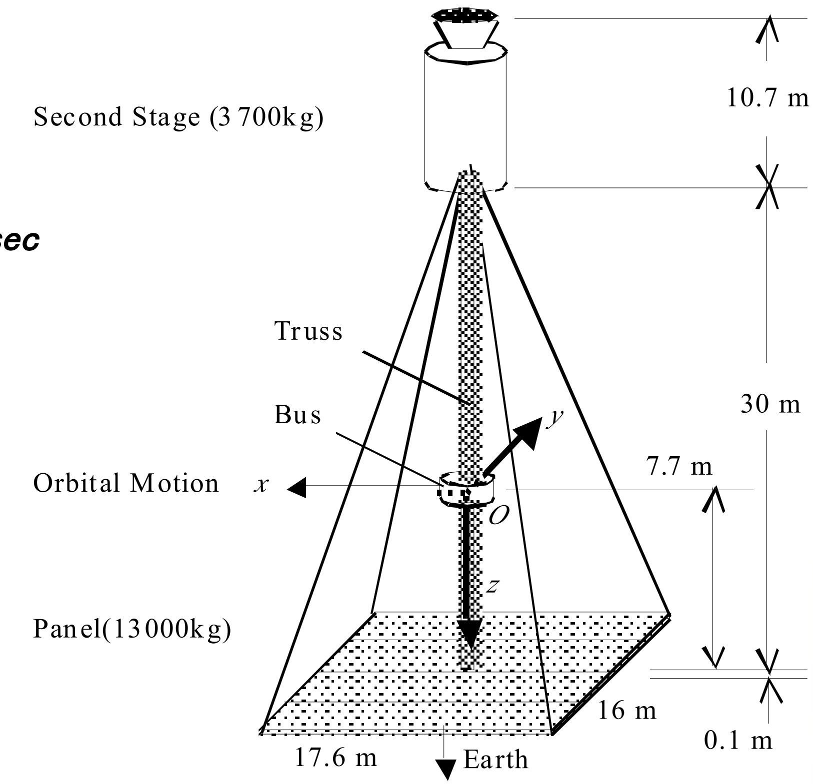
**Ground** — **Beam power density profile**

**In-situ** — **Electrons temperature, Plasma density, Plasma waves, Back-scatter waves**

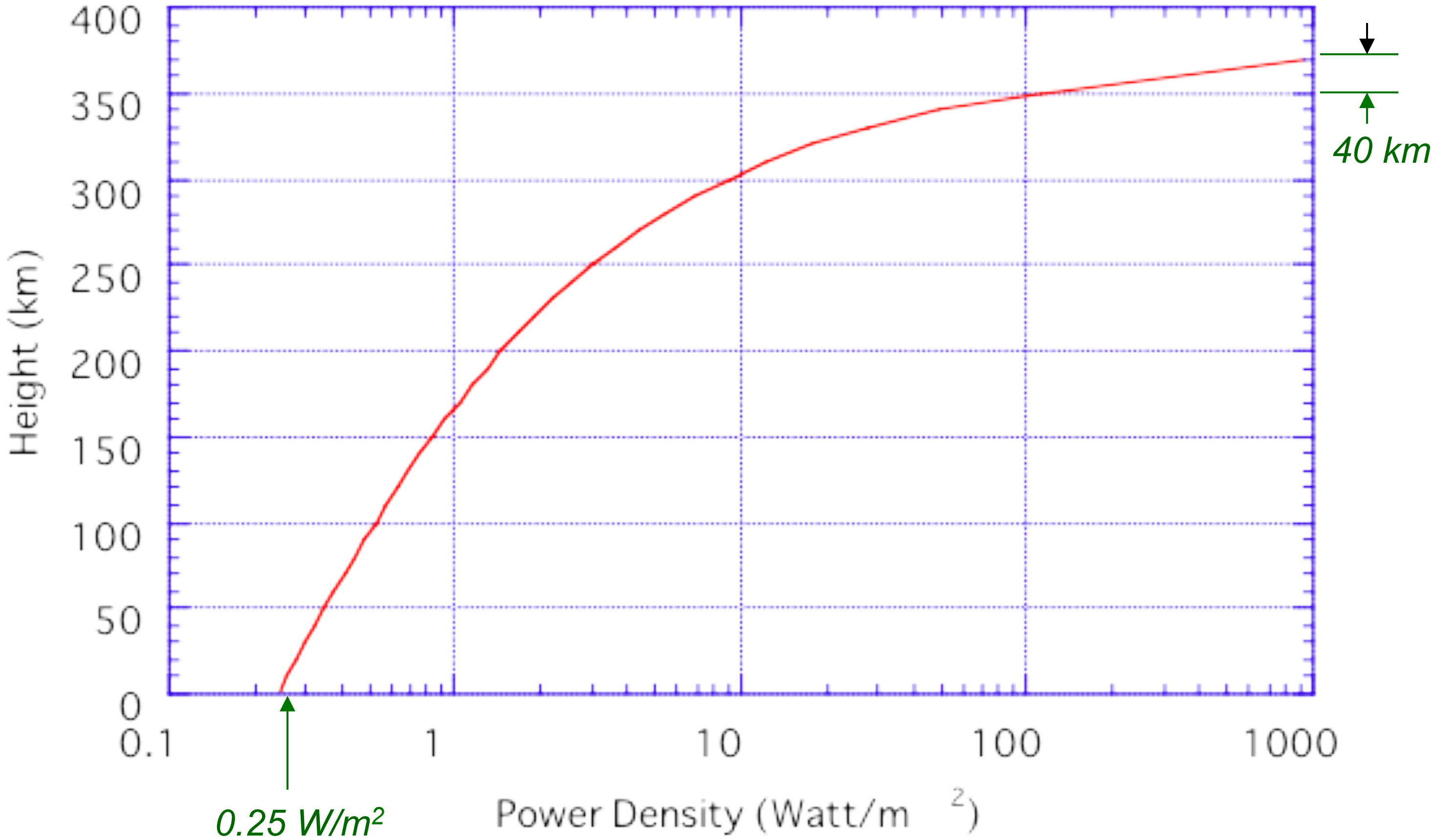
| Verification items | | | Mode A | Mode B |
|---|---|---|---|---|
| Direction of microwave power beam | | | Ground | Orbit parallel |
| Ionospheric plasma irradiation time | | | 0.2ms | 10ms |
| Research subject | | | Observation | |
| Ionosphere interaction | Heating | F-layer electrons heating | partially | 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 |

# 100 kW class Demonstration Experiment

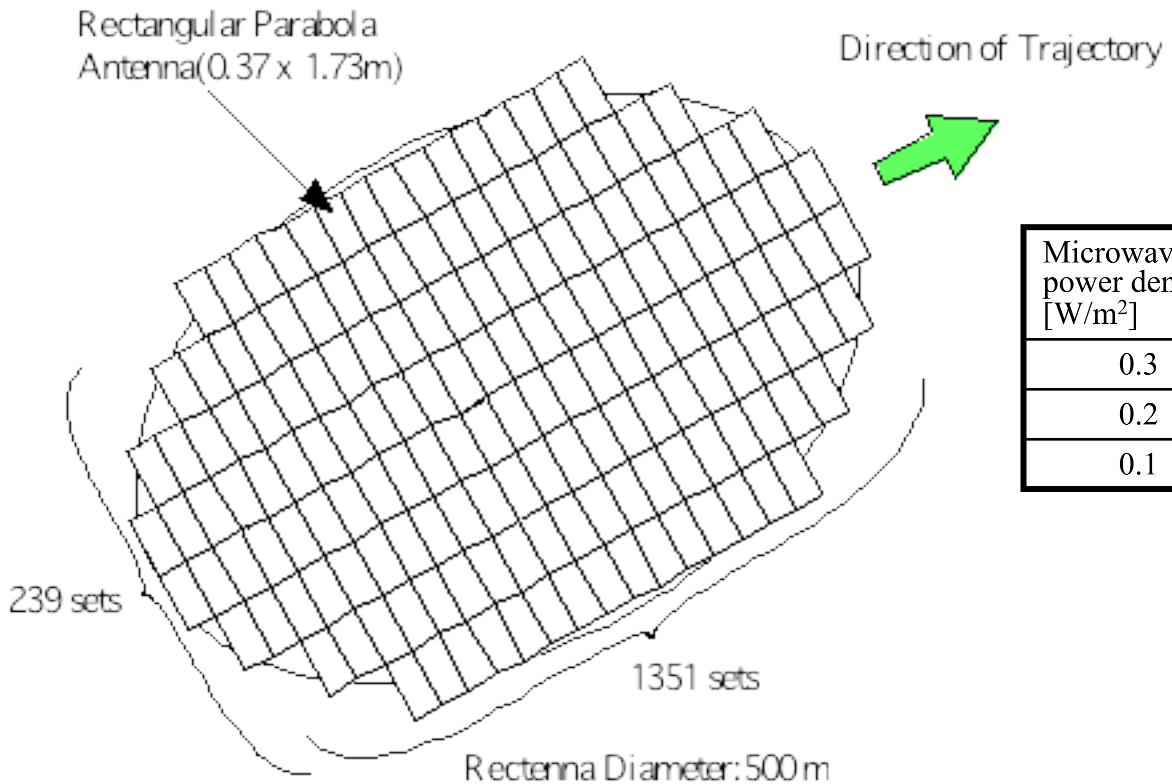
| | |
|---|---|
| *Size* | *40.8m x 17.6m x 16.0m* |
| *Total Weight* | *18,100 kg* |
| *Power Generation* | *36 kW max* |
| *Power Transmission* | *420 kW～140 kW* |
| *Beam Control* | *retrodirective control* |
| *Microwave Frequency* | *5.8 GHz* |
| *Operation* | *full power for 16 sec*<br>*10% power for 4 min* |
| *System Configuration* | *panel, truss, tether,*<br>*weight mass* |
| *Panel Configuration* | *80 foldable panels*<br>*400 power modules*<br>*250,000 antennas* |
| *Attitude Control* | *gravity gradient force* |
| *Altitude* | *370 km* |
| *Rectenna type* | *parabola collector* |
| *Rectenna output* | *30 kW～10 kW*<br>*(500 m diameter)* |




# *Height profile of the microwave power density*



# Configuration of Rectenna for 100 kW class Demonstration Experiment




| Microwave power density [W/m$^2$] | Efficiency for rectification [%] | Output Power [kW] |
|---|---|---|
| 0.3 | 70.3 | 29.5 |
| 0.2 | 67.2 | 18.8 |
| 0.1 | 57.7 | 8.1 |

Fujino, 2003

***Roadmap towards Commercialization***

***Conclusion& Summary***

# Verification Matrix towards Commercial SPS

| Phase / Verification | Ground Demonstration | Small Satellite or JEM on Space Station | Large Satellite | Small Plant | Verification Plant |
|---|---|---|---|---|---|
| | kW Ground | kW Low Earth Orbit | 100kW Low Earth Orbit | 2MW 1000 km Altitude | 200 MW Geostationary Orbit |
| Beam Control | 50-100m | 400km | 400km | 1000km | 36000km |
| Ionosphere/ atmosphere transmission | - | 1kW/m$^2$ | 1kW/m$^2$ | 1kW/m$^2$ | 1kW/m$^2$ |
| Power Transmission | (Test Rectenna kW) | - | Small Rectenna 10kW | Large Rectenna 2MW | Large Rectenna 200MW |
| SPS Total Function | - | - | 10kW | 2MW | 200MW |
| Power for Practical Use | - | - | - | 2MW | 200MW |

# Research Phase

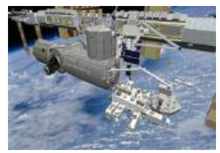


09 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19

Ground demonstration


Small-scale on orbit demonstration

WPT Selection (microwave or laser)

100kW class on orbit demonstration

Configuration selection

# Development Phase

20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29

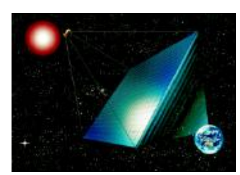
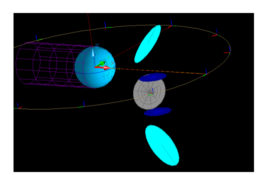
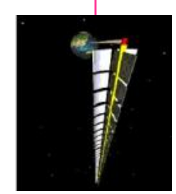
2MW class demonstration

200MW class plant

# Commercial Phase

30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39

1GW class first commercial model

Commercial SPS（1SPS/year）

# Summary and Conclusion

- One of the most critical technologies for the SPS is microwave power transmission from the geosynchronous orbit to the ground.
- Evolutionary microwave transmission technologies are required for a high power conversion efficiency more than 80 % from/to DC and an extremely high-precise beam control with 10 μrad accuracy.
- These technologies will be partially verified in the ground demonstration experiment within several years and will be fully verified in the space experiments within 10 years.
- Although the required technologies are quite challenging, continuing research activities along with the proposed roadmap will lead to  opening the new SPS era in 2030‘s.