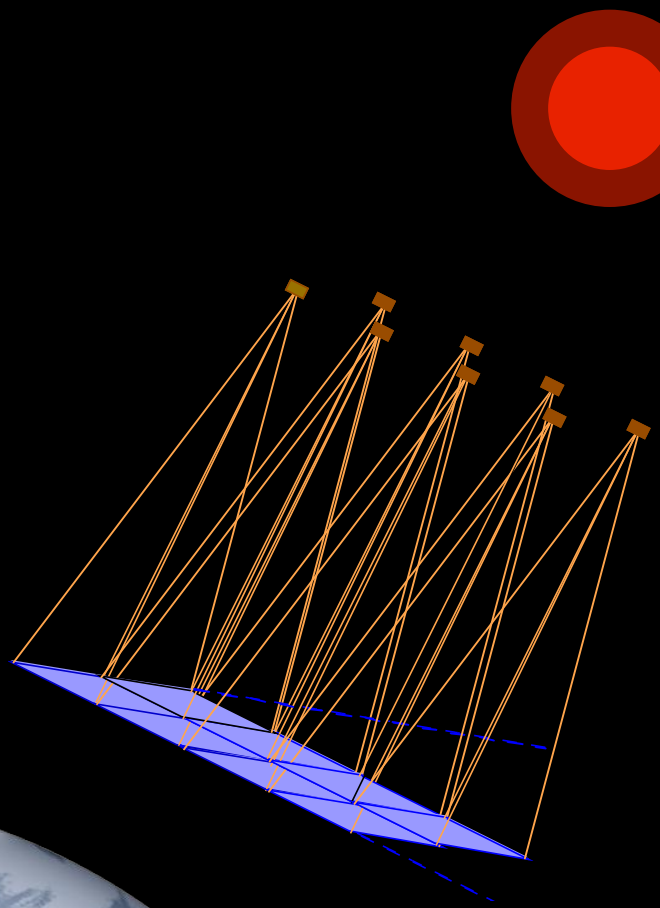
23 Questions about Solar Power Satellite

- Frequent Questions from Students -



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Solar Power Satellite

23 Questions about Solar Power Satellite(1/2)

- Frequent Questions from Students -

1. *What is Solar Power Satellite?*
2. *What are the advantages of power plant using solar energy?*
3. *What are the advantages of solar power plant in space as compared with that on the ground?*
4. *Where in Space will Solar Power Satellite be constructed?*
5. *What technologies are required to realize Solar Power Satellite?*
6. *Which is better, microwave or laser, for wireless power transmission from space to ground?*
7. *Laser propagates in a narrow beam, but microwave expands. Can microwave beam be directed to the receiving site?*
8. *How is Solar Power Satellite constructed?*
9. *What kind of rockets are used to transport construction materials to the orbit?*
10. *Is it possible to construct Solar Power Satellites on the geosynchronous orbit that is already much crowded?*
11. *Construction of Solar Power Satellite seems to be expensive. Can the power cost from Solar Power Satellite be reasonable?*

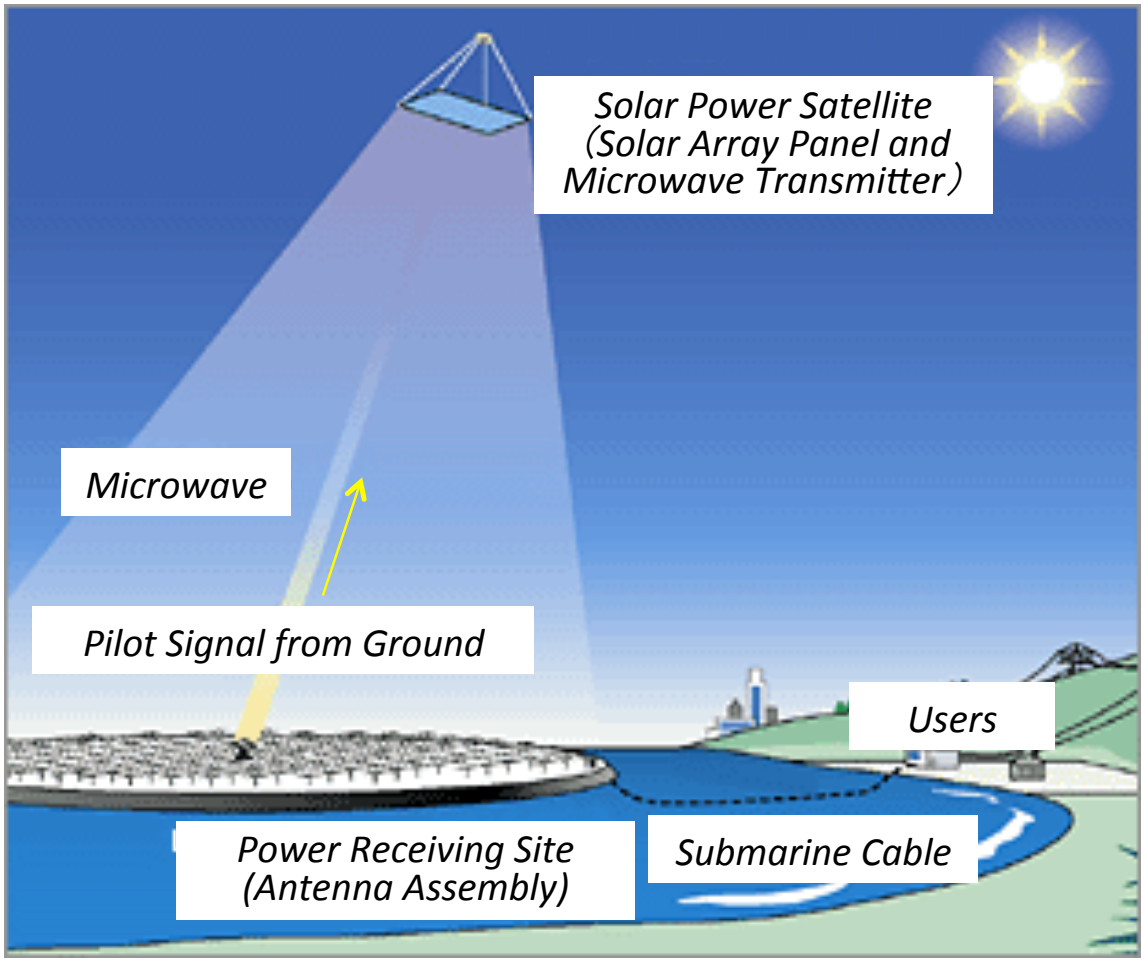
23 Questions about Solar Power Satellite(2/2)

- Frequent Questions from Students -

12. *Will Solar Power Satellite be destroyed by the debris or meteorites impacts?*
13. *How long is the life of Solar Power Satellite?*
14. *What happens when the life of Solar Power Satellite is expired? Is it going to be a space junk?*
15. *Is Solar Power Satellite safe?*
16. *Is there any possibility that the ionosphere is strongly heated or depleted by the microwave beaming?*
17. *Solar Power Satellite provides additional energy to the Earth. Will the temperature of the Earth increase?*
18. *When is Solar Power Satellite realized?*
19. *Is Solar Power Satellite studied in Japan?*
20. *Who are making the solar power research in Japan?*
21. *What are the global research situations for Solar Power Satellite?*
22. *Will Solar Power Satellite be developed national or international efforts?*
23. *Will our society change with Solar Power Satellite?*

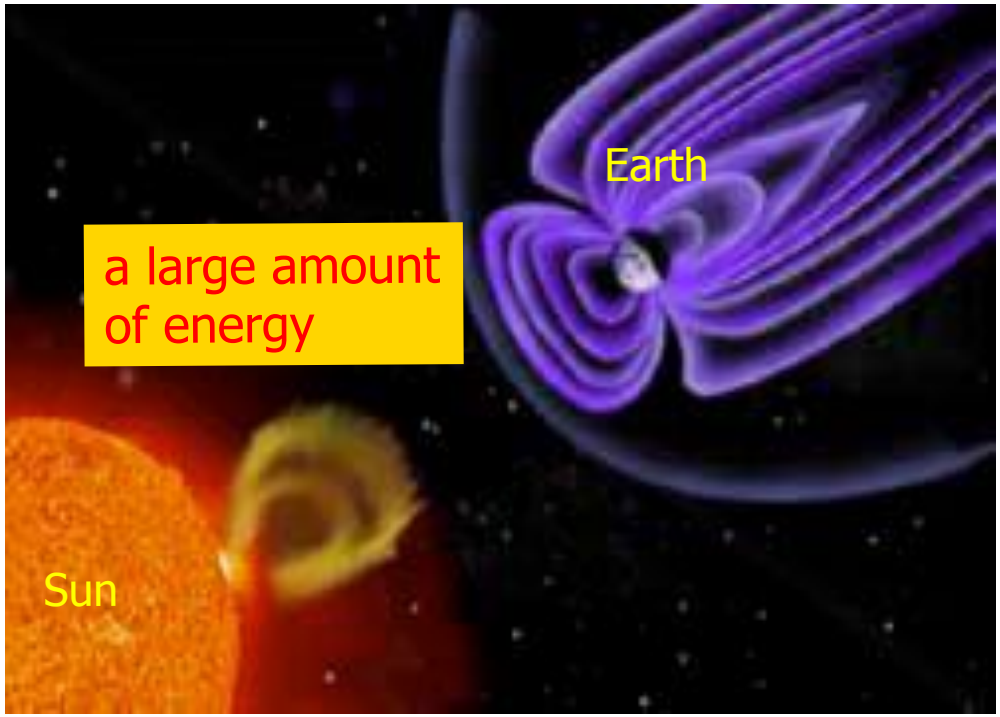
1. What is Solar Power Satellite?

Solar Power Satellite is a power plant in space to convert the solar energy into electric power using photovoltaic cells. The generated power is transmitted to the ground via microwave or laser.



2. What are the advantages of power plant using solar energy?

Power from the Sun to the Earth is 10,000 times more than global power consumption. By converting the Sun's energy into electric power, we can obtain limitless energy without environmental impact (no CO_2 emission).



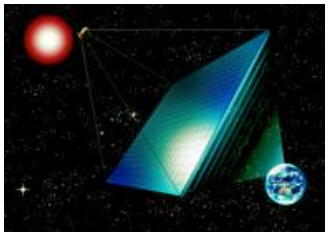
The resources of coal, petroleum, natural gas. and uranium will be depleted within 50-150 years.

The fossil fuels, such as coal, petroleum, and natural gas emit CO_2 that affects the global environment.

Nuclear power generation has the safety problems in operation and issues for disposal of radioactive waste.

3. What are the advantages of solar power plant in space as compared with that on the ground?

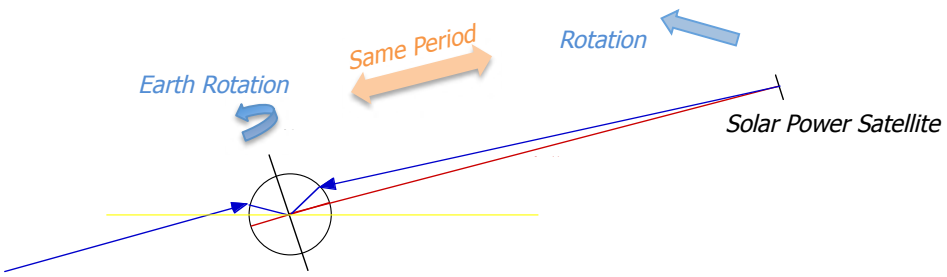
Solar energy can be collected more and stably in space!

Solar Power Plant on Ground		Solar Power Plant in Space
 Rainy and cloudy days		 No rainy or cloudy day
 Night	Contrast	 No night (depending on the orbit)
 Land problem		 No land problem

4. Where in Space will Solar Power Satellite be constructed?

Geosynchronous orbit is believed to be the most potential orbit for Solar Power Satellite .

The satellite in the geosynchronous orbit (36,000 km height) looks like stationary when we look it from the Earth, as shown in the figure below. We can get the electric power always from the same Solar Power Satellite in the geosynchronous orbit. The Solar Power Satellite in the other orbits looks like moving observed from the Earth. When it disappears from the sight, the power transmission is interrupted. In order to get the power from space continuously, we need to have many Solar Power Satellites distributed on the orbit. This is the reason why the geosynchronous orbit is considered beneficial. Since the access to the lower orbits is easier and cheaper than the geosynchronous orbit, the lower orbits will be also used in the initial demonstration phase.



The rotation speed of a satellite in geosynchronous orbit is same as that of the Earth (once per day). Solar Power Satellite in geosynchronous orbit is always seen in the same direction from the Earth..

Orbit	Orbital Characteristics (example)	Characteristics of Orbit	Reception Frequency	Size of Transmitting Antenna	Transportation Cost
Geosynchronous Orbit	36,000km	Always visible	Always	Large	High
Sun Synchronous Orbit	Inclination around 100 degrees, LEO	Always Sun Shining	Once/day (Twice/day)	Middle	Middle
Phase Repeating Low Earth Orbit	Inclination less than 90 degrees, Altitude 370km	Sun Shine/Shadow	Once/several days	Small	Low
Low Earth Equatorial Orbit	1,100km	Maximum Shadow Rate 1/3	Every two hours	Small	Low

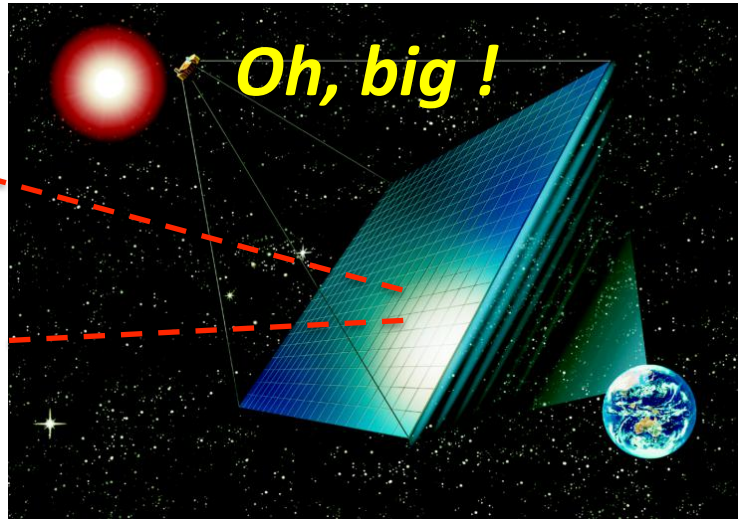
Candidates of Orbits for Solar Power Satellite

5. What technologies are required to realize Solar Power Satellite?

The output of power plant on ground is typically 1 GW (10^9 W). The size of GW class Solar Power Satellite is several square km. The weight exceeds 10,000 tons. We need technologies for construction of the large scale structure in space and low-cost rockets for material transportation from the ground. Technologies to transmit the microwave or laser precisely to the receiving site with a high efficiency are also required.

International Space Station is the largest space infrastructure we have now.

International Space Station, 100 m size



Solar Power Satellite, 1,000 -2,000 m size

6. Which is better, microwave or laser, for wireless power transmission from space to ground?

Microwave is considered more promising at this stage.

Microwave is categorized into radio waves while laser is categorized into light. Both are a kind of electromagnetic wave with different wave length. Microwave can transmit through the clouds and light rain, but laser cannot. Thus the microwave system is regarded more efficient and more reliable (stable) than the laser system.

However since the size of the transmitter and receiver is proportional to the wave length, the size of the laser system can be much smaller than that of the microwave system.

The microwave system is currently the main stream now, but the laser system is also studied. Either microwave or laser will be selected considering safety and the power cost. There is a possibility that both are used depending on the application.

Medium	Microwave	Laser
Frequency/Wave Length	~several GHz	~1 μm
Power Conversion	Solar-DC-RF・・・DC	Solar-DC-Laser-・・・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	Space-Ground	Space-Space Space-Ground

advantage

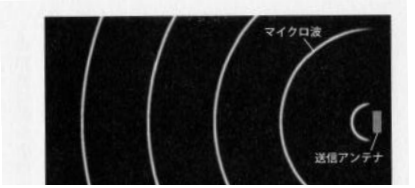
7. Laser propagates in a narrow beam, but microwave expands. Can microwave beam be directed to the receiving site?

Yes, we can direct the microwave beam precisely to the receiving site.

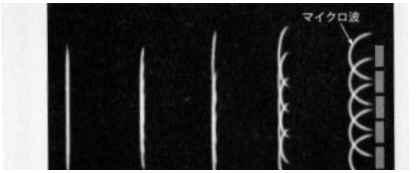
The expansion angle of electromagnetic waves (microwave and laser) is expressed as shown in the right. If we use a large single antenna, we can form a sharp microwave beam with a small expansion angle, just like laser. The expansion angle for the microwave radiated from a 1 km diameter antenna is almost equivalent to that of laser radiated from 1 cm diameter lens.

Since the size of the laser optical system is small, the direction of laser is controlled by adjusting the part of optics mechanically. But in the case of microwave, it is almost impossible to control the direction of 1-km antenna mechanically. Instead, a number of small antennas distributed in a large area are used to control the beam direction by adjusting the phase of microwave from each antenna. This type of antenna is called as the phased array antenna.

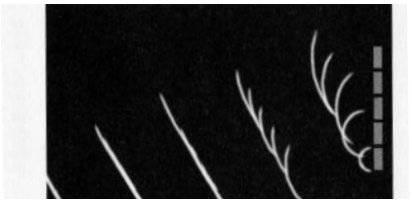
$$\text{Expansion Angle} \sim \frac{\text{Wave Length } (\lambda)}{\text{Size of Antenna(or Lens) } (D)}$$



Electromagnetic wave radiated from a single small antenna



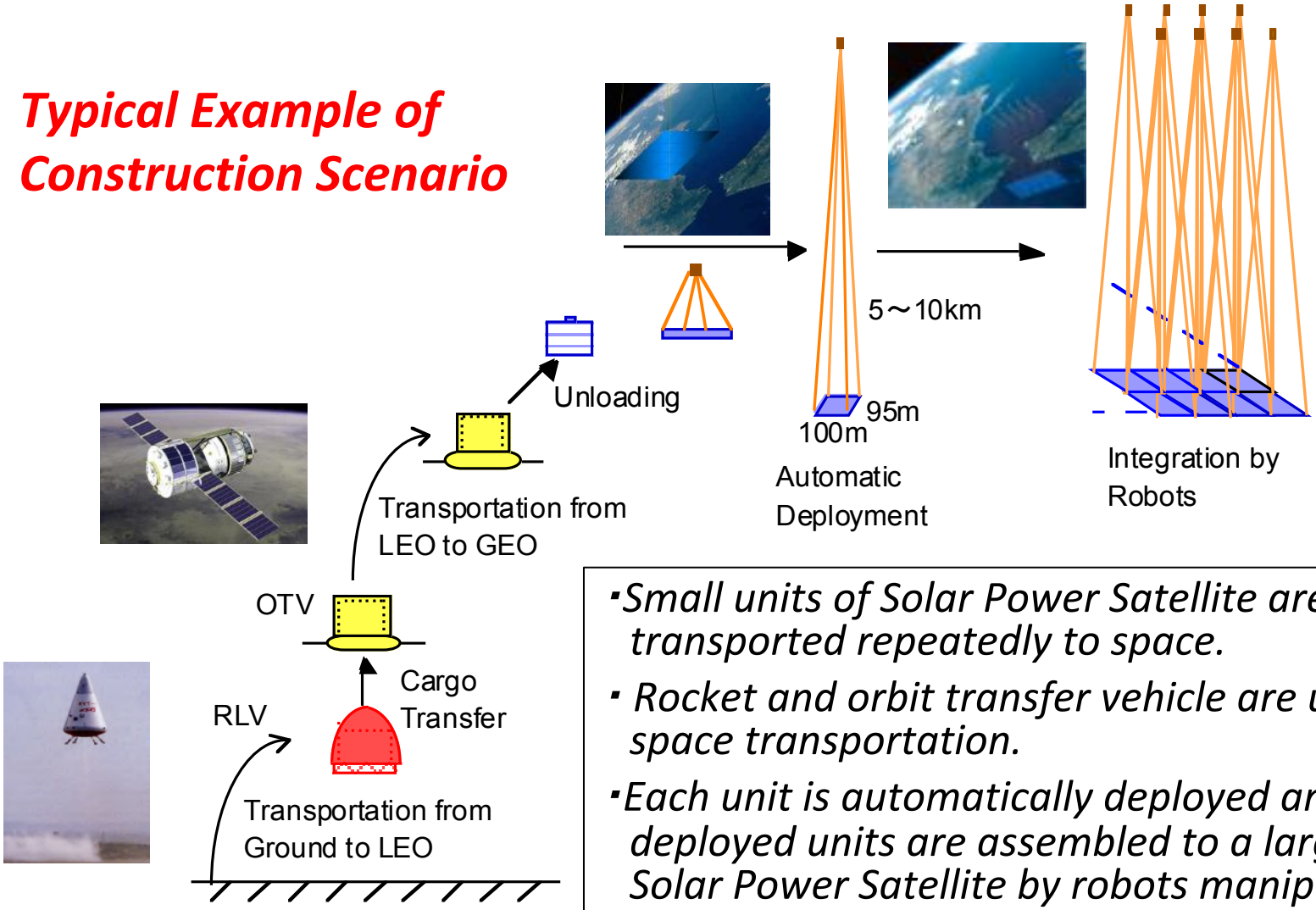
Electromagnetic wave radiated from an array of small antennas with a same phase



Electromagnetic wave radiated from an array of small antennas with a controlled phase variation. The beam direction is electrically controlled by changing the phase .

8. How is Solar Power Satellite constructed?

Typical Example of Construction Scenario

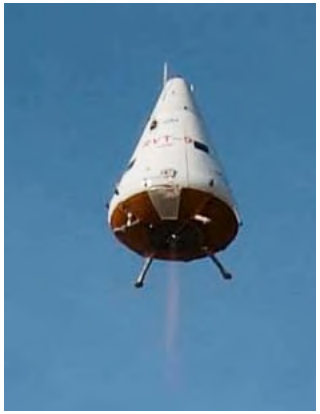


- *Small units of Solar Power Satellite are transported repeatedly to space.*
- *Rocket and orbit transfer vehicle are used for space transportation.*
- *Each unit is automatically deployed and the deployed units are assembled to a larger Solar Power Satellite by robots manipulated from ground operation center.*

9. What kind of rockets are used to transport construction materials to the orbit?

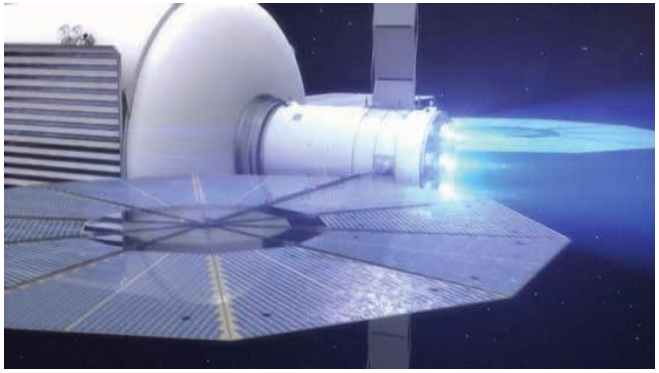
Reusable launch vehicle (RLV) will be used for transportation from ground to the low earth orbit around 500 km. The reusable launch system guarantees lower cost and more frequent flight as compared with the existing expendable launch vehicle.

Orbit Transfer Vehicle (OTV) with electric propulsion system will be used for transportation from the low earth orbit to the geosynchronous orbit. The electric propulsion system is operated by the electric energy generated by the solar power. It needs working gas, but does not need the fuel for combustion.



Reusable sounding rocket under development in JAXA. Vertical takeoff and landing.

Reusable space plane, Skylon, using Synergistic Air-Breathing Rocket Engine, designed by British company REL.



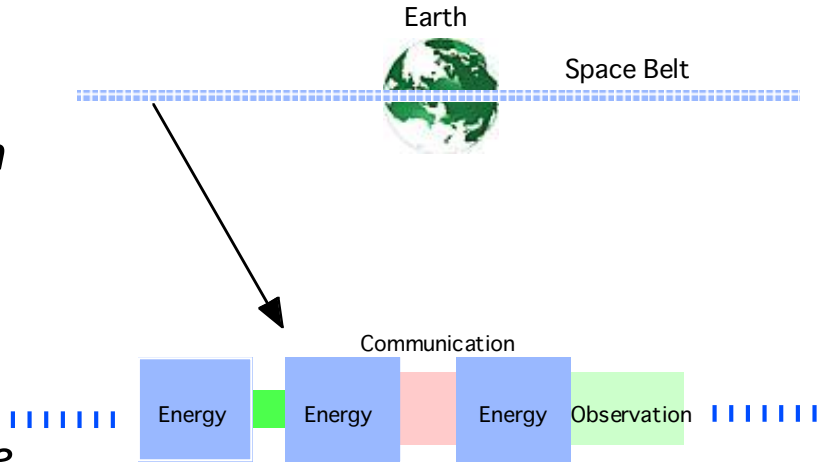
A large solar electric propulsion system illustrated in the Global Exploration Roadmap 2013 by ISECG.

10. Is it possible to construct Solar Power Satellites on the geosynchronous orbit that is already much crowded?

Yes, it's possible !

The satellite on the geosynchronous orbit looks like it is stationary when we look from the Earth. Many satellites for communication and broadcasting are usually put into this convenient orbit.

It is very difficult to place the Solar Power Satellites between the existing satellites on the geosynchronous orbit. However, since the Solar Power Satellites are big enough, they can incorporate the other satellites' functions as a complex.



Complex of facilities for Energy, Communication, Earth Observation, Space Telescope, Space Experiment, and Maintenance in Geosynchronous orbit.

Or, as shown in the right figure, it is possible to connect the facilities for solar power generation, communication, and broadcasting along the geosynchronous orbit. The infrastructure connecting the facilities is called as "Space Belt". In future, space hotels and space factories could be connected to the Space Belt.

If we construct solar power plant in the space belt 2 km wide along the geosynchronous orbit, 14 % of the round ring can satisfy the global energy demand（13,000 GW）.

11. Construction of Solar Power Satellite seems to be expensive. Can the power cost from Solar Power Satellite be reasonable?

Yes, it can be!

- *Past studies have shown that the power cost from the Solar Power Satellite can be competitive with that from the existing power plants if the costs for space transportation and electrical parts are remarkably reduced.*
- *It is required that the space transportation cost is reduced by 1/50 of current one. The cost of semiconductors needs to be lowered by several times to one order. These targets are quite challenging, but are considered technically feasible. Much more research is required to achieve them.*

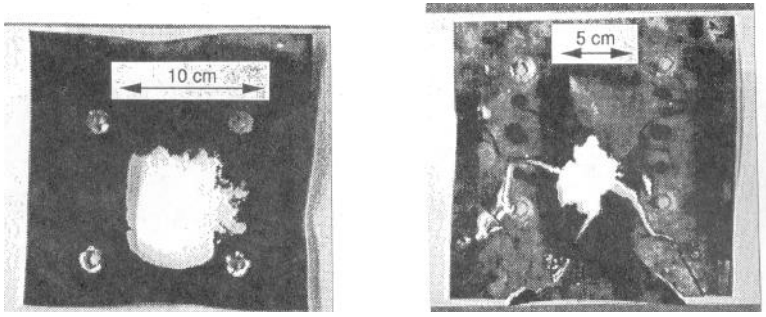
An image of reusable rocket like airplane. Using the reusable system like this, the space transportation cost can be remarkably reduced.

12. Will Solar Power Satellite be destroyed by the debris or meteorites impacts?

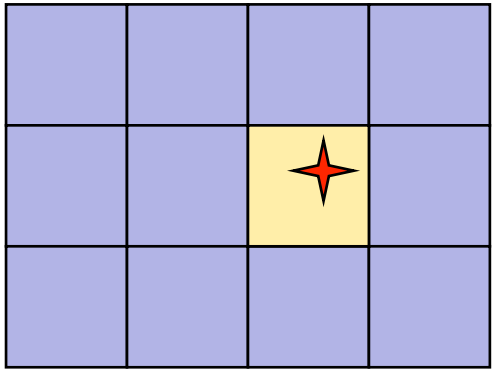
Yes, the impact point and its surrounding are inevitably destroyed, but it can be designed to localize the damage so as that the damage is within an allowable range of the solar power plant.

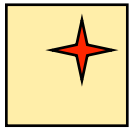
Collision frequency (impacts/km^2) for the geosynchronous orbit is:
once per 70 years for 10 cm size object,
once per 3 years for 1 cm size object, and
2400 times per year for 1mm size object.

The solar panel will be designed so as that the impact damage is localized in a module. If we adopt a module size of 0.5 m x 0.5 m, the power loss during 40 years will be 4.8%.

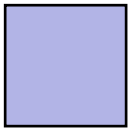


An example of damage observed in hyper-velocity impact experiment. The target is a plate simulating the solar panel. The damage size often reaches 10 times larger than the size of the projectile.





Failed module by impact



Good module

The solar array panel is designed that the impact damage does not propagate to other modules.

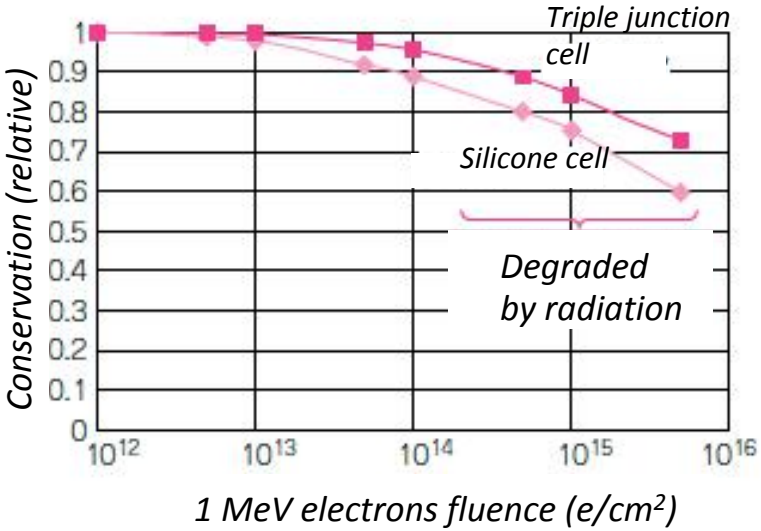
13. How long is the life of Solar Power Satellite

The life of Solar Power Satellite is designed to be 40 years.

The performance of power generation decreases year by year mainly due to the radiation deterioration of the photovoltaic cells and the impact damage by the debris and meteorites. Degradation less than 10 % in 40 years is the design target for Solar Power Satellite.

Multi-junction compound semiconductor solar cells with a high conversion efficiency are usually used in space. The radiation deterioration for the current photovoltaic cells in space is typically 10-15 % in 10 years as shown in the right panel. Some of new types of thin film type solar cell have lower radiation deterioration less than 5 % in 20 years. Further research is required to reach radiation resistance less than 5 % loss in 40 years.

The degradation by the impact damage can be less than 5 % in the 40 years if we adopt the appropriate modular design, as shown in No.12.



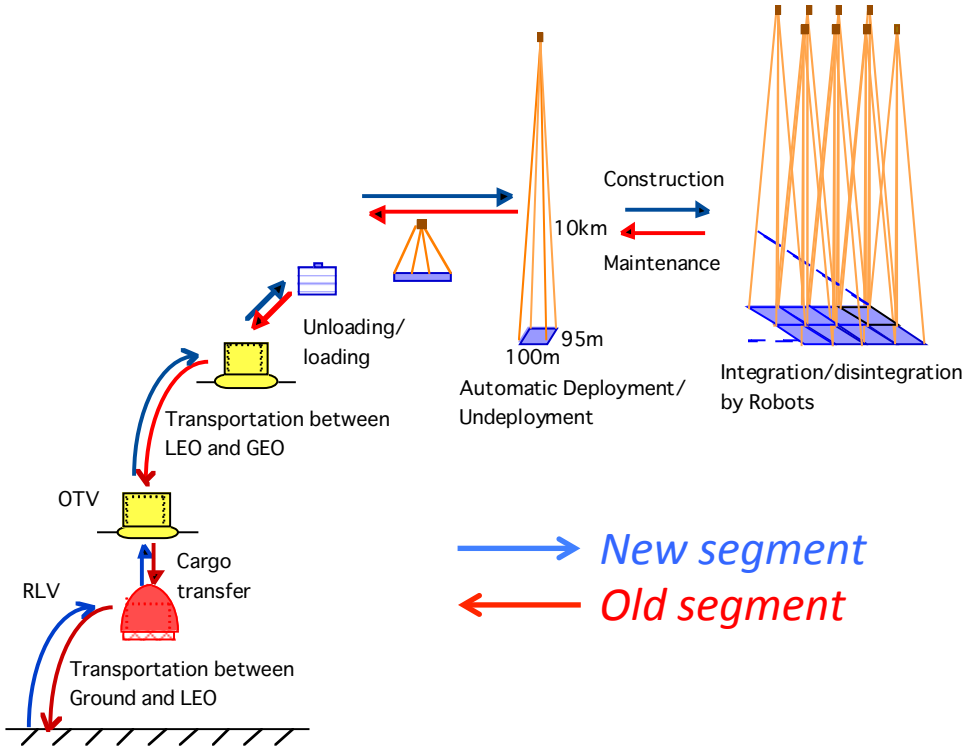
10^{15} corresponds to the fluence during 10 years on the geosynchronous orbit. Solar Power System, ③…Satellite, Nozaki, pp.137, Transistor Gijutsu (Japanese Journal), March 2010.

14. What happens when the life of Solar Power Satellite is expired? Is it going to be a space junk?

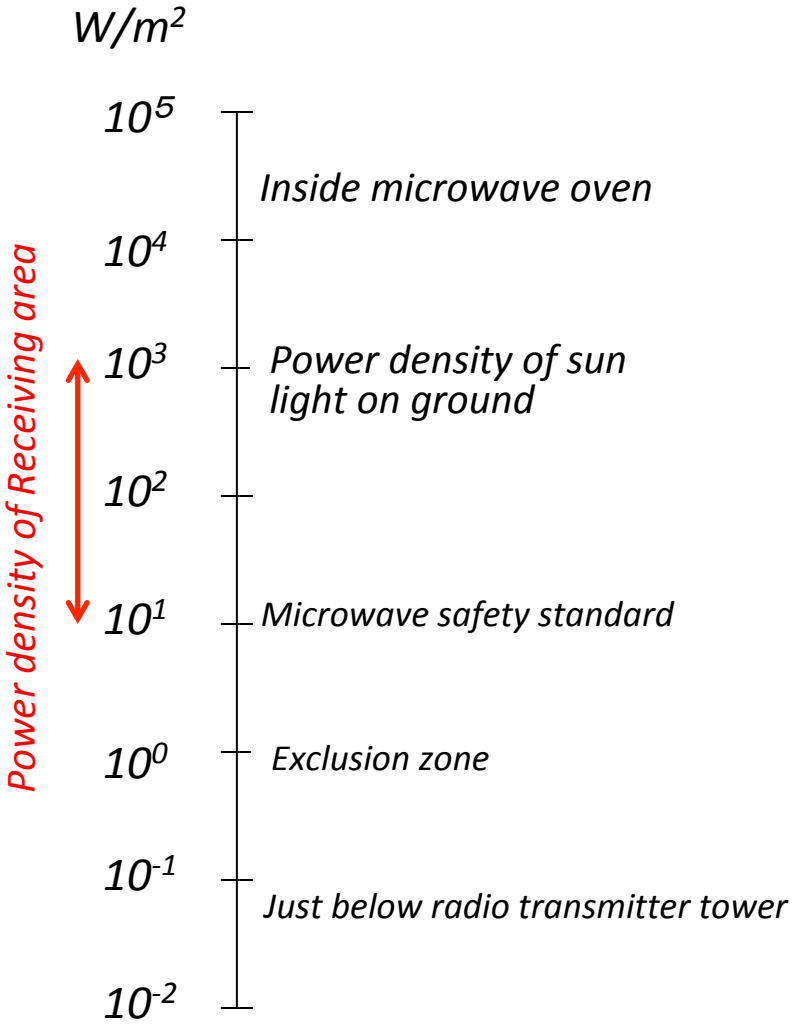
No, any junk is left in space in the life cycle of Solar Power Satellite.

Solar Power Satellite loses the power generation capability by 10 % in 40 years. Around this timing, Solar Power Satellite is renewed. All the old segments of Solar Power Satellite are exchanged by new segments, as shown in the below figure.

The old segment is transported to the ground by the orbit transfer vehicle and by reusable launch vehicle that carry the new segment to the orbit. The old segment is refurbished on ground by changing the life-limited. In this scenario, no junk is left in space. This recycling operation requires establishment of space transportation infrastructure for massive cargo flow between space and ground at low cost.



15. Is Solar Power Satellite safe?



Yes, it can be designed safe !

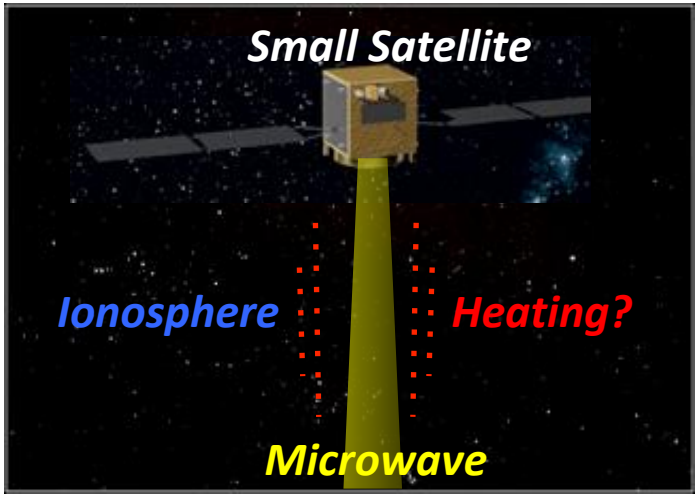
- The major concern on Solar Power Satellite is the influence of microwave on human health. The peak intensity of the microwave beam is at the center of the receiving site which is about the intensity of solar irradiation. The intensity at the edge of the receiving site corresponds to the microwave safety standard ($1mW/cm^2$). The exclusion zone will be set at 1/10 of the safety standard.
- Since the maximum microwave power intensity is about the solar irradiation localized near the beam center, there will be no hazard for birds, insects, and airplanes to fly through the microwave beam.

16. Is there any possibility that the ionosphere is strongly heated or depleted by the microwave beaming?

No, many theories have shown that no strong interaction is expected between the microwave from Solar Power Satellite and the ionosphere.

Theoretically, strong heating and resulting depletion of the ionosphere are excited by nonlinear interaction process if the intensity of the microwave is strong enough. But the microwave intensity equivalent to the sun light is considered to be much smaller for the nonlinear effect.

However, this is a theoretical prediction. It is highly necessary to confirm the prediction by space experiment as early as possible.



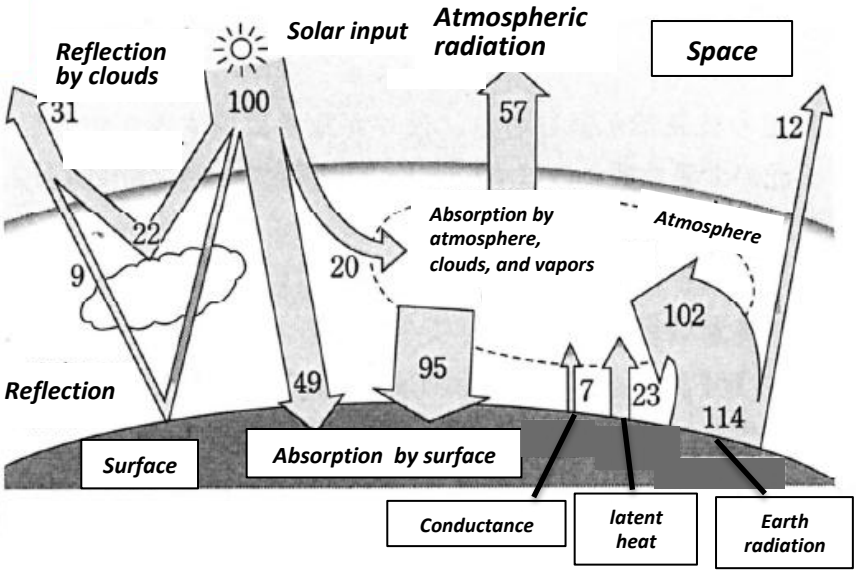
A plan for the small satellite experiment to study the effects of microwave beam on the ionosphere. This experiment has been proposed in Japan, but not yet accepted.

17. Solar Power Satellite provides additional energy to the Earth. Will the temperature of the Earth increase?

The temperature rise is practically negligible.

The input power from the Sun to the Earth is almost 10,000 times of global power consumption. The same amount of the input power is released from the Earth, as shown in the right figure. If all global energy is provided from space to the Earth as an additional energy flow, still the flow is negligibly smaller than the flow-in energy from the Earth and flow-out energy from the Earth. In fact, the temperature rise is calculated as 0.007℃.

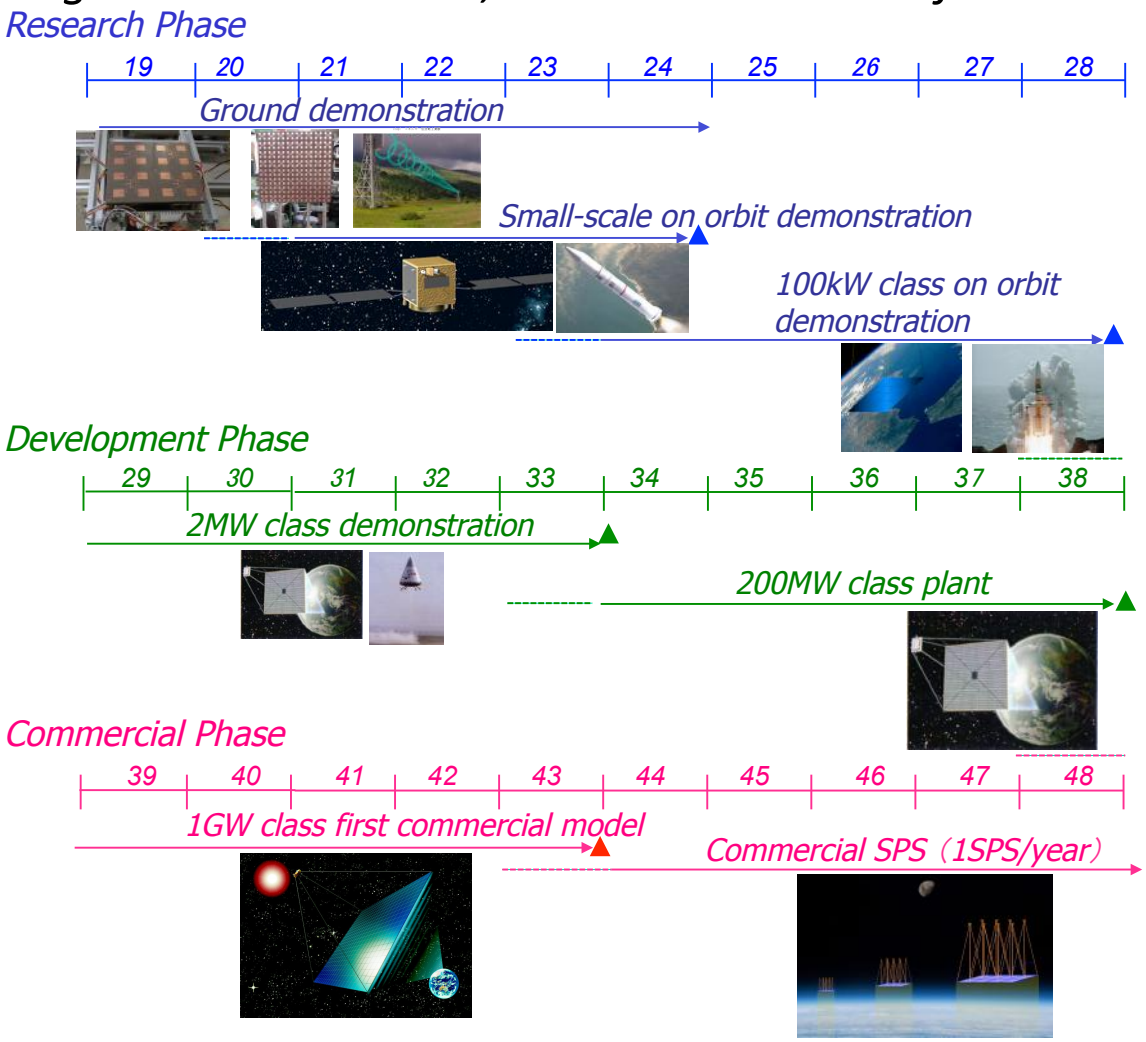
Actually, there is about 2 % fluctuation in the solar energy intensity depending on the solar activity. The global energy consumption is only 5% of the fluctuation. The temperature change due to the additional input by the Solar Power Satellites is well below the natural fluctuation.



Flow-in energy from the Sun: 100%
Flow-out energy from the Earth: 100%
Reflection from the clouds and the ground: 31%
Thermal radiation from the atmosphere: 57 %
Radiation from the Earth surface: 12%

18. When is Solar Power Satellite realized?

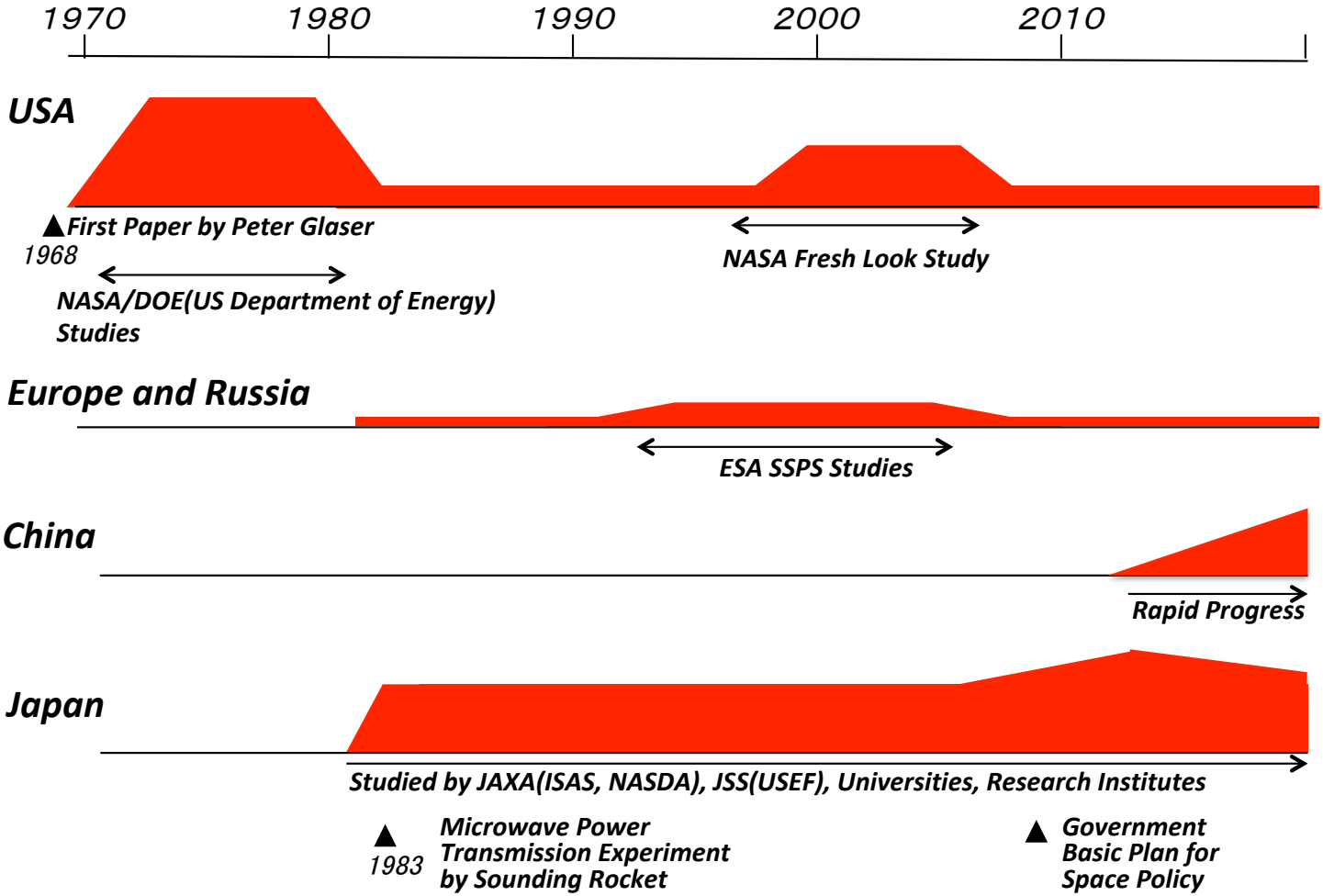
If we follow the roadmap below, we will be able to realize the first commercial Solar Power Satellite of 1GW class in mid-2040's. Increasing the number of the Solar Power Satellites year by year , both the issues, the depletion of energy resources and deterioration of the global environment, will be overcome before 2100.



19. Is Solar Power Satellite studied in Japan?

Yes, very actively.

The international research activities on Solar Power Satellite is shown below. The height of red area indicates the research activities qualitatively. The research started almost 50 years ago in the USA. Now, Japan is the leading country in the research and development of Solar Power Satellite.



20. Who are making the solar power research in Japan?

Japan Aerospace Exploration Agency (JAXA) (RDD, ISAS) :

System Study, Microwave Power Transmission, Laser Power Transmission, Power Generation, Large Space Structure, Space Robotics, Feasibility Study of Demonstration Experiment in Space, , Study of Solar Power Satellite Development Scenario

Japan Space Systems（JSS）:

System Study, Microwave Power Transmission, Application of Solar Power Satellite Technologies to Commercial Technologies(Spin-off), Study of Solar Power Satellite Development Scenario

Universities and Research Institutes :

Microwave Power Transmission, Laser Power Transmission, Large Space Structure, Space Robotics, Power Generation, Application of Solar Power Satellite Technologies to Commercial Technologies(Spin-off)

Companies :

Microwave Power Transmission, Laser Power Transmission, Large Space Structure, Application of Solar Power Satellite Technologies to Commercial Technologies(Spin-off)

The research for space transportation for Solar Power Satellite is conducted mainly at JAXA and Universities.

21. What are the global research situations for Solar Power Satellite?

1. U.S.A. : NASA was making a systematic research in the 1970's and 1990's. Now researchers of universities, think tanks, Naval Research Laboratory, and other research institutes are making investigation and researches.

2. Europe: A researcher's group of ESA and space companies are continuing the research, but not so active.

3. Russia : Formerly, universities and research institutes were making research, but now the research remains individual researcher's level.

4. China: Research has rapidly advanced in the SPS system design and associated technologies.

Space transportation system: Reusable launch vehicles, including sub-orbiters, are studied mainly in the USA, Europe, and Japan.

22. Will Solar Power Satellite be developed by national or international efforts?

International framework is essentially required for Solar Power Satellite.

Solar Power Satellite utilizes the space resource that is common property of humanity. Solar Power Satellite will be developed to ensure benefits for all countries in a framework of international collaboration based on the international space laws.

The demonstrations of Solar Power Satellite in the research phase can be conducted by single nation or jointly by several nations, but large-scale verification in the development phase will be conducted in the international framework. In the commercial phase, the management, development, and benefit allocation are controlled by an international agency composed of all countries.

23. Will our society change with Solar Power Satellite?

Yes, it certainly will !

If we could realize Solar Power Satellite.....

- *limitless clean energy will be obtained,*
- *global environment will be restored and preserved,*
- *international conflicts over energy resources will be terminated,*
- *creative and comfortable society will be established,*
- *..... and, new civilization and culture will be developed in the creative and vigorous society expanding into space.*