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Moon and Mars Solar Power Satellites (SPS) in Comparison to Earth SPS

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Abstract

In this project, the study of Lunar SPS and Mars SPS were conducted. And the technical problems related to them were clarified. For each, orbits, transmission time, required number of satellites, the area of the solar array, and the size of the antenna were considered. For Lunar orbit, we found that the required number of satellites is two when the apoapsis altitude is 6000 km, and the periapsis altitude is 100 km. For Mars orbit, the apoapsis altitude is 11,000 km and the periapsis altitude is 200 km. In addition, at a frequency of 5.8 GHz, the transmission antenna size was 1.2 km for Lunar orbit and 2.2 km for Mars orbit. The transmission distance changes in elliptical orbits. The changes of efficiency caused by them are also estimated. In order to reduce the antenna size, it is necessary to choose higher frequency as operating band and have to use RF power amplifier designed for high frequency band. However, there are some technical problems. Therefore, instead of the RF power amplifier, the use of electron tubes was considered.
Keywords: SPS, Lunar, Mars, WPT, Orbit

Nomenclature

e : Euler's number
λ : Wavelength
π : Pi
η : Beam transmission efficiency
τ : Square root of η
L : Antenna dimension
d_r : Radius of the rectenna
d_t : Radius of the transmit antenna
D : Distance between two antennas
H : Length of Farfield region

Acronyms/Abbreviations

SPS : Solar Power Satellite
WPT : Wireless Power Transmission
RF : Radio Frequency
DC : Direct Current
GEO : Geosynchronous Equatorial Orbit
PV : Photo Voltaic
SA : Solar Array
PAE : Power Added Efficiency
MMIC : monolithic microwave integrated circuit
TWTA : Traveling Wave Tube Amplifier
ISRU : In Sitsu Resource Utilization
JAXA : Japan Aerospace Exploration Agency
ICNIRP : International Commission on Non-Ionizing Radiation Protection

1. Introduction

In recent years, the use of fossil fuels has been reconsidered, because of global issues such as global warming, climate change. Renewable energy is expected to be an alternative energy source to fossil fuels. On the other hand, renewable energy has a large drawback that it is difficult to supply energy stable.

To overcome these issues, the Solar Power Satellite (SPS) has been proposed [1]. The concept of SPS is that SPS generates electricity from sunlight using a huge PV cell array in outer space and transmits generated energy wirelessly to Earth via microwave beam. It is expected that SPS will be a huge clean, stable, and sustainable energy source alternative to the conventional ones depended on fossil and nuclear resources in the future.

Nowadays, the possibility of SPS is not only for earth, but also other celestial bodies. Human have been exploring space for a long time. The history of lunar exploration began with the Lunar program conducted by Soviet Union [2], and since then humans have carried out projects such as Apollo program conducted by the U.S. The history of Mars exploration began in the 1960's and many projects represented by Viking program conducted by the U.S. have been carried out. Recent years, the exploration programs for these two celestial bodies are kicked into the next phase. In lunar exploration, the Artemis program was launched in 2017. The purpose of the Artemis program is not only for sending mankind to Lunar surface, but also making a foundation for permanent residence on the moon and commercial use. Furthermore, the Artemis program is expected to prove out the technologies that will take us to Mars and beyond.

Even if humans live outside of Earth, we will still need electricity as an energy source to support our daily lives, science experiments. According to the scenario devised by JAXA [3], around 2030, a 10-kW class power generation facility will be constructed, and a small number of people will be stationed there to conduct water resource surveys. A hydrogen production plant will be constructed around 2040, and huge amount of electricity will be required to operate it. Exploration and settlement on Mars will require as much or more power than on the Moon. At that time, SPS will be a candidate of the power source for use there.

In this paper, we considered and discussed the concept of SPS assuming use on each celestial body. As a prerequisite, we used Tethered SPS model for the earth as a base model. In other words, the onboard equipment of SPS for other celestial body was assumed to have the same configuration as SPS for Earth. This research was conducted from the following perspectives:

1. Overview of tethering SPS with the earth
2. Environment of each celestial body
3. Operational orbit, constellation
4. Satellite size and operating frequency
5. Clarification of technical issues.

2. Summary of the original tethered SPS for Earth

The first concept of SPS was proposed by Peter. E. Glaser in 1968[1]. Ever since, many countries did research activities about SPS and a lot of types of SPS models have been considered. Tethered SPS is one of them. Tethered SPS as shown in Fig. 1. was proposed around 15 years ago. And this concept was studied by a team organized by the Institute for Unmanned Space Experiment Free Flyer (USEF) (current J-spacesystems). In this chapter, the structure, the equipment, and the operating environment of tethered SPS are described shortly.

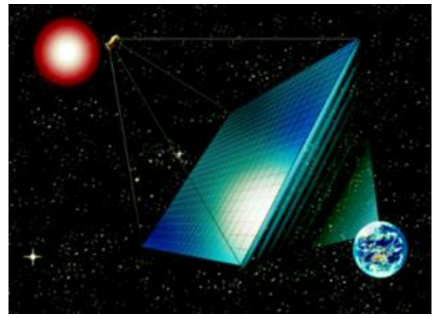
Fig. 1. Illustration of tethered SPS

2.1 Structure of tethered SPS

The most significant feature of tethered SPS is a modular structure to ensure robustness, economical cost, and easy assembly. In this model, a tethered SPS unit consists of 38,000 panels which have functions for both power generation and power transmission. 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. 2.). This model has a relatively simple and robust structure, which contributes to the low-cost production and high reliability [4,5].

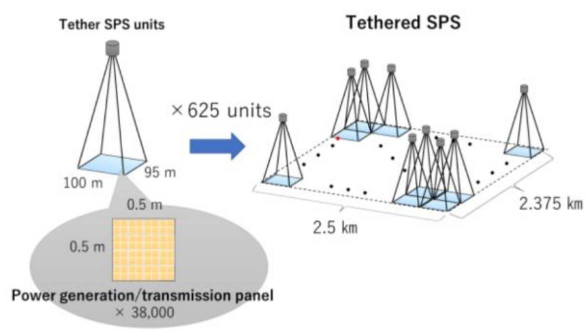

Fig. 2. Illustration of tethered SPS.

2.2 Equipment of power generation/transmission panels

The main components of the generation/transmission panels are shown in Fig. 3. The onboard equipment is classified into the power generation section, direction finding section, and power transmission section. In the generating part, the electric power is generated by PV cells. And then, the voltages which are loaded to PV cells are controlled by the MPPT and correct the power effectively. The generated power is divided into capacitors and DCDC converters by MPPT, and from the DCDC converters into onboard equipment such as OBCs and TCMs. RF is generated by the Transmitter and is passed through several amplifiers and radiated from the antenna (see Fig. 4.). Direction finders identify the transmission direction. And OBC control equipment. As shown in Fig. 4., after the power is entered into the power transmission section, RF signal is phase-shifted by a phase shifter, the RF power is amplified by the Low noise amplifier and the Power amplifier.

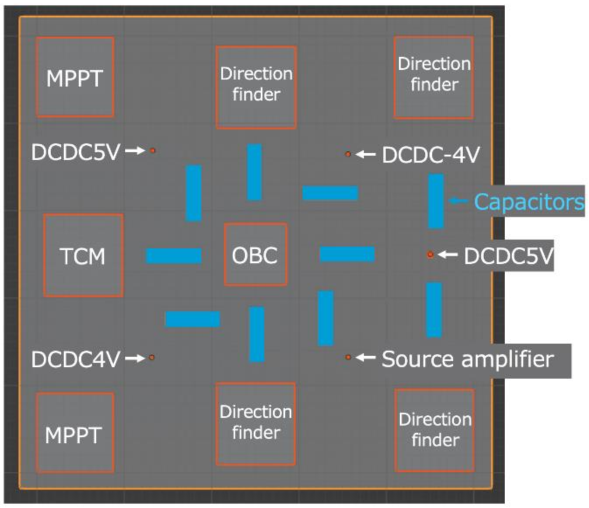

Fig. 3. On-board equipment layout

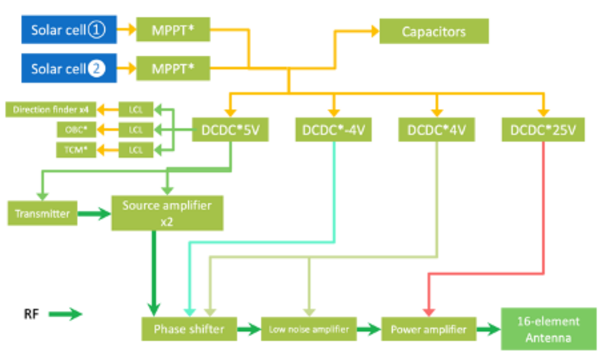

Fig. 4. Equipment Configuration for SPS

2.3 Operating environment

SPS for the earth will be placed in the GEO. The altitude of the GEO is about 36000 km. At the orbit, the orbital period of the satellite is approximately 24 hours. It means that SPS can point to one place for 24 hours entirely. And due to the altitude, SPS is out of the Earth's shadow for most of the year, it can generate electricity day and night, except about 70 minutes for about 6 weeks around the spring and autumn equinoxes. On the GEO, the forces worked to the satellite are gravity and centrifugal force. And these two forces are equal on the GEO. So, the satellite continues to the orbit, and the attitude of large structures can be controlled by gravity gradients.

The energy density of sunlight in geostationary orbit is defined as solar constant, approximately 1.37 kW/m^2. On the other hand, the density of sunlight on the ground is affected by attenuation by the atmosphere and the angle of incidence of sunlight. Therefore, the energy density can't be stable depending on latitude, season, and time. And it decreases to about 140 W/m^2 on average. In other words, if solar power is generated in the GEO, about 5 to 10 times more energy can be obtained from sunlight than on the ground. Even if approximately 50% energy loss occurs in the process of converting the generated electricity into microwaves and convert it as electricity again, the overall system has the potential to obtain electricity with an efficiency approximately 2.5 to 5 times higher than that of ground solar power generation.

As same as sunlight intensity, microwaves are also attenuated when they pass through the atmosphere. However, it is known that RF waves at specific frequencies are less affected by attenuation and scintillation in the atmosphere and ionospheric layer. Fig. 5. shows the relationship between frequency and attenuation levels caused by several factors. In this figure, the effects of (a) Ionospheric layer scintillation, (b) Rain attenuation, (c) Atmospheric absorption during clear skies, and (d) Atmospheric scintillation are indicated. The smaller attenuation can be confirmed at approximately 1 GHz to 10 GHz frequency range. In addition to that, the frequency from 2.4 to 2.5 GHz and 5.725 to 5.875 GHz are assigned to the ISM band frequency. The ISM bands are universal and open frequency bands intended for use in industry, science, and medical applications. For these reasons, SPS for Earth is being considered to use RF in the 5.8GHz frequency band.

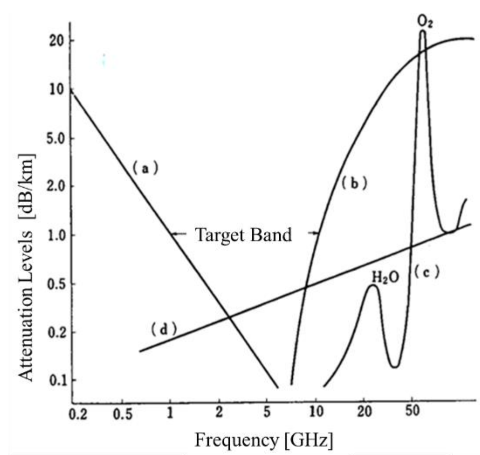

Fig. 5. Microwave attenuation by atmosphere and Ionosphere [6]

When operating SPS on Earth, it is necessary to consider the effects of microwaves on life and electronic equipment. According to the guidelines set by ICNIRP, the safety standard value for microwave exposure to the human body is set to be 0.08 W/kg or less at frequency range 10 MHz to10 GHz [7]. For this reason, rectenna construction sites are set in areas with little impact, such as coastal areas.

3. The SPS for Lunar

3.1 Environment of the Lunar

There are so many differences in the environments between Earth and Lunar. Some of them need to be taken into consideration when considering SPS operations on the Moon. In this section, the atmospheric composition, the contamination of lunar regolith, and sunshine hours will be described.

Firstly, atmospheric composition is described. The moon's atmosphere is less than 1/100 trillion times smaller than that of Earth. The pressure rises and falls around approximately 3×10^{-15} atmospheric pressure, and the total weight is about 25 tons. In conclusion, there is almost no atmosphere on the moon. Since there is no attenuation caused by the atmosphere or the ionosphere, when operating SPS on the Moon, it is possible to operate at a higher frequency band than on Earth.

It is known that the surface of Lunar is covered with the sand named Regolith. Most of lunar regolith is less than 1mm in size, with some being as small as 10μm. These are smaller than common earth sand. The samples of lunar regolith were brought back to Earth on past space missions. And research has been conducted on their composition. Through this research, it is reported that lunar regolith contains metallic iron powders. In preparation for lunar surface exploration and settlement, research is also being conducted on how the lunar surface regolith will affect wireless power transmission. The study about wireless power transmission using short-range electromagnetic coupling reported that as the iron content of regolith-simulating samples increases, wireless power transmission efficiency decreases by several percentage points [8]. Therefore, we need to consider and evaluate the impact of regolith on the efficiency of very long distance WPT.

On the other hand, Lunar regolith may also provide benefits. It is known that Lunar regolith also contains other metallic elements, hydrogen, Oxygen, and silicon. Research is being carried out to create water using the hydrogen and Oxygen contained in regolith and research to create construction materials like concrete. By refining and utilizing the abundant silicon element within the lunar regolith, it is expected that solar cells from the lunar regolith are produced on lunar in the future. The manufacturing to utilize these resources are known as ISRU.

If the base or settlement site is selected to the polar region, and demand power is less than dozens kW, solar power generation on the lunar surface is an effective power source in areas where there is almost constant sunlight. On the other hand, even in such areas, there are 2.79 consecutive days with no sunlight, and it is estimated that it will take 7.54 days to return to 100% power generation. In addition to that, it is said that even if the height is increased and a 1000m tower type power generation system is adopted, it will not be possible to obtain 100% sunlight rate [9].

3.2 Orbit of Lunar SPS

Currently, there are plans to construct a manned base on the Moon. The south polar region is often a candidate for the site of a base. In this study, we considered an orbit through the South Pole so that energy could be sent to this base. In addition, the location of the rectenna was assumed to be the center of the Shackleton Crater in the south polar region [10]. The wall angle of Shackleton crater is 30°. As the elevation angle increases, there is concern about interference at the crater rim. Considering this, we assumed that power could be transmitted within an elevation angle of ±45° [10].

In general, there are trade-offs between the orbit altitude and the required number of satellites. As the altitude is increased, power transmission available time ratio during one period increases. Lower altitude requires a greater number of satellites because power transmission available time ratio during one period is shorter, and higher cost. Therefore, we considered elliptical orbits to increase power transmission available time ratio during one period and to reduce the number of satellites.

We used STK to consider the orbits. The analysis condition was set to TwoBody. We conducted the analysis on a certain day with an orbit inclination of 90°. The following Fig. 6. shows the simulated orbit. Table 1. shows the difference between circular and elliptical orbits with a periapsis altitude of 100 km.

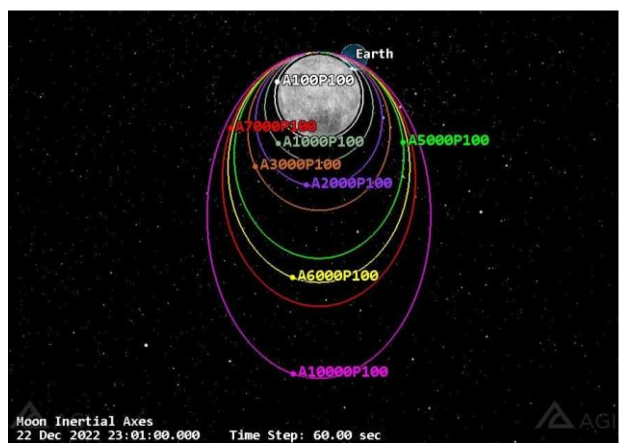

Fig. 6. Simulation Analysis of Each Lunar Orbit by STK

Table 1. Power transmission time and the required number of satellites for each Lunar orbit

Apoapsis altitude [km]	Orbital period [s]	Power transmission available time [s]	Power transmission time ratio during one period [%]	Required number of satellites
100	7067.4	115	1.6	62
1000	9816.8	1430	14.6	7
2000	13206	3360	25.4	4
3000	16914	5820	34.4	3
5000	25191	11940	47.4	3
6000	29783	15660	52.6	2
7000	34560	19620	56.8	2
10000	50177.9	33300	66.4	2

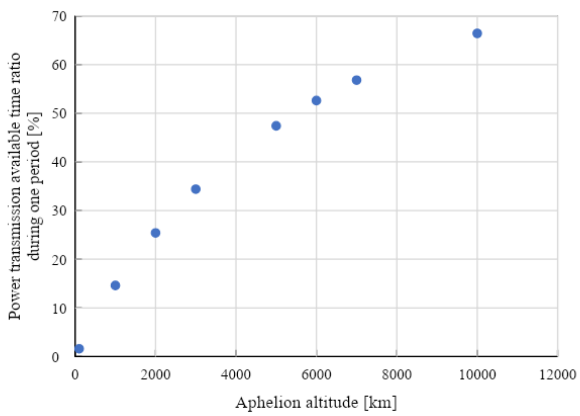

Fig. 7. Relationship between apoapsis altitude and power transmission time ratio for lunar orbit

In circular orbit, the power transmission available time ratio during one period is 1.6 % and the required number of satellites is 62 satellites. On the other hand, in elliptical orbits, when the apoapsis altitude was increased from 100 km to 10,000 km, power transmission available time ratio during one period increased to 66 % (see Fig. 7.). Required number of satellites can be reduced from 62 satellites to 2 satellites. In addition, the higher the altitude, the larger the size of the antenna and the higher the cost. Therefore, from the viewpoint of cost reduction, this study focuses on a lunar polar elliptical orbit with an apoapsis altitude of 6,000 km and a periapsis altitude of 100 km.

3.3 Size of PV cell array for Lunar SPS

We calculated the size of the required solar array. The orbit was set to the Lunar orbit with an apoapsis altitude of 6000 km, a periapsis altitude of 100 km, and an elevation angle range of ±45°. In this orbit, power transmission is possible for approximately 53 % of 496 minutes of a period. When 2 satellites transmit 1 GW, each satellite must transmit 0.95 GW. Assuming a solar array conversion efficiency of 35 % and an energy conversion efficiency of 50 %, the required area of the solar array will be approximately 4.0 km². In order to reduce the required area of the solar array, we considered improving the efficiency. Assuming a solar array conversion efficiency of 50 % and an energy conversion efficiency of 80 %, the required area of the solar array will be smaller to approximately 1.7 km² (see Table 2.).

Table 2. Power transmission and required area of the solar array for Lunar orbit

Power transmission per one period [GJ/period]		29783
Required number of satellites		2
Power transmission per one satellite [GW/satellite]		0.95
Required area of the solar array [km²]	SA : 35 %, Energy : 50 %	3.97
	SA : 50 %, Energy : 80 %	1.74

3.4 Size of Transmission antenna for Lunar SPS

Once the altitude of SPS is determined, the size of the antenna can be determined. In this section, the orbit proposed in the previous section, a lunar polar elliptical orbit with an apoapsis altitude of 6,000 km and a periapsis altitude of 100 km, will be the base orbit.

When the microwaves propagate, the region where microwaves propagate as plane waves is called the Far field. And the border height of this region is expressed equation. 1. Fig. 8. shows the relation between the antenna diameter and height of the Fairfield region at each operating frequency. In this region, beam transmission efficiency is expressed by the Friis's formular (eq. 2). Therefore, the antenna size to be used is determined once the beam transmission efficiency, wavelength, and power transmission distance are determined.

$$H = \frac{2L^2}{\lambda} \quad (1)$$

$$\eta = \left(\frac{\pi d_t d_r}{4\lambda D}\right)^2 \quad (2)$$

If the altitude is below the border, equitation. 3 and 4. are used to determine the beam transmission efficiency [11], instead of eq. 2.

$$\eta = 1 - e^{-\tau^2} \quad (3)$$

$$\tau = \frac{\pi d_t d_r}{4\lambda D} \quad (4)$$

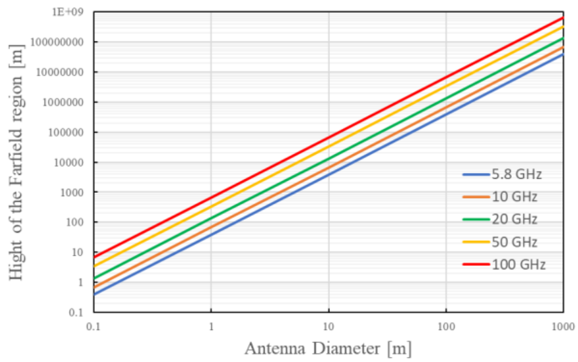

Fig. 8. Relationship between the antenna diameter and the Farfield region

Assuming an apoapsis altitude of the determined Lunar orbit to be the altitude of SPS, the power transmission distance will be 6000 km. And the diameter of the rectenna is assumed to be 500 m, Beam transmission efficiency is assumed to be 0.9. At this time, assuming that the operating frequencies are 5.8, 10, 20, 50, and 100 GHz, the size of the power transmission antenna was calculated. Fig. 9. shows the relation between the operating frequencies and transmit antenna.

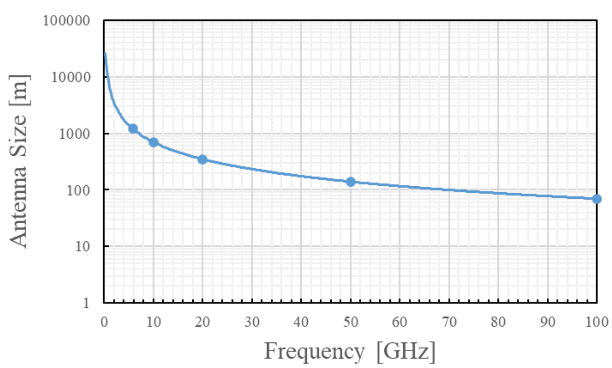

Fig. 9. Relation between the operating frequencies and the size of transmit antenna for the Lunar SPS

From the Fig. 9., the size of the transmission antenna at 5.8GHz is 1.2 km long, but if 100 GHz is selected as the operating frequency, the size can be reduced to about 70 m. By simple calculation, the antenna dimension decreases by 5.8%, so the antenna area decreases by 0.3%. This miniaturization is very effective from the viewpoint of antenna transportation costs. That means the transportation cost of the power transmission antenna will be 3/1000 times lower.

On the other hand, as mentioned in the previous section, to generate GW class electricity in that orbit, a SA with an area of approximately 4.0 km² is required. This extreme gap between the size of the transmission antenna and the SA makes it difficult to employ power generation/transmission panels. Therefore, if a high frequency band around 100 GHz is selected as the operating frequency, it is necessary to reconsider the structure of the SPS. In addition to that, devices that use high frequencies have some technical problems. This will be discussed in the discussion chapter.

4. The SPS for Mars

Recently, plans to migrate Earth to other planets are attracting attention. It is confirmed that Mars has H_2O (see Fig. 10.). Therefore, it is considered a candidate site for colonization. We investigated whether SPS could be used as a power plant for living on Mars. We also considered technical issues that need to be resolved.

The Mars migration plan proposed by SpaceX and Artemis program plan to go to Mars and live there [12,13]. Possible locations for the base include caves, Hellas Planitia, and the North Pole [14,15]. This time, we decided on the location of the base by focusing on H_2O. The reason for focusing on H_2O is;

1.Water is essential for human life,

2. If water exists, it is possible to create fuel cells and store electricity,

3.Water becomes a rocket propellant.

Currently, H_2O is observed on Mars in the atmosphere and polar caps. It is said that H_2O exists underground in the subsurface and in hydrated minerals [16, 17, 18]. In this study, we focused on the polar cap, which has already confirmed the existence of a large amount of H_2O. In particular, the temperature difference in the North Pole is smaller than in the South Pole, and it is thought that there is a large amount of H_2O ice, so this paper assumed that a base would be built in the North Pole [19].

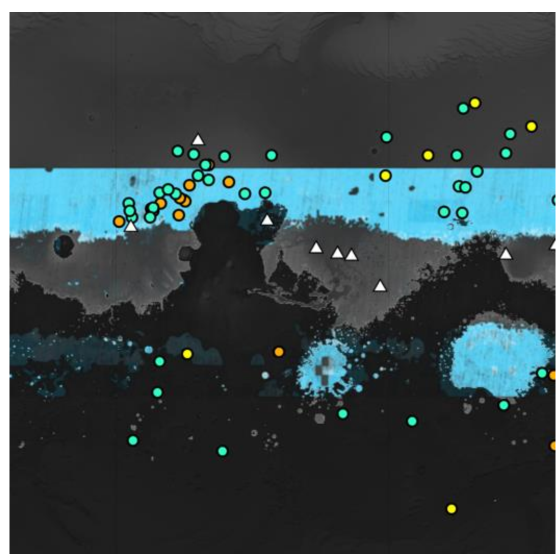

Fig. 10. Distribution of water on Mars

4.1 Environment of the Mars

We will summarize Mars's orbit, mass, dust storm, atmosphere, magnetic field, and topography as environmental factors on Mars. The comparison of main parameters of Mars and Earth is shown in Table 3.

Table 3. Comparison of main parameters of Mars and Earth [20]

	Mars	Earth
Rotation period	24h37min	23h56min
Orbital period	687day	365day
Mass (Earth :1)	0.1074	1
Radius [km]	3396.2	6378.1
Satellite	2(Phobos, Deimos)	1 (Lunar)
Satellite dimension [km]	Phobos: 13×11×9 Deimos: 8×6×5	Moon (radius): 1737.4
Rotation axis inclination [deg]	25.19°	23.44°
Orbit length radius [km]	149.6M	227.9M

Mars is covered in regolith, which is small particles containing iron oxide formed by weathering of rocks and other materials over a long period of time [21]. Mars also has four seasons because its axis is tilted 25.19 degrees. This creates a temperature difference, which generates updraft, and it makes a dust storm. Furthermore, because Mars moves in an elliptical orbit, large-scale dust storms that completely cover Mars occur once or twice during summer in the southern hemisphere [22,23]. However, because of large temperature differences throughout the year, CO_2 repeatedly sublimates and solidifies. It changes the atmospheric pressure by about 30% and changes the composition of the atmosphere. Regarding the magnetic field, Mars has no magnetic field. Therefore, it is said that magnetic torquer attitude control cannot be used. Regarding the magnetic field, there are Mount Olympus, which is over 21 km high, and Marineris Canyon, which is 11 km deep. [24,25]

4.2 Orbit of Mars SPS

In the same way, we also considered an orbit through the pole of Mars. The location of the rectenna was assumed to be in the north polar region. We assumed that power could be transmitted within an elevation angle of ±45°. As with the Lunar orbit, we considered an elliptical orbit to reduce the number of satellites and costs. The analysis condition was set to TwoBody. We conducted the analysis on a certain day with an orbit inclination of 90°. The following Fig. 11. shows the simulated orbit. Table 4. shows the difference between circular and elliptical orbits with a periapsis altitude of 200 km.

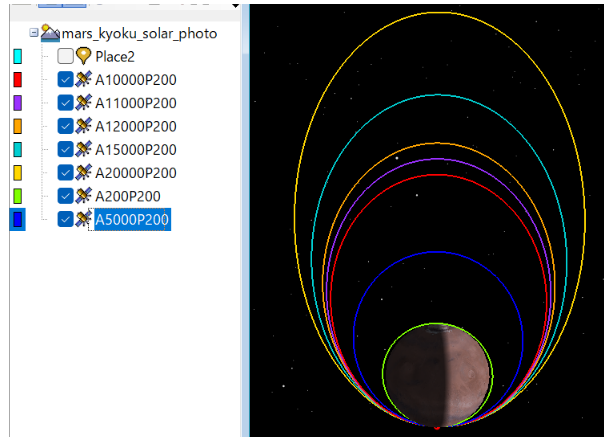

Fig. 11. Simulation analysis of each Mars orbit by STK

Table 4. Power transmission time and the required number of satellites for each Mars orbit

Apoapsis altitude [km]	Orbital period [s]	Power transmission available time [s]	Power transmission time ratio during one period [%]	Required number of satellites
200	6549	119	1.8	56
5000	14157	4380	30.9	4
10000	23837	11520	48.3	3
11000	25966	13200	50.8	2
12000	28156	15000	53.3	2
15000	35068	20760	59.2	2
20000	47663	31920	67.0	2

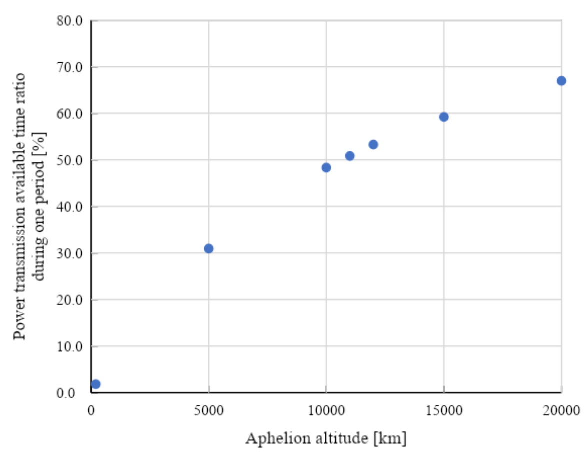

Fig. 12. Relationship between apoapsis altitude and power transmission time ratio for Mars orbit

In circular orbit, the power transmission available time ratio during one period is 1.8 % and the required number of satellites is 56 satellites. On the other hand, in elliptical orbits, when the apoapsis altitude was increased from 200 km to 20,000 km, power transmission available time ratio during one period increased to 67 % (see Fig. 12.). From the viewpoint of cost reduction, this study focuses on a Mars polar elliptical orbit with an aphelion altitude of 11,000 km and a periapsis altitude of 200 km.

4.3 Size of PV cell array for Mars SPS

We calculated the size of the required solar array. The orbit was set to the Mars orbit with an apoapsis altitude of 11,000 km, a periapsis altitude of 200 km, and an elevation angle range of ±45°. In this orbit, power transmission is possible for approximately 51 % of 433 minutes of a period. When 2 satellites transmit 1 GW, each satellite must transmit approximately 0.98 GW. Assuming a solar array conversion efficiency of 35 % and an energy conversion efficiency of 50 %, the required area of the solar array is approximately 9.6 km². As with the Lunar orbit, in order to reduce the required area of the solar array, we considered improving the efficiency. Assuming a solar array conversion efficiency of 50 % and an energy conversion efficiency of 80 %, the required area of the solar array is approximately 4.2 km².

4.4 Size of Transmission antenna for Lunar SPS

The orbit for Mars has been determined, the power transmission antenna size can be calculated in the same way as for the orbit of Lunar. In this section, the orbit proposed in the previous section, a Mars polar elliptical orbit with an apoapsis altitude of 11,000 km and a periapsis altitude of 200 km, will be the base orbit.

As in the case of the Mars orbit, assuming an apoapsis altitude of the determined Lunar to be the altitude of SPS, the power transmission distance will be 11000 km. And the diameter of the rectenna is also assumed to be 500 m, Beam transmission efficiency is assumed to be 0.9. At this time, assuming that the operating frequencies are 5.8, 10, 20, 50, and 100 GHz, the size of the power transmission antenna was calculated. Fig. 13. shows the relation between the operating frequencies and transmit antenna.

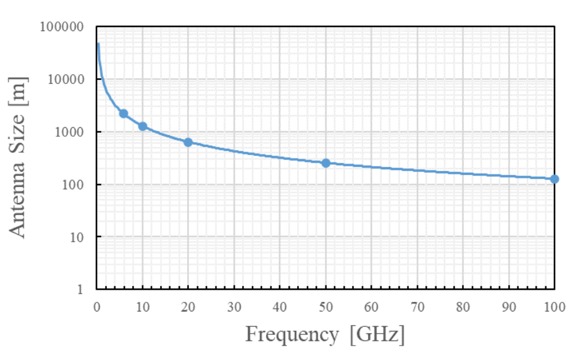

Fig. 13. Relation between the operating frequencies and the size of transmit antenna for the Mars SPS

From the Fig. 13, the size of the transmission antenna at 5.8GHz is 2.2 km long, and it is similar to the size of SPS for Earth. Although, if 100 GHz is selected as operating frequency, the size can be reduced to about 128 m. By the same calculation as in the case of Lunar, the antenna area decreases by 0.3%, and the transportation cost will be 3/1000 times lower.

On the other hand, as mentioned in the previous section, to generate GW class electricity in that orbit, a SA with an area of approximately 9.6 km² is required. This extreme gap between the size of the transmission antenna and the SA makes it impossible to employ power generation/transmission panels. Therefore, if a high frequency band around 100 GHz is selected as the operating frequency, it is necessary to reconsider the structure of the SPS.

5. Discussion

5.1 Variation of WPT efficiency in elliptical orbits

As mentioned in section *3.2* and *4.2*, since the number of aircraft can be reduced, elliptical orbit has an advantage in terms of cost. On the other hand, variations in Beam transmission efficiency are expected.

In an elliptical orbit, the distance from the SPS to the rectenna changes significantly. For the Lunar orbit selected in this study, the maximum distance between the surface of Lunar and SPS is 6,000 km and the minimum is 4,763 km. The fluctuation rate is approximately 26%. In the same way, for the Mars orbit selected in this study, the maximum distance between the surface of Lunar and SPS is 11,000 km and the minimum is 8,937 km. The fluctuation rate is approximately 23%. The size of power transmission antenna, which has the maximum beam transmission efficiency η in the shortest distance, decreases from 1.20 km to 673 m, in the case of Lunar. In the case of Mars, the size decreases from 2.2 km to 1.27 km. In the calculation, the frequency was set to be 5.8 GHz, and the rectenna size was multiplied by $\sqrt{2}$ to take into account the effect of an elevation angle of 45 degrees. It was found that as the size of the transmitting antenna became smaller, the efficiency of Beam transmission efficiency η decreased from 0.9 to 0.78 for the Lunar case and from 0.9 to 0.76 for Mars case.

In order to optimize cost and efficiency, it will be necessary to determine the axis ratio by examining the balance between the visible time and reduction of WPT efficiency.

5.2 Technical problems around high frequency devices

As mentioned in section 3.4, the use of RF above the 5.8 GHz can reduce the size of the antenna. However, there are technological problem in the design of RF amplifiers. At low frequencies below 10 MHz, over 90 % of PAE has been achieved. On the other hand, it is difficult to improve the efficiency of PAE above the 20 GHz. Above 20 GHz, one-half of the wavelength is less than 7.5 mm. Therefore, hybrid mounting is difficult, and MMIC must be applied. In the case of MMIC, the substrate thickness of the microstrip line is approximately 80 µm and the strip conductor width is less than 100 µm. Therefore, the circuit loss by conductors increases and the PAE becomes low. For array antennas above 90 GHz, the MMIC, including the antenna, must be configured on a single wafer. This is very difficult to realize, including heat dissipation and power bus [10].

For the alternative of amplifiers, the use of electron tubes is considered. Electron tubes that use microwaves are classified into types Traveling Wave Tube, Klystron, Magnetron, and Gyrotron. As a recent trend in development, the following development results of electron tubes have been reported. The Q-band TWTA which is a kind of Traveling Wave Tube, manufactured by NEC Networks & Sensors, could achieve a rated output of 190W and an efficiency of 37 % at frequencies of 42.5 GHz to 45.5 GHz. And its weight is 3.4 kg [26]. The Gyrotrons, which are a kind of microwave oscillation tube, produced by Cannon Electronic Devices, could achieve a rated output of 1MW and an efficiency of 50% at frequencies of 170 GHz. And its weight is 3.4 kg. [27, 28].

If an electron tube is installed in SPS instead of an amplifier, it will be possible to achieve much higher amplification efficiency than that of a microwave amplifier in the high frequency range. On the other hand, since the size and mass of these electron tubes are significantly different, the structural consideration of SPS must be required.

6. Conclusions

In this project, Lunar SPS and Mars SPS were examined and the technical issues of them were clarified. For each, orbits, the transmission time, the required number of satellites, the area of the solar array, and the size of the transmission antenna were considered. The results are shown in the Table 5 and 6.

Table 5. Obtained data for Lunar orbital SPS

Distance of power transmission [km]		6000
Beam control angle [°]		± 45
Power transmission per one period [GJ/period]		29783
Required number of satellites		2
Power transmission per one satellite [GW/satellite]		0.95
Required area of the SA [km²]	SA : 35 %, Energy : 50 %	3.97
	SA : 50 %, Energy : 80 %	1.74
Operating frequency [GHz]		5.8
Size of power transmission antenna [km]		1.2

Table 6. Obtained data for Mars orbital SPS

Distance of power transmission [km]		11,000
Beam control angle [°]		± 45
Power transmission per one period [GJ/period]		25966
Required number of satellites		2
Power transmission per one satellite [GW/satellite]		0.98
Required area of the SA [km²]	SA : 35 %, Energy : 50 %	9.56
	SA : 50 %, Energy : 80 %	4.18
Operating frequency [GHz]		5.8
Size of power transmission antenna [km]		2.2

We chose elliptical orbits to reduce the number of satellites and costs. For Lunar orbit, we found that the required number of satellites is two when the apoapsis altitude is 6000 km and the periapsis altitude is 100 km. For Mars orbit, the apoapsis altitude is 11,000 km and the periapsis altitude is 200 km.

The power transmission distance changes in elliptical orbits. And we found that this change led to a reduction in WPT efficiency of tens of precent.

In addition, to reduce the size of the antenna, it is necessary to use high frequency. However, RF power amplifiers at high frequencies have technical problems. As an alternative, we considered using an electron tube.

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References

[1] Peter. E. Glaser, Power from the Sun: Its future, Science Vol. 162, issue 3856, pp857-861, (1968), American Association for the Advancement of Science
[2] Dr. David R. Williams, Lunar Exploration Timeline, 4 September 2023 http://www.gizmag.com/spaceport-america-hits-nags/36200/, (accessed 05.09.23).
[3] Mitsubishi Research Institute, Ltd., Research and development to promote space development and utilization (energy-related technology development on the lunar surface. 163 (2010) 51–59.
[4] Photovoltaic utilization committee, Achievement report related technologies to advance solar power application, separate volume, p.22, 2006, March 2007, in Japanese.
[5] S. Sasaki, et al., A new concept of solar power satellite: Tethered SPS, Acta Astronautica 60 , 2006, 153-165.

[6] N. Shinohara, Forest of knowledge, Space solar power, in: IEICE (Ed.), Ohmsha, Ltd., Tokyo, 2012, in Japanese.
[7] ICNIRP, Guidelines for Limiting Exposure to Electromagnetic Fields (100kHz — 300 GHz),
[8] Shanti M. Garman, et al., Magnetic field coupling with lunar soil simulants, Nature report, 2023,
[9] Adrian Stoica et al, Trans Formers for Extreme Environments: Projecting Favorable Micro-Environments around Robots and Areas of Interest (2017), Jet Propulsion Laboratory, May 2014
[10] Japan Space Systems, Result Report of Development of Energy-Related Technologies for the Lunar Surface (Organizing technical issues related to electric power), 2022, (in Japanese).
[11] T. Uno, S. Adachi, Design of microwave wireless power transmission using maximum transmission efficiency aperture distribution, The Transactions of the Institute of Electronics and Communication Engineers of Japan, p1013-1018, 1983-08
[12]Moon to Mars Architecture Aug 30, 2023,https://www.nasa.gov/MoonToMarsArchitecture, (accessed 15,9,23)
[13]MARS&BEYOND29/8/2023,https://www.spacex.com/human-spaceflight/mars/(accessed 15,9,23)
[14]THE UTILITY OF GEOTHERMAL ENERGY ON MARS 1997,http://www.users.globalnet.co.uk/~mfogg/fogg1996.pdf(accessed 15,9,23)
[15]Systems engineering and design of a Mars Polar Research Base with a human crew 2019,https://infoscience.epfl.ch/record/26409(accessed 15,9,23)
[16]Composition of Equipment Fuel Cell Mechanism and Characteristics 3/17/2020,https://www.energia.co.jp/energy/general/newene/newene3.html(accessed 15,9,23)
[17]Mars Education | Developing the Next Generation of Explorers | Water, https://marsed.asu.edu/mep/water(accessed 15,9,23)
[18]Long-term drying of Mars by sequestration of ocean-scale volumes of water in the crust 16 Mar 2021,https://www.science.org/doi/10.1126/science.abc7717(accessed 15,9,23)
[19]MMGIS09/15/2023,https://ammos.nasa.gov/marswatermaps/?mission=MWR(accessed 15,9,23)
[20] What is Mars? 07/31/2023,https://www.nao.ac.jp/astro/basic/mars.html(accessed 15,9,23)
[21]Mars Closest Approach 2003(Commentary New Mars Image) Atmosphere and Climate of Mars 10/2003,https://hirahaku.jp/hakubutsukan_archive/tenmon/00000025/72.html(accessed 15,9,23)
[22]The 6th PLANET-B: The Past and Present of the Martian Atmosphere 7/1998,https://www.isas.jaxa.jp/ISASnews/No.208/mars.html(accessed 15,9,23)
[23]Mars Education | Developing the Next Generation of Explorers | Dust, https://marsed.asu.edu/mep/dust(accessed 15,9,23)
[24]Over 20,000 m above sea level! The World of "Space Mountains" Different in Scale from the Earth 31/07/2022,https://yamahack.com/3303(accessed 15,9,23)
[25]PIA02031: Maps of Mars Global Topography 27/05/1999,https://photojournal.jpl.nasa.gov/catalog/PIA02031(accessed 15,9,23)
[26] Sosuke Higashibata, et.al. , Q-band 190W Helix TWT with Two Stage Collector, IEEE, 2022.
[27] Yasuhisa Oda, et al, Development of the first ITER gyrotron in QST, Nuclear Fusion, Volume 59, No 8 (2019).
[28] Keishi Sakamoto, "small special feature Progress of ECH･ECCD in Fusion Plasmas 3. Progress of ECH・ECCD Experiments, 3.1 Progress of ECH・ECCD Devices, J. Plasma Fusion Res. Vol.85, No.6 (2009) 351-356.