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

Tanaka laboratory

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Backgrounds

Length of Stay
Four astronauts can stay for **a week.**

Base Location
the polar region

Artemis Mission

SPS is Essential!

Length of Stay
It is necessary to stay there **for a long period of time** so that human exploration missions and scientific research data can be obtained.

Base Location
the polar region

Mars Migration Plan

We are facing the phase;
to think about the migration to other stars,
to consider the Power supply systems for use on there like SPS .

What is our project?

The purposes and goals of this project is:

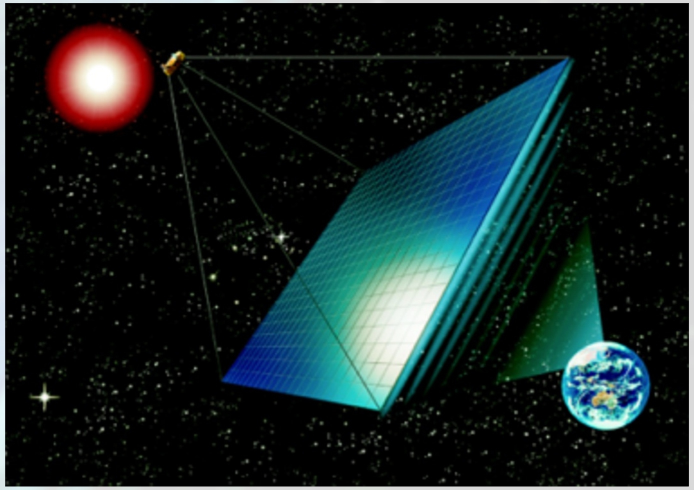
to consider applying SPS to Moon and Mars based on SPS for Earth,
to clarify technical problems to realize SPS for Moon and Mars

Our steps toward goals

1. **Summarize** the original concept of the Tethered SPS
2. **Investigate** environmental factors
3. **Examine** the orbits and **Calculate** the number of satellites
4. **Consider** suitable satellite size
5. Goal: **Clarify technical problems** of SPS on Moon and Mars with reference to the Tethered SPS

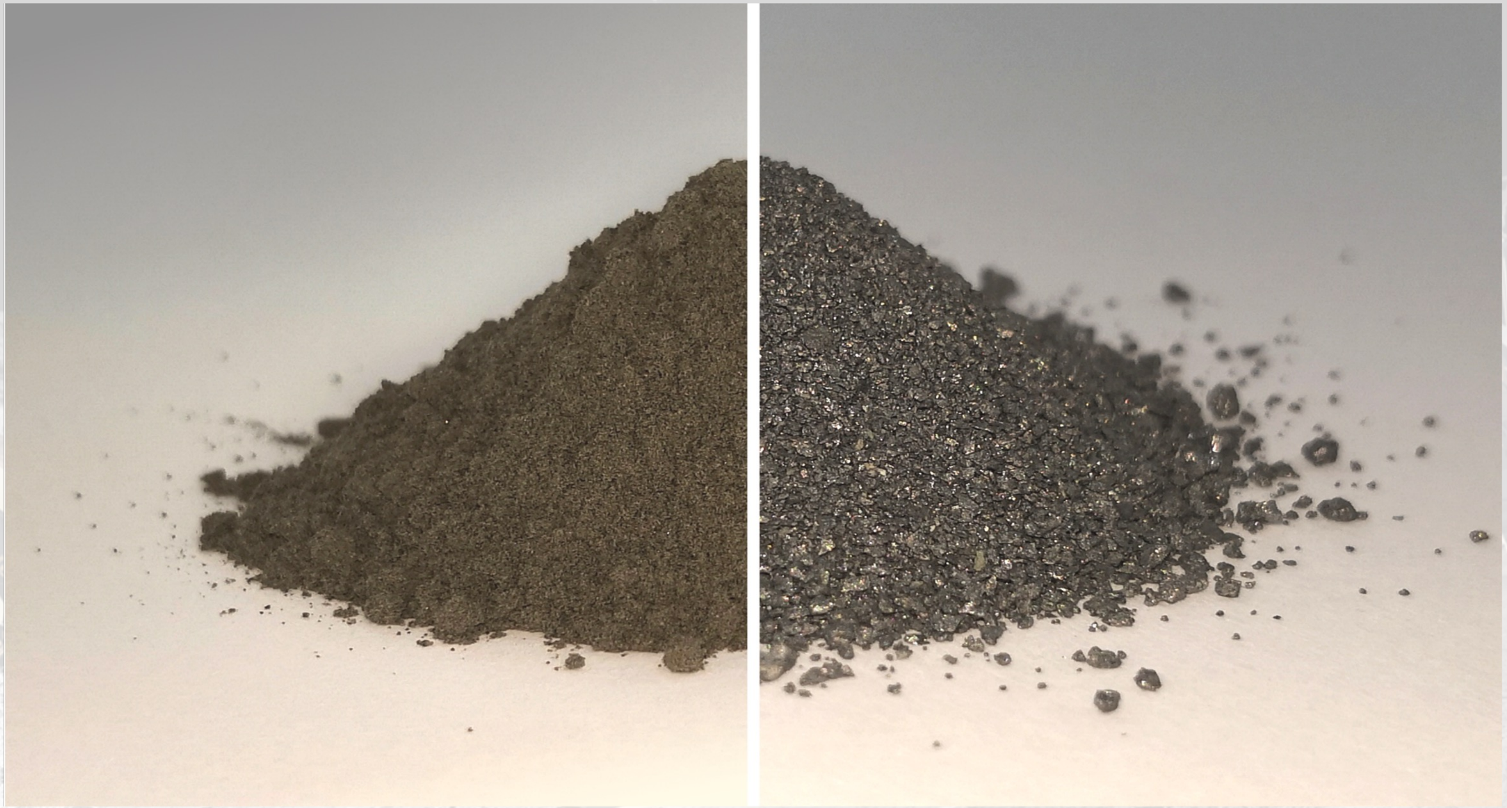
The tethered SPS for Earth

Size	2.5km×2.375km×0.02m
Frequency	5.8GHz
Orbit	GEO
Total power generation	1GW
Directional Control	Phase Shifters
50cm square panel	23.75 million



The Environment for the Lunar SPS

- **No Atmosphere** →No Attenuation of the MW
- **Regolith**→ Decrease of WPT efficiency, ISRU



Lunar Regolith*

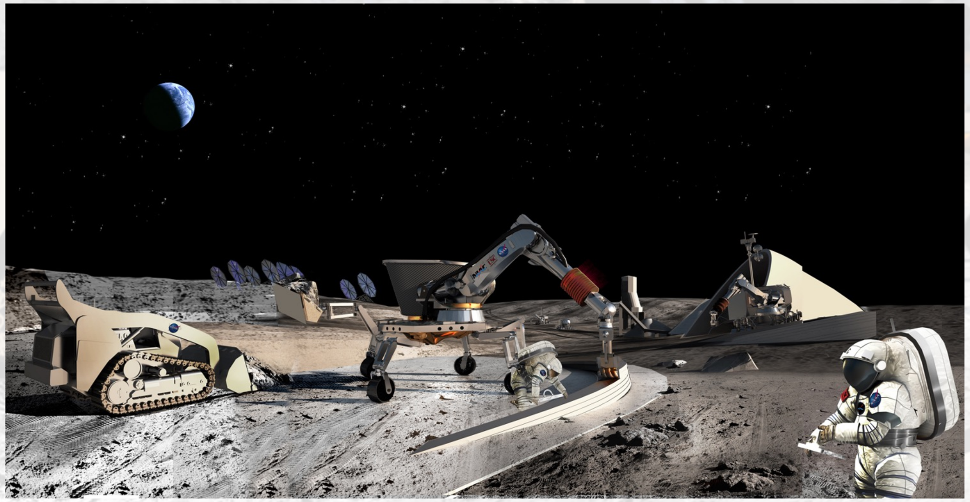
*ESA - Oxygen and metal from lunar regolith

The Environment for the Lunar SPS

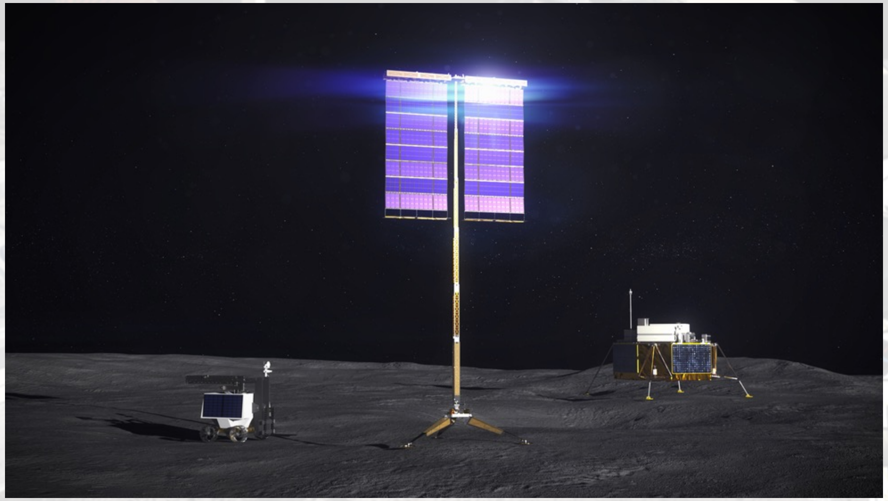
- **No Atmosphere** →No Attenuation of the MW
- **Regolith**→ Decrease of WPT efficiency, ISRU
- **Sunlight and H_2O**

↓ base site : south pole region

Sun light intensity （Solar Tower →▲）



Lunar ISRU **



Solar Tower ***

**ISRU-Based Robotic Construction Technologies for Lunar and Martian Infrastructures | NASA

***NASA, Industry Mature Vertical Solar Arrays for Lunar Surface | NASA

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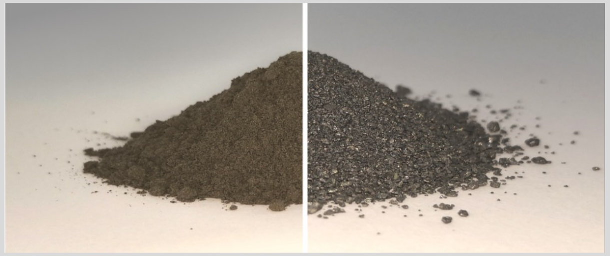

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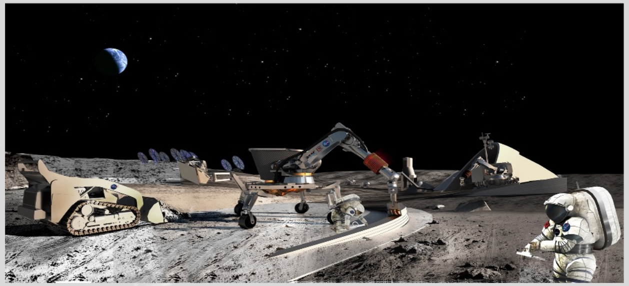

Lunar ISRU**

Solar Tower***

Therefore, We examined

SPS for Lunar which can provide 1GW power stable to the Shackleton Crater.

*ESA - Oxygen and metal from lunar regolith

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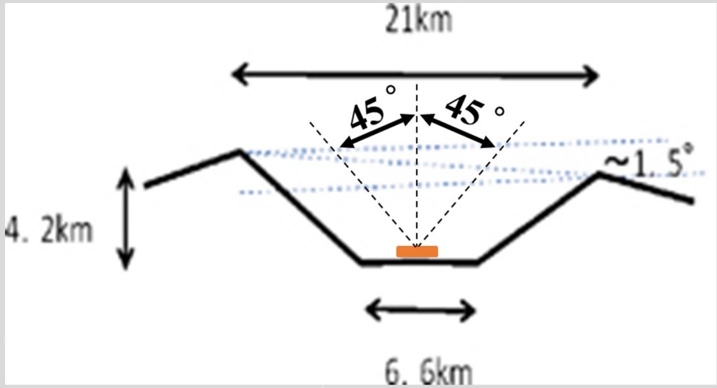
***NASA, Industry Mature Vertical Solar Arrays for Lunar Surface | NASA

The Orbits for Lunar

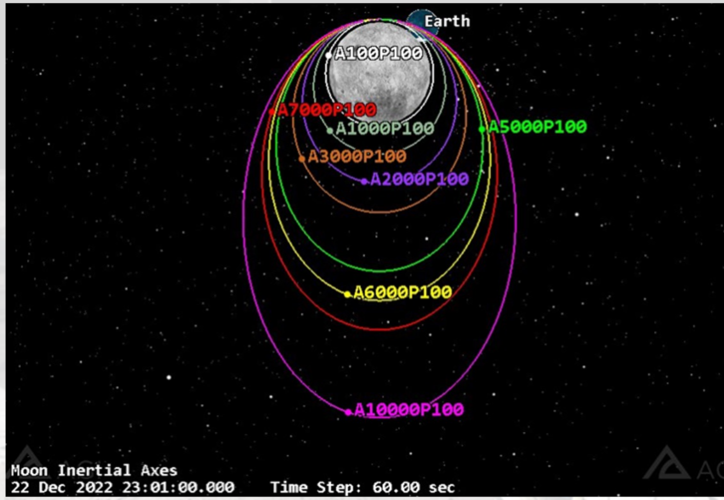
- Transmission to the base in the **Shackleton Crater**
- Elevation angle : **± 45 °**
- Trade-off between orbit altitude and the number of satellites
- **Elliptical orbit** (to increase transmission time)

Apoapsis altitude [km]	Periapsis altitude [km]	Orbital period [s]	Transmission available time [s]	Transmission time ratio [%]	Required number of satellites
100	100	7067	115	1.6	62
1000	100	9817	1430	14.6	7
2000	100	13206	3360	25.4	4
3000	100	16914	5820	34.4	3
5000	100	25191	11940	47.4	3
6000	**100**	**29783**	**15660**	**52.6**	**2**
7000	100	34560	19620	56.8	2
10000	100	50178	33300	66.4	2

→apoapsis 6000 km, periapsis 100 km orbit selected



Shape of Shackleton Crater*



Simulation analysis by STK

* https://www.isas.jaxa.jp/j/topics/topics/2008/1024.shtml

Required Area of the Solar Array for Lunar

We calculated the required area of solar array to transmit 1 GW in total.

- Orbit : Apoapsis 6000 km, Periapsis 100 km

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

- Almost the **same** area as Earth SPS
  → Almost the same distance from the sun

Required Area of the Solar Array for Lunar

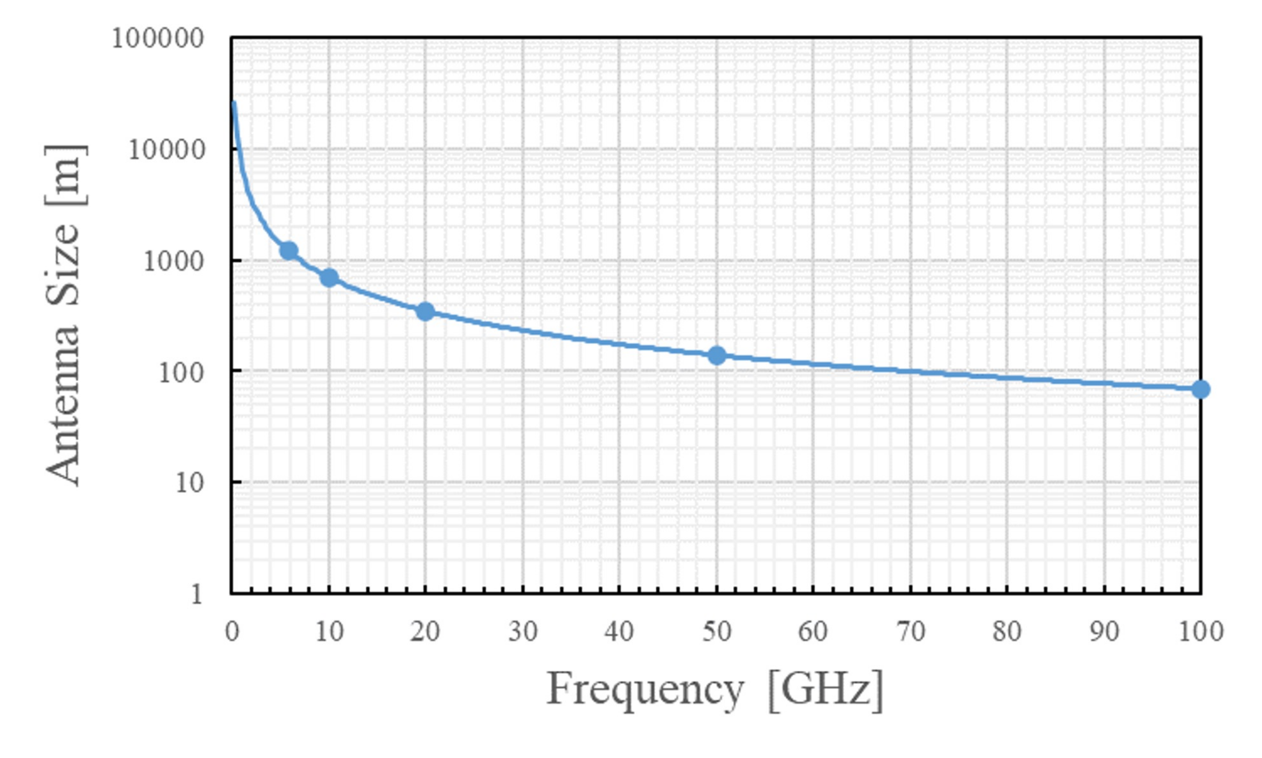
The size of Transmission antenna is

1.2 km (5.8 GHz) ➡️ **70 m** (100 GHz)

(Rectenna *d*r: 500m, η: 0.9)

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

$$\tau = \frac{\pi d_t d_r}{4\lambda D} \qquad (2)$$



Required Area of the Solar Array for Lunar

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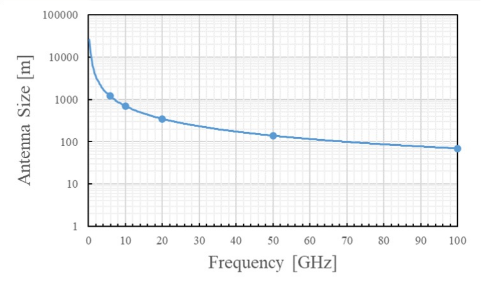
	Antenna Diameter [%]	Antenna Area [%]
5.8 GHz	100	100
100 GHz	5.8	0.3



Adapting the high frequency like 100 GHz brings benefits in terms of size and cost.

There are difficulties in using 100 GHz.

The SPS for Mars Environment

Regolith

→Be covered

Axis

→Tilt 25.19 degrees

Dust storm

→ Large-scale : twice during summer
Small-scale : frequently

Atmospheric composition

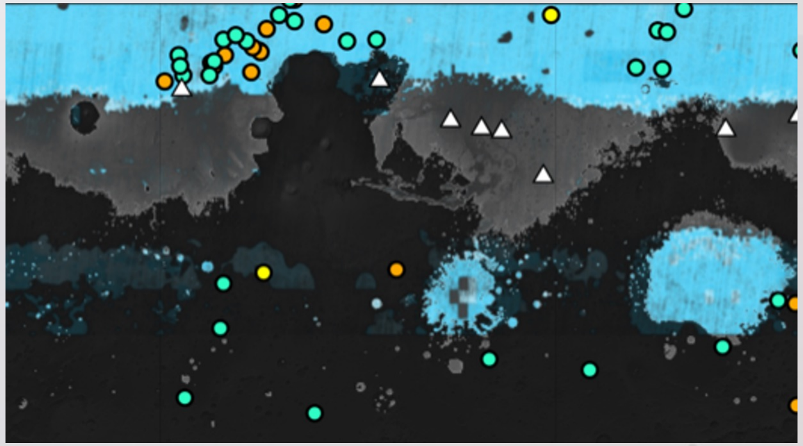
→CO2 repeatedly sublimates and solidifies

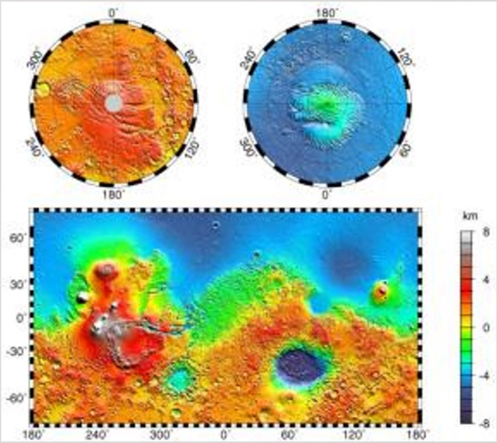
Magnetic field

→Non

Landscape

→Mountains over 21 km high,
Valleys over 11 km deep





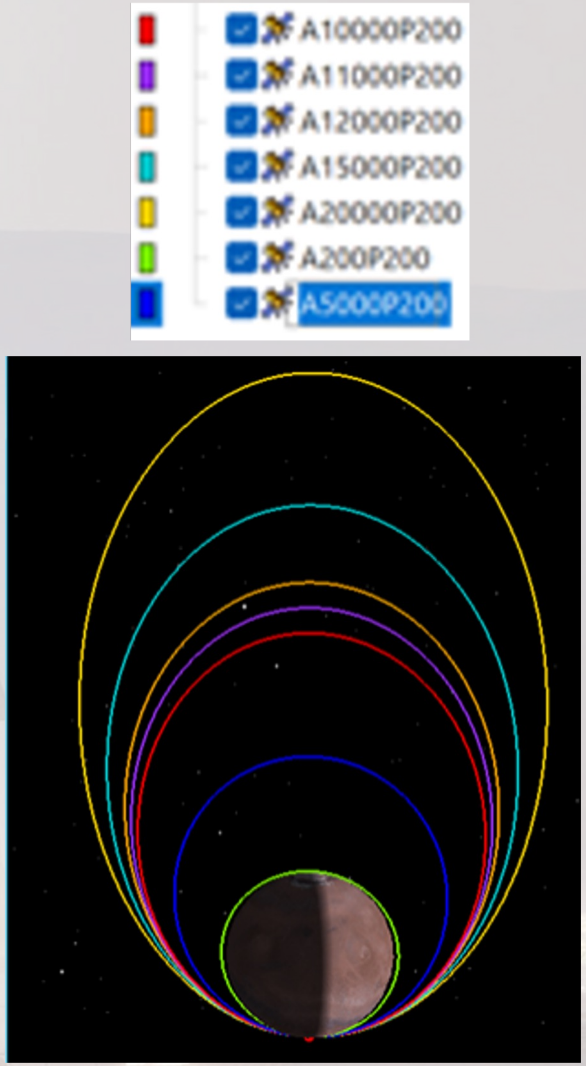
	Mars	Earth
Rotation period	24h37min	23h56min
Orbital period	687day	365day
Mass (Earth :1)	0.1074	1
Radius [km]	3396.2	6378.1
Satellite	2(Phobos, Deimos)	1 (Lunar)
Satellite dimension [km]	Phobos:13×11×9 Deimos:8×6×5	Moon (radius):1737.4
Rotation axis inclination [deg]	25.19°	23.44°
Orbit length radius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

- https://www.tesmanian.com/blogs/tesmanian-blog/starlink-mars
- https://ammos.nasa.gov/marswatermaps/?mission=MWR

The Orbits for Mars

- Transmission to the **North Pole**
- Elevation angle : **± 45 °**
- Trade-off between orbit altitude and the number of satellites
- **Elliptical orbit** (to increase transmission time)

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



Simulation analysis by STK

→ **apoapsis 11000 km, periapsis 200 km orbit** selected

Required Area of the Solar Array for Mars

We calculated the required area of solar array to transmit 1 GW in total.

- Orbit : Apoapsis 11000 km, Periapsis 200 km

Power transmission per period [GJ/period]		25966
Required number of satellites		2
Power transmission per satellite [GW/satellite]		0.98
Required area of SA [km^2]	SA : 35 %, Energy : 50 %	9.56
	SA : 50 %, Energy : 80 %	4.18

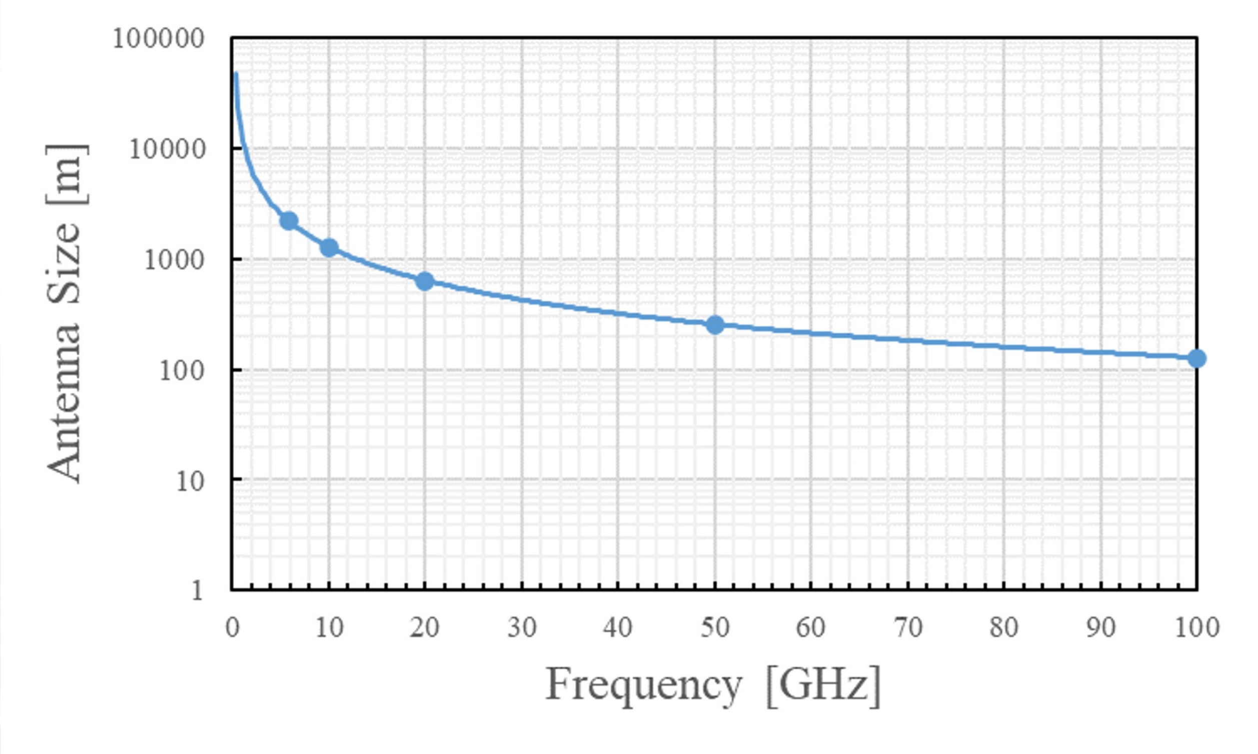
- More than **twice larger** than the area of Earth SPS and Lunar SPS
  → Far from the sun

Required Area of the Solar Array for Mars

The size of Transmission antenna is

2.2 km (5.8 GHz) ➡️ **128 m** (100 GHz)

(Rectenna *d*r: 500m, η: 0.9)



Required Area of the Solar Array for Mars

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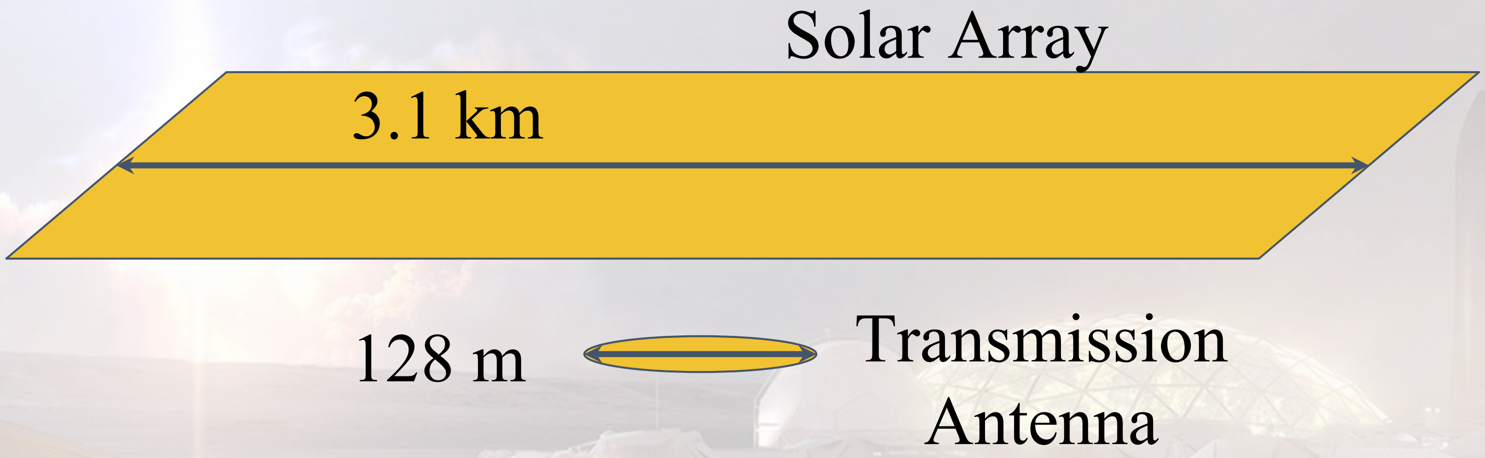
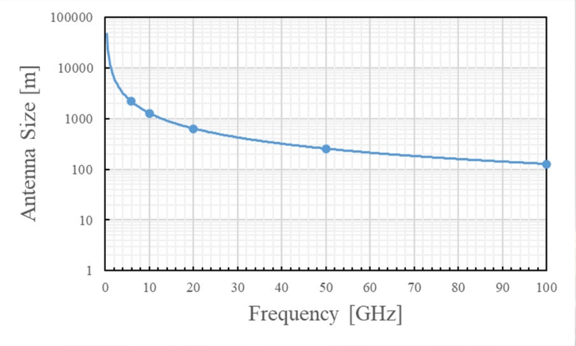


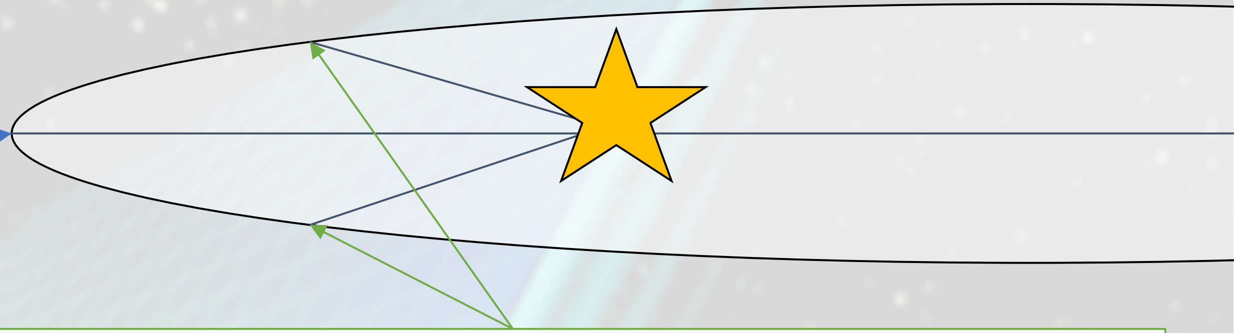


There is a large gap between
required **Solar Array Size** and required **Transmission Antenna Size**.

Consideration ~Elliptical orbit~

Variation of WPT efficiency

Elliptical orbit



Maximum distance
Moon : 6,000 km
Mars : 11,000 km

Minimum distance
Moon : 4,763 km (74 % of Maximum)
Mars : 8,937 km (77 % of Maximum)

1.Set here as max WPT efficiency point.

2.Calculate the efficiency change.

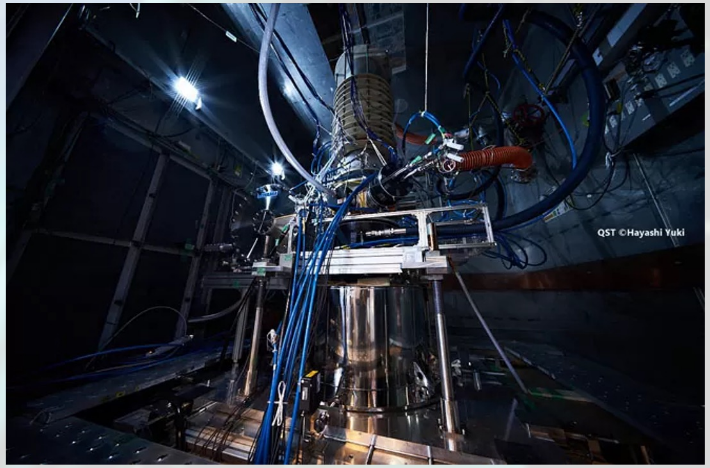
If the size of Transmission Antenna based on the minimum distance,

Transmission Antenna	WPT efficiency
Moon : 1.2 km → **673 m**	Moon : η = 0.9 (1.2 km) → $\boldsymbol{\eta = 0.78}$
Mars : 2.2 km → **1.27 km**	Mars : η = 0.9 (2.2 km) → $\boldsymbol{\eta = 0.76}$

Consideration ~ Technical Problems ~

RF can reduce the size of the antenna → **technical problems**

- 20 GHz ~ : increased circuit loss, decrease of PAE
- 90 GHz ~ : MMIC configured on a single wafer → **very difficult** to realize



High Power Microwave Source Gyrotron
ITER

Electron tubes (alternative of amplifiers)

	Frequency	Output power	Efficiency
TWTA*	42.5~45.5 GHz	190 W(CW)	37 %
Gyrotron**	170 GHz	1 MW	50 %

Using electron tubes instead of amplifier → achieve **higher efficiency**

* Sosuke Higashibata, et.al., Q-band 190W Helix TWT with Two Stage Collector, IEEE, 2022.
** Yasuhisa Oda, et al, Development of the first ITER gyrotron in QST, Nuclear Fusion, Volume 59, No 8 (2019).
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.

Conclusion

In this project,

- The study of **Lunar SPS** and **Mars SPS**
- Identified **technical problems**

		Lunar	Mars
Operating frequency [GHz]		5.8	
Beam control angle [°]		± 45	
Distance of transmission [km]		6000	11000
Transmission per one period [GJ/period]		29783	25966
Required number of satellites		2	2
Transmission per satellite [GW/satellite]		0.95	0.98
Required area of SA [km^2]	SA : 35 %, Energy : 50 %	3.97	9.56
	SA : 50 %, Energy : 80 %	1.74	4.18
Size of transmission antenna [km]		1.2	2.2

~ Future Works ~

- Study of Lunar SPS and Mars SPS **smaller than 1 GW**
- Study orbits considering the **influence of surrounding satellites**
- Experiments on the **impact of regolith and CO_2 on WPT**
- Structural consideration of SPS when using electron tubes

Thank you !