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Verify the Wireless Power Transmission in Space using Satellite to Satellite System

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ABSTRACT: Wireless Power Transmission technology using a satellite-to-satellite system represents a valuable and convenient technology for transferring power wirelessly among Space Solar Power Satellites to Satellite and potential future interplanetary missions. This direct transmission can help replace traditional power storages and reduce the weight and ultimately the costs of launching satellites. This paper discusses the Wireless Power Transmission between one small-scale Space Solar Power Satellite to another operational satellite, followed by a demonstration of small-scale Space Solar Power Satellites and evaluating the possibility for future implementation. It will increase the performance and operational lifetime, especially for small and cube satellites using microwaves and laser-based power transmission. The development and demonstration of this technology can help fulfill Space Solar Power Satellites idea to transfer gigawatts of renewable energy to Earth.

Keywords: Space Solar Power, Wireless Power Transmission, Microwave Power Transmission, Laser Power Transmission, Satellites, Orbital Demonstration, Energy Orbit, Satellite Constellation.

Abbreviations: BCE, Beam Collection Efficiency; BTE, Beam Transmission Efficiency; CPU, Central Processing Unit; DC, Digital Current; E-Orbit, Energy Orbit; E-Sat, Energy Satellite; ESA, European space agency; GEO, Geostationary Earth Orbit; JAXA, Japan Aerospace Exploration Agency; KU, Kyushu University; LD, Laser Diode; LEO, Low Earth Orbit; LPT, Laser Power Transmission; MPT, Microwave Power Transmission, PV, Photovoltaic; SS, Satellite to Satellite; SSDL, Space System Dynamic Laboratory; SSO, Sun Synchronous Orbit; SSPS, Space Solar Power Satellite/ Station; UAV, Unmanned Aerial Vehicle; WPT, Wireless Power Transfer;

I. INTRODUCTION

WPT technology has undergone several enhancements in recent history. Nikola Tesla designed the Wardenclyffe Tower, also known as the Tesla Tower, one of the earliest experiments to prove a potential WPT [1-3]. In 1973, Dr. Peter Edward Glaser coined the idea of an SSPS capable of transmitting power via microwaves from a GEO to a ground microwave collector station on Earth [4, 5]. Microwave energy transmission can be conducted at all frequencies above 1 GHz. An optical band lower is preferred because of its efficiency to transmit from the atmosphere, rain, and a gray area. [6]. More than 28 SSPS proposed designs are currently investigated by China, the ESA, Japan, Russia, and the United States of America [7, 8]. Most of the designs are capable of generating and transmitting from 10 kilowatts to 10 gigawatts. WPT offers promising solutions for providing convenient and constant energy sources to electronics and avionics, and its transmission distance capabilities can define technological improvement as near-field and far-field transfer [9-10]. Fig. 1 shows that inductive coupling and capacitive coupling come inside the near-field transfer methods whose effective range varies from few centimeters to few meters, as shown in table 1.

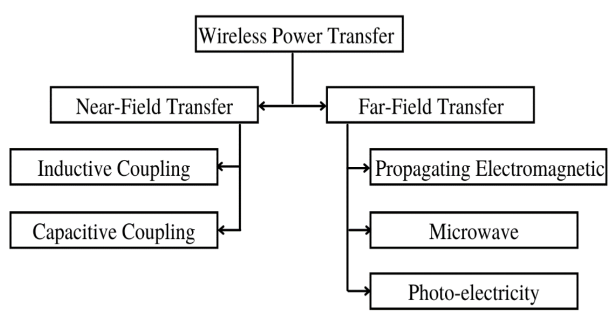


Fig. 1. WPT method via distance base.

Table 1: Comparison of Different WPT Techniques [15,16].

Parameters	Inductive Coupling	Microwave	Laser
Distance	Few millimeters	Up to 100s km	Few meters can be increased by highly intensive beam
Transmitted Power	~ few watts	~100s MW.	~100s MW.
Efficiency	Low	High	Medium
Penetration (clouds/ fog/ rain)		Very High	No
Aperture size (transmitter and receiving antenna)	Small	Large	Small
Cost	Economical	Expansive	Economical
Safety (Biological point of view)	Safe	Dangerous due to radiation but controllable	Dangerous

The comparison of WPT technology, range, efficiency, size, and cost of technology to develop. This WPT technology is currently used in mobile charging. In addition, the investigation and research on the far-field transmission, long-distance SSPS system, including MPT, LPT, electromagnetic waves, are undergoing as shown in Table 1.

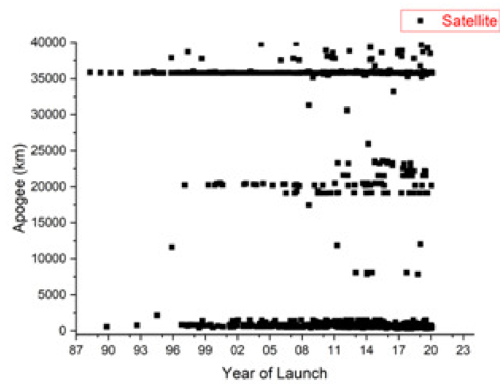
Most of the SSPS studies conducted by the space agency and private entity are based on MPT. It can transmit energy in cloudy regions, remote regions, high transmission efficiency, and a more mature technology than LPT. In such a system, the PV cells generated power in DC and then converted it into microwaves using magnetron and klystron with high beam efficiency. The Laser of an LPT can be generated from the solid-state laser diode and solar pumping laser generator. LPT undoubtedly shows the highest prospects for long-distance, small beam divergence with high-energy transmission [11]. The receiving and transmission antenna of an LPT system is comparatively smaller than the traditional MPT system. Therefore, developing the LPT system can deliver energy further than any other WPTS [12-14].

Section 2 describes the necessity of power required by the global space industry to grow space technology in different orbits such as LEO. The idea of an SSPS can be realized by materializing current SSPS technology and influencing prospective space sector investors to invest in the materialized technology. This paper summarized how the technology involves designing small SSPS and WPT systems between two satellites. This direct transmission can help replace traditional power storages and reduce the weight and ultimately the costs of launching satellites.

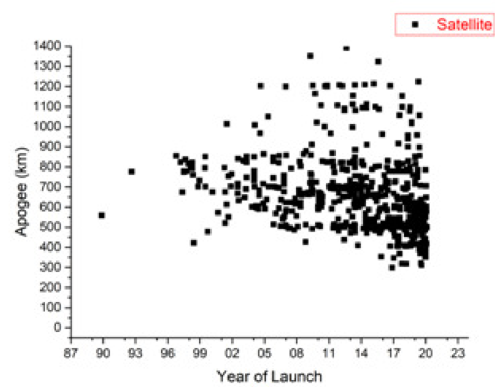
II. GLOBAL SPACE INDUSTRY AND POWER REQUIREMENTS

Today more than 3,370 satellites are currently orbiting in space, including the first artificial satellite Sputnik 1 (Спутник-1), 1957. In LEO, more than 2,600 satellites are presently in operation [17]. The satellite industry covers between 271 Billion USD of 366 Billion USD of the global space economy [18]. The launched satellites, primarily located in LEO, GEO is used for telecommunication, remote sensing, navigation, research, science experiments, and military application. As shown in Fig. 2 (a), satellite increments have increased exponentially in space in the last three decades.

Fig. 2 (b) shows the LEO-based satellite population. In the previous two decades, most satellites are launched and placed between 400 – 900km. The constellation designing for fast communication is establishing by SpaceX and One Web company. Shortly it will increasingly be 9,000 satellites by the end of this decade.



(a)



(b)

Fig. 2. Satellites launched in space (a) nearby earth orbit (b) satellites in LEO.

A satellite requires a continuous power source for theon board sensor, maintaining attitude, telecommunication, and payload. The required power varies with size, orbital planes, attitude, functionality, and payload. For example, the international space station uses 75 to 90 kW while generating 84 to 120 kW using four PV array sets. Fig. 3 (a) illustrates the power generated and utilized by satellites in the last three decades. Fig. 3(b) the previous five-year generated power using satellites. The above Fig. 3 indicatesthat most satellites operate below 5kW with a load of onboard operation and payload functionality. Therefore, most of the time-space industry relies on PV arrays for power supply. However, it is expansive, having multiple losses due to wiring, blocking diode, mismatch, calibration, cover glassing, UV, micro-meteorites, and change in temperature [19]. The demonstrative mission of WPT will provide a solution to the above problems and change the way of space utilization.

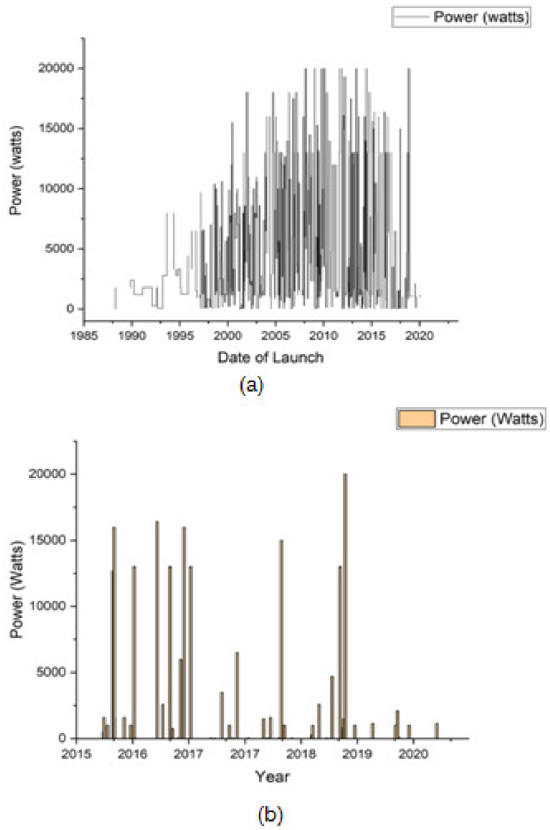


Fig. 3. Power generated by satellite (a) in last three decades (b) in last five years.

III. SATELLITE TO SATELLITE WIRELESS POWER TRANSMISSION MISSION OVERVIEW

Agencies for manufacturing, utilizing, and managing satellites use traditional power generation and management systems, such as photovoltaic cells and nuclear generation units, respectively. Such systems are bulky in size and costly to operate and maintain. Using SS system for future satellite designing [20] will change the way of utilization, generation, and management of power system unit; the existence of the WPT system allows for the bulky intermediates to be compromised, which would minimize the cost of power production and maintenance.

The SS WPT holds the key to solving the significant obstacles in making the SSPS system: new designs can open a new way to look into the future and perspective of a new space mission. As shown in Fig. 4, SSPS can be placed in GEO for continuous power generation and supply unit for the Earth. The most significant advantage of the SSPS constellation would be extended access to remote areas and a constant power supply twenty-four by seven that can also be used for interplanetary and research-based missions outside of Earth to provide power to humans, robotics, satellite, and UAV based tasks. The constellation can be considered a power unit to provide satellites' continuous power, cutting down costs and increasing any satellite's lifetime by making E-Orbit using small E-Sat/ small SSPS[21,22].

This paper discusses a mission plan for SS WPT [23] to create an E-Sat for the prominent constellation of E-Orbit. The SS is on E-Sat with one standard satellite for showing functionality. The E-Sat/ Mother satellite is a Small-scale satellite for generating power using the solar panel and transmitted using WPT. The simulation and mission design are based on 2020 technology. The WPT system is integrated inside the satellite bus to convert, transmit and maintain the power system for satellite and cube satellite. It can be applied to perform various aspects of SSPS application, as shown in Fig. 4.

Primary objective: "Designing a small SSPS system to utilize microwaves and laser for inter-space generation, conversion, and wireless power transmission." The goal can be achieved by sending two satellites, which will define the satellite agency's future to increase performance while lowering costs. The SS WPT system is adequately designed to scientifically investigate and demonstrate the practicality of using such innovative technology for future satellite power management systems. The SSDL of KU is working to change and upgrade satellites' power generation units. The most practical solution is not to improve battery or PV cells but with more advanced technology. The SSDL team came up with an innovative idea of creating an E-Orbit with a constellation of small SSPS to efficiently deliver power to other future Satellites.

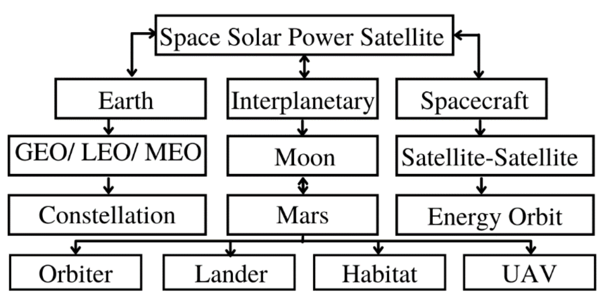


Fig. 4. Use of Space Solar Power Satellite.

The first step is to demonstrate the possibility of both microwave and laser-based WPT systems by optimizing the distances between the two satellites as mother and daughter satellites, placed in SSO 900 km with an inclination of 98.6 degrees. Both operational satellites will be launched together in a single bus and then perfectly stabilized in a 900 km SSO orbit. After that, the separation processes will start from the main bus, the daughter satellite (cube satellite) from the mother satellite. The first objective is to establish a secure connection between both separated satellites using a bacon signal. After confirmation, the daughter satellite will fire the electro thruster engine to a distance of 1 meter from the mother satellite. Then, the mother satellite will generate and convert electricity in microwave / Laser and start transmission to the daughter satellite. The data of transmission and reception will be shared with the ground-based stations from satellites.

Similarly, satellites' distance will be increased by 5 meters, 10-meter, 100 meters, and 10,000 km. The utilization of WPT by daughter satellite will be checked and used for the electro-thruster and onboard experiment using transited electricity. It can demonstrate the future power source for satellites. The data will be compared and used for evaluation to define the future prominent constellation and SSPS design.

IV. SPACECRAFT SYSTEM OVERVIEWS

This section describes the mother and daughter satellites, including their deployment mechanism, power transmission, and reception technology. First, as shown in Fig. 5, the SSPS (mother satellite) collects energy from PV. Then transmission and reception connect a small pilot signal between mother and daughter satellite to establish a secure connection. Then connection triggers the required transmission of energy using MPT and LPT from the mother satellite to the daughter satellite and equipping daughter satellites with rectenna and PV cells to receive MPT and LPT's power signals.

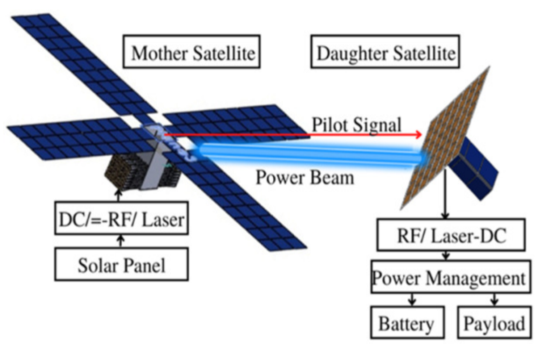


Fig. 5. Satellite-to-Satellite Power Transmission.

A. Mother Satellite

The mother satellite (in SSPS) will collect the energy directly from the sun using 70 m^2 solar panels mounted on one side of the spacecraft in the "plus-sign" structure (Fig. 5). With efficiency expected to be about 30%, aim to generate approximately 21.4 kW, calculated using solar energy output of PV system of mother satellite by Eq. (1) the conversion efficiency Eq. (2). This satellite weight is estimated to be around 700 kg to 900 kg, depending on operational efficiency selection.

Solar Energy O/P of PV system = $E = A \times r \times H \times PR$ (1)

Conversion Efficiency
($\eta\%$) = (P_{mp}/Incident solar energy)% (2)

Here. E, A, r, H, PR, and P_{mp} is respectively energy (kW), total solar panel area(m^2), solar panel yield or efficiency (%), annual average solar radiation (%), and performance ratio, maximum power (kW) and considering coefficient for losses in range 0.5~0.9 (default value 0.75). The PV array will be deployed using a rolling mechanism. Every single PV cell is joined with three PV cells, which can be opened one by one in all four directions. Inside the satellite, magnetron and solid-state laser diodes will be installed to convert DC into microwave and Laser, respectively, efficiently. The satellite consists of a CPU, communication unit, power management system, conversion, rectifier unit, and a thermal heat management system. The primary purpose of the satellite is to convert and transmit sufficient energy using an antenna. An antenna can be a dipole microstrip or a horn antenna with a waveguide system for MPT and a points antenna for LPT. First, a pilot signal will be transmitted to the daughter satellite to confirm the distance with an error accuracy of ±0.1 degrees. This pilot signal approved establishing a satellite link and stabilized connection by sending an inter-satellite link signal to start the transmission.

$$T = (A_t A_r)^{1/2} / (\lambda D) \quad (3)$$

Boundary distance between the satellites is determined by Eq. (3), in which, A_t is the transmitted aperture, A_r is receiving aperture, λ is the wavelength of microwave power being transmitted (in this case ISM band 5.8GHz frequency), and D is the separation distance between two apertures [7, 24]. The boundary distance equation is also applied to the pilot signal and MPT. It will accurately determine the maximum distance that can be achieved while supporting total power transfer efficiency. The accountable accuracy is a function of the distance between satellites and the minimum amount of power acceptable to be received [24]. It can be seen using Fig. 6 the high transmission probability if it is nearby. However, if the distance will change, the transmission connection will be lower. The boundary condition is designed with 5.8GHz MPT with a circular aperture.

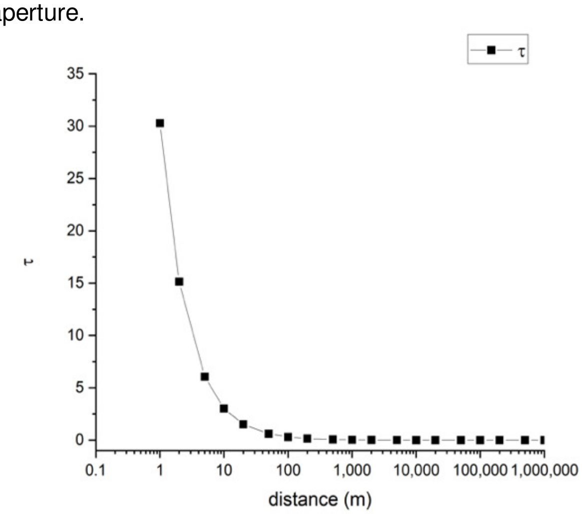


Fig. 6. Change of boundary distance between the satellites.

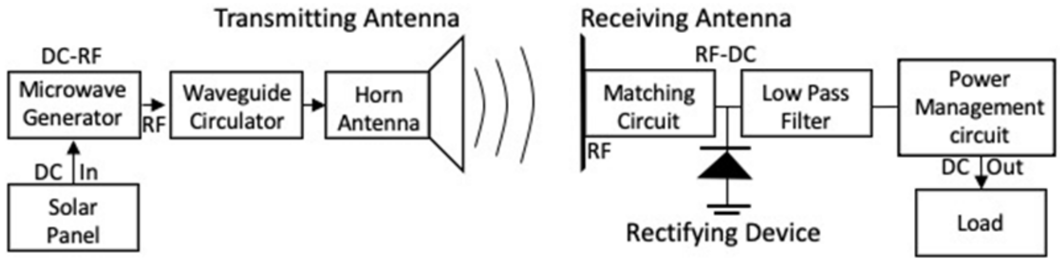


Fig. 7. Schematic Diagram of Microwave Power Transmission System.

Microwave Power Transmission. The electric energy coming from the PV array is managed correctly and rectified with a power management system and hardware section. Successful conversion of DC-to-RF will be achieved and transmitted to the daughter satellite using MPT, as shown in Fig. 7, the schematic diagram of the MPT transmission system. The power density received at the center of the rectenna can be defined by Brown and Eve's Eq. (4).

$$Pd = (A_t P_t) / (4 \lambda^2 D^2) \quad (4)$$

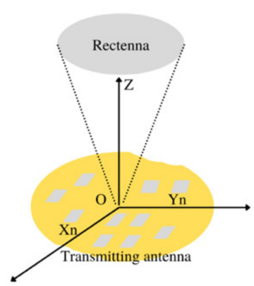


Fig. 8. The geometry of transmitting antenna and rectenna (25).

P_d is power density at the center of the rectenna; $P_t$is the total radiated power from the transmitter (all power in kW). The transmitting antenna has a high beam efficiency, as shown in the Geometry of both antennas in Fig. 8, obtained from the BCE Eq. (5). Therefore, the BTE can be calculated by Eq. (6). On the other hand, the total MPT of a system can be calculated using both equations [25, 26].

$$BCE = P_\Psi / P_\Omega \quad (5)$$

$$BTE = P_\Omega / P_\Psi \quad (6)$$

In the above equations, P_Ψ is the power radiating over the angular region, and P_Ω is the total power transmitted over the visible region. The antenna can generate various types of errors due to vibration, high-temperature change, radiation. These errors can be minimized during launch and by maintaining the orbit.

Table 2 shows the general efficiency of the MPT [7, 27] system for the mother satellite and transmitted power to the daughter satellite. Furthermore, the total efficiency depends on the selection of frequency and PV cells. The output DC power is approximately 10kW with the $P_{DC\ output}$ and avionics efficiency. The Naval research laboratory demonstrated using Photovoltaic Radiofrequency Antenna Module Flight Experiment (PRAM-FX) in orbit as a sandwich model for space solar architecture. During the experiment, 8.4 W RF power was generated with 37.1% DC to RF conversion efficiency, and the total module efficacy was 8% [12].

Table 2: Supposed Efficiency and Power for SSPS by Laser.

Elements	Efficiency (%)	Power Level (kW)
PV array	30	P_{DC} = 21.4
DC to Laser power	56	P_L = 11.98
Beam collection	90	P_r = 10.78
Laser to DC Power	59	$P_{DC\ output}$ = 6.36

Laser Power Transmission. The Laser based SSPS Research Team of JAXA has been researching and investing in developing technology to perform high-efficiency LPT with the controlled direction of a laser beam with an accuracy of 1 μrad (5.7×10^{-5}deg) to limit the divergence to few centimeters when transmitting for several hundreds of km. The high-power laser beam sends electric power to the daughter satellite. Commercially, LD offers a high efficiency of about 40%~60% with around 1 kW laser power. As the power will be a more few 100W, the dissipated heat is high, due to which the cooling system will be more complicated. Their collection is achieved with PV cells' help on daughter satellites [28].

A pilot signal is sent by the mother satellite to the daughter satellite in the LPT system to verify the secure connection concerning distance. The generated DC power is rectifying and send to the laser driver circuit to solid-state diode to generate a high-power laser system and transmit through the optical antenna, as shown in Fig. 9. The daughter satellite's PV cells receive the laser power and convert it to desired operational power, which will be utilized by electro thruster, CPU, communication, and sub-mission payload. The designed SSPS system output is approximately 6.36 kW, which is significantly high for a typical operational satellite. However, recurred power can be adjusted according to the desired application by an inbuilt avionics system. Table 3 shows the supposed efficiency of the standard SSPS system using LPT. The beam collection and Laser to DC power efficiency depend on PV cells.

Table 1: Supposed Efficiency and Power for SSPS by Laser.

Elements	Efficiency (%)	Power Level (kW)
PV array	30	P_{DC} = 21.4
DC to Laser power	56	P_L = 11.98
Beam collection	90	P_r = 10.78
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The lasers must be coherently arrayed at the source, or their beams may be incoherently combined at the receiver site. Generally, the diodes must be arrayed coherently and combined efficiently for transmission [29]. As a result, the LPT system is low mature and low transmission conversation efficiency than the MPT system for high power transmission, as shown in Fig. 10. However, the LPT system can have long-distance transmission compared to MPT [30].

Daughter Satellite. The daughter satellite is a small Nanosatellite, separates and simultaneously distances itself from the mother satellite after becoming stable at 900 km. Then, it starts to send data across long distances via a communication channel located inside the satellite. The following modules will be installed in the daughter satellite; a rectenna to receive solar energy in microwave and PV arrays, a laser to transmit energy, a conversion unit, and a rectifier circuit to receive MPT and LPT. The satellite will additionally carry a power management system, a communication unit, attitude measurement sensor, orbital parameter detection sensor, CPU, an electro-thruster, and a side experimental payload-like debris detection.

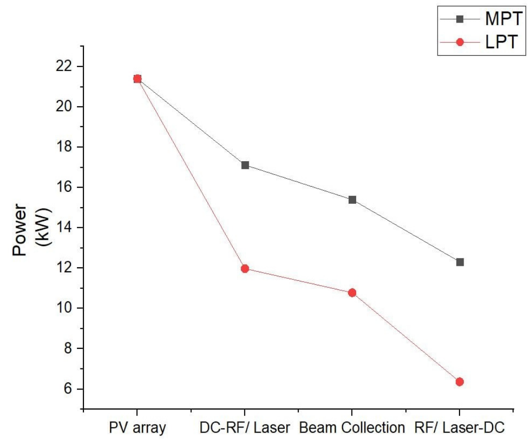

Fig. 10. Generation and Transmission of Power between MPT and LPT.

Table 2: Satellite-to-Satellite mission Architecture details.

Elements	Description	Mother Satellite (SSPS)	Daughter Satellite (CubeSat)
Subject	WPT and onboard experiment	Scientifically investigate and demonstrate WPT from SSPS to achieve a significant level of efficiency of the transmission system and the entire spacecraft. - Pinpoint LPT for long-distance.	-Receive WPT by rectenna. -feedback to the mother sat. - Convert MPT & LPT into electricity to maintain orbit and maneuver in space using the electric thruster. - Extra experiments like debris detection
Payload	Hardware system	PV Cells, Microwave generator, laser setup, avionics, Central processing Unit (CPU), orbit maintenance instrument sensor, and tracer. Communication unit.	Reception and conversion unit, CPU, communication unit, electric thruster, data processing unit. Extra experimental sensor and detection unit
Frequency	Selection of frequency	MPT (5.8 GHz) and LPT (282.823 THz or 1060nm)	
Spacecraft Bus	Customized	Crated to efficient power collection and transfer	
Orbit	Best operational orbit	SSO orbit 900km with an inclination of 98.6 degree	
Data handling	Communication between satellite and ground segment	Direct communication between SSDL and both satellites.	
Responsiveness	Time delay and task management	Real-time data trans-receiving system	
Availability	Level of redundancy	0, available for 24x7	
Ground segment	Mission control center and satellite communication system	SSDL satellite communication system at KU.	
Launcher	Cost-effective to put in the desired orbit	Long March 3B, Polar satellite launch vehicle (PSLV), space X falcon 9, HII	

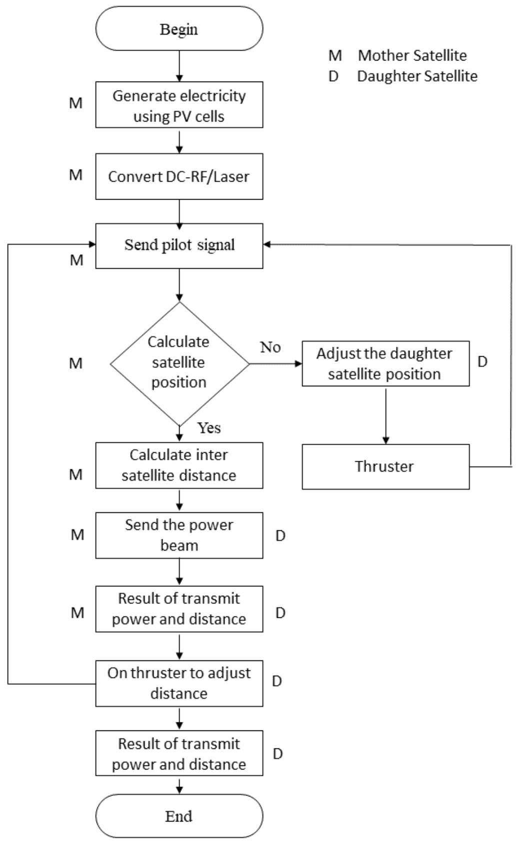

Fig. 11. flow chart of mission design.

V. MISSION PLANING

The SS LPT mission demonstration is the first phase of creating an E-Orbit. In this, the satellite will be launched in SSO at an altitude of 900km. The preferable launch vehicle will be low-cost and capable ofplacing in SSO. The PSLV, Long March 3B, Falcon 9, or H-II are appropriate and affordable launch vehicle systems. Due to the small size of the demonstrative Mother-Daughter satellite, share riding in this launch vehicle firing system will be used. After securing the desirable SSO location, the daughter satellite will start making distance with feedback loop by on board propulsion system. the aiming and pilot RF signal play an essential role in aligning satellites. The pilot signal follows quadrature phase-shift-keying modulation to determine the daughter satellite's position from the mother satellite. The attitude, orbital orientation, and orbital data will be sent back to the mother satellite. Then, with the help of a feedback loop, the daughter satellite will adjust the orientation and align with the mother satellite by performing onboard thruster to receive power, as described in Fig. 9. The payload on the daughter satellite will be the electro-thruster and secondary missions like communication or debris removal. The secondary mission shows that WPTS can achieve the maximum performance of any satellite. Table 4 shows the mission architecture requirement and operational details to fulfill the SS power transmission system. The target of SS WPTS to achieve real-time transmission with zero redundancy. The spacecraft bus is customized and can be launch from the above-provided launcher services. Kyushu University operates ground communication and mission operational systems.

VI. FUTURE WORK

Initially, the investigation of mother and daughter stellate is started, and two satellites will be carried out soon as name E-Sat. Further, it will be the SSPS constellation or an E-orbit using multiple E-Sat. It can establish a space-based power corporation to provide the necessary energy to the operational/ customer. Such a system will enable the operational satellite to get power in real-time 24 hours a day, whenever it perturbs into an E-Orbit. The future satellites will be free from traditionally operated under Photovoltaic cells, to virtually remain in orbit forever, as their energy source is now consistent and non-degradable. The experimental E-Orbit will be a first of its kind and must consist of a necessary minimum of six capable satellites to sufficiently cover an entire 900 km SSO.

Moreover, the other entire constellation of 1600 satellites will cover the altitude of 400 km to 1400 km. MPT will transmit approximately an average and constant power of 10 kW to satellites within orbital range, while LPT would supply energy to peripheral satellites. The LPT power beaming includes orbit maneuver, transfer orbit, or removing satellite from orbit by providing sufficient thrust to the needed satellite.

VII. CONCLUSION

This paper presents that MPT and LPT technology is a suitable WPT system for satellites and demonstrates that WPT integrated SSPS systems can improve satellites' traditional use. The power is beaming, and the appropriate use of wireless electricity can be achieved using this demonstrative mission. The technology is not carried out or demonstrated till now. However, ongoing experiments will provide new results and create a highly efficient system. In the study, the MPT is a highly reliable and effective technique for WPT because of its maturity. However, the LPT system has a promising future for long-distance. This technology can improve any operational satellite's lifespan and drastically cut down the direct costs of manufacturing and launching. This technology can also serve as a gateway for applying prospective SSPS technology demonstrated using this SS WPT system. Future projects include developing LPT technology for stabilizing and controlling dead satellites through high power beams in space. Such technology can be introduced as compulsory instruments on electro-thrusters' future satellites to receive power for deorbiting and prevent debris production.

This paper's primary purpose is to represent SS WPT as crucial in executing the constellation SSPS for the E-Orbit project, enabling a scientific and innovative approach to use satellites to its total efficiency. The E-Orbit itself will provide power to all future communication satellites, GPS, university satellites and potentially extend the CubeSats lifespan to negate any concerns overpower insufficiency. Successful execution of this technology demonstrates high potential for collaborating with investors to establish E-Orbit as a space electricity corporation

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CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Aditya Baraskar: Conceptualization, Methodology, Writing, Visualization. - original draft, Hongru Chen: Supervision. Yasuhiro Yoshimura: Methodology, Formal analysis, Supervision, review & editing. Shuji Nagasaki: Methodology, Supervision, review & editing. Toshiya Hanada: Methodology, Supervision, review & editing.

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