SpaceOps-2023, ID #519

Assembly of Space based Solar Power Satellite using Space Robotics

A Sejal Jain[a], Prathmesh Barapatre[b*]

[a] *Electronics and Communications Engineering, PES University, Bangalore, India*, sejaljain52618@gmail.com
[b] *National Space Society (USA)-Mumbai, President, Mumbai, India,* prathmesh.barapatre@outlook.com

Abstract

With increasing global warming and natural calamities occurring unseasonal, it is evident that conventional, especially non-renewable resources have been excessively exploited. A hunt for alternative and renewable sources of energy is a must before they get exhausted. In order to tackle the alarming issue, a promising source of energy generation is Space Solar Power with the use of 38% efficient Gallium Arsenide panels. This paper highlights the assembly and infrastructure setup of Space Solar Power to generate energy and beam transmit it to the earth station. Modular Solar Panels shall be deployed in Horus or B-roll origami pattern with four sets of the solar array. These arrays will be coupled with a backend system that collects, modulates DC power to the Microwave power source utilising microwave oscillators, and finally received at the ground station by rectantenna array. Furthermore, a megastructure like the Space Solar Power cannot be self-assembled; undoubtedly, it depends on spacewalk or space robotics-based assembly. The continuation of this concept also highlights the use of potential space robotics wherein robotic outstation consisting of maintenance bots instilled with RCS thrusters will help to assemble and deploy full infrastructure with repair and replacement capability, and Human Robotic Interface via Manual control using Teleoperation.
Keywords: Space solar power, Horus pattern, B-roll pattern, microwave oscillators, Rectantenna, RCS thrusters, Teleoperation.

Nomenclature

η	Power Conversion Efficiency
P	Input solar power
P_{max}	Maximum DC output power
V_{MP}	Voltage at maximum power
J_{MP}	Current density at maximum power
d	Transmission distance between orbit and Earth
λ	Wavelength of the transmitting beam
D_{beam}	Diameter of beam reaching the ground
D_{trans}	Diameter of transmitting antenna.

Acronyms/Abbreviations

DC	Direct Current
DSSC	Dye Sensitized Solar Cells
Ga-As	Gallium-Arsenide
GW	GigaWatt
JPL	Jet Propulsion Laboratory
MPT	Microwave Power Transmission
NASA	National Aeronautics and Space Administration
PCE	Power Conversion Efficiency
PV	Photo-Voltaics
RCS	Reaction control system
SPS	Solar Power Satellite
SSPS	Space Solar Power Satellite
WPT	Wireless Power Transmission

1. Introduction

Proposals for candidatures to extract solar energy are abundant with a strong case of depleting non-renewable sources of energy. Alternative approaches facilitated surface solar power plant installations thus accounting for 22% growth in terms of renewable energy generation in the year 2021[1]. Yet, the concern of day/night cycles for terrestrial solar panels and accelerating demand for sustainable energy sources put in efforts to explore space solar power satellites(SSPS).

Receiving focus since the 1960s and yet remaining without a confirmed mission, solar power satellites are extensively research oriented and functional electrical power stations in space. Typically placed in an orbit with maximum solar energy collection capabilities, it is therefore converted into an electromagnetic transmittable beam and focussed directly onto a pivotized large antenna array on Earth. This captured Electromagnetic energy further undergoes conversion to generate electrical power.

This paper describes in detail yet another way of ideating space solar power satellites(SSPS) with a variation in design and arrangement of solar panel arrays. Furthermore, a mega station as such cannot be assembled easily for which a space based robotic assembly consisting of maintenance bots will help to assemble and deploy full infrastructure. Additional features would include repair and replacement capability, and Human Machine Interface(HMI) via teleoperation. Correspondingly, future perspectives with regards to an opportunistic SPS system is also discussed, considering the global renewable energy marketplace.

2. Material and methods

The key structures for infrastructural setup to launch, assemble and maintain a SPS system are explained in subsections listed below.

2.1 The Solar Energy Collector

Conventionally, semiconductor based photovoltaic cells have been prominently used to capture sunlight as the source of renewable energy to reduce the exploitation of fossil fuels . The unique conversion property of semiconductors that allows free flow of electrons through the material is due to the appropriate band gap between valence and conduction bands. The most widely used silicon based photovoltaic cells convert ~27% of absorbed solar energy into electricity in its monocrystalline form[2]. Furthermore, Ga-As based solar panels have proved to be the most efficient of all the solar panels with a conversion rate of approximately 38%. However, this accounts to be the conversion rate for ground based systems.The day/night cycle on Earth allows capturing of sunlight only during the day leaving the panels unused during the dark.

Meanwhile, an SPS is illuminated by sunlight 99.9% of the time making it a promising application for photovoltaic effect. Panels used in space missions already incorporate several folds and rolls aiming to ease the launch and deployment process. Dating back to Brian Trease's research on potential application of origami on space-bound technology, NASA JPL worked on origami-inspired solar arrays with folds that open up as blooming flowers[3]. Alongside, a Japanese astrophysicist invented the Miura fold that opened up solar panels in the Space Flyer unit, a 1995 Japanese satellite[4].

Similarly, away from traditional methods of panel array deployment, a proposal is made to overlap art and technology for best fit area around the satellite system: A satellite system outfitted with 4 solar panel structures designed to deploy in origami formations. A combination of B-roll and Horus origami folds of solar panels automatically unfurl once reaching the destined Geo Synchronous orbit. Placed in the orbit, the satellite focusses on a particular region constantly, 24 times 7.Since the satellite never encounters darkness, a sort of perpetual daytime created makes it extremely convenient for extracting space solar power. Two sets of Horus with each array structured in the form of B-roll are positioned equally across 360 degree surroundings. These design considerations are made to angularly position the arrays across the satellite in a simplified manner and maximise the solar output.

2.2 DC to Microwave Converter

Generally, WPT systems utilise electromagnetic waves for smooth and effective end-to-end transmissions. Typically in a SPS system, microwaves would behave as energy carriers for transmission. In order to convert generated DC to RF, microwave vacuum tubes are proposed considering their high conversion efficiencies. Microwave vacuum tubes such as klystron and magnetrons behave like RF power generators which convert DC solar power to microwaves of desired frequency. Basically there are electron tubes wherein interaction between electric and magnetic fields produce microwave oscillations with high peak power[5]. An added advantage of using a klystron over magnetron is its signal amplification capabilities.

Generally, MPT systems best operate in the range of 2.45 GHz-5.8GHz. Overall efficiency of a 2.45 GHz MPT system, which includes transmission and reception is comparatively higher than 5.8Ghz system[6]. A recent research directed towards a phase-controlled magnetron which is said to have achieved both high efficiency and beam controllability.

2.3 Beam Transmit

A large aperture antenna is required to pivot point the microwave output to ground station. Ultimately, beam width can be monitored by diffraction due to the dish size in relation to the wavelength of the electromagnetic radiation used to make the beam. A focussed beam transmit with minimal side lobes of radiation proves to provide an effective space to ground transmission system. Microwave power transmission is preferred over laser beam transmission for the following reasons. Unlike lasers which are obstructed by rain and clouds, MPT is unaffected by atmospheric conditions, thus offering seamless transmission to the target ground station. Conversion efficiency of laser based transmission systems is lower which does not create substantial impact. However, gigawatts of energy is generated by one SPS system that uses microwave based transmission. Safety concerns such as blinding and weaponization could raise major issues in constructing laser based solar satellites whereas microwave based are much safer to be deployed into orbit.

2.4 Final Rectification and Energy Supply

Once beamed, the energy needs to be captured, stored and converted to a usable electricity supply. The mentioned functions are performed by a rectenna array. A large area spread of combined collector antennas and rectifying circuits form the ground base segment. Several factors are taken into consideration before building a few kilometre long array to collect the microwave beams transmitted by the solar power satellite. For the receiver antenna to be highly efficient, factors like large antenna aperture, non-directive nature, ability to operate efficiently over a pre-defined microwave frequency range, ease of installation, easy mechanical tolerances and minimal radio frequency interferences are of prime importance.

The antennas are backed by a rectifying circuit to convert the microwaves back to electrical power with negligible harmonics present. Figure 2 explains the schematic of a single rectenna[7]. Low pass filters are employed to eliminate harmonic radiation. A basic semiconductor based schottky diode, depending on input levels, rectifies the RF power to DC power. For proactive rectification, diode cut off frequency should be to times the operating frequency. Further a DC bypass filter is added to ultimately transport the desirable DC, which then passes through an inverter for AC supply across the grid. A half wave dipole antenna based rectenna has been able to produce rectifying efficiency of around 90%[8], making it a significant applicant for the ground receiver segment.

2.6 Robotic Outstation for Maintenance and Repair

The Robotic Outstation will be a hub for the robots that will be used to repair the Space Solar Power station. After the SSPS has been deployed, proper examination needs to be done to verify if it's intact and in good health. How does one achieve this? Infact, a fleet of four robots inside the robotic outstation will now enter the main scenario. The outstation will be powered with the help of solar panels and will be controlled in orbit using the GNC system on board which uses Reaction control system (RCS) thrusters, to provide attitude control and translation. It will remain in the same orbit as per the SSPS.

The Station will consist of four Robots with different functionalities, by default they will be capable of performing in-orbit servicing and handling equipment. They can be reprogrammed according to our requirements and usage. For deployment they will rely on release mechanisms which are traditionally used to deploy cube-satellites.

Welding Bot - It will be used to repair short damages made due to Space debris or Wear and Tear of the SSPS

Maintenance Bot - They will be used for routine checkup and predictive maintenance of the SSPS

The Station will have capability to be controlled manually as well as function autonomously. It will have functionality to connect and fetch various sensor data and structures. Integrity report from the station and from earth command crew to perform necessary repairs required by SSPS. (Sensor data to create digital twins for ground stations to better understand areas that require repairs).But what about its refuelling and maintenance?

By collaborating with in-orbit service providers, the outstation will be refuelled in space with the help of a refuelling outpost coming up soon in the upcoming decade.

3. Theory and calculation

3.1 Equation numbers

A key characteristic of any solar panel is its ability to convert light into electricity.The PV ability is defined by PCE which is a ratio of incident light to converted electrical power output. Thus,

$$\eta = \frac{P_{max}}{P} = \frac{V_{MP} J_{MP}}{P} \qquad (1)$$

As far as observed, a typical multi junction Ga-As based solar cell has displayed the highest conversion solar to DC conversion rates, accounting to 38%[9]. These Ga-As based semiconductor solar panels arrays have vastly been used for high end applications, especially for space missions. As suggested, an interfaced B-roll and Horus Ga-As Photovoltaic deployment shall increase the efficiency of an SPS system to nearly 144% unlike Earth power stations.

Once solar energy is captured, they are converted to monochromatic microwaves which are further directed towards Earth via transmitting antennas. The main parameters include frequency, the diameter of the transmitting antenna, the output power beamed to Earth and the maximum power density. Furthermore, diameter of beam reaching the ground is calculated using,

$$D_{beam} = \frac{2.44 d\lambda}{D_{trans}} \qquad (2)$$

Furthermore, the actual power density received at the designated rectenna ground system will peak at around 200-300 W/m2 in the center of the rectenna and taper off at the edges to a few W/m2, bringing the average to around 100-150W/m2 .

3.2 Figures

A generalised block diagram for a space solar power satellite is shown in fig.1. Together with is an extended schematic of a single rectenna circuit acting as a microwave receiver in fig.2.

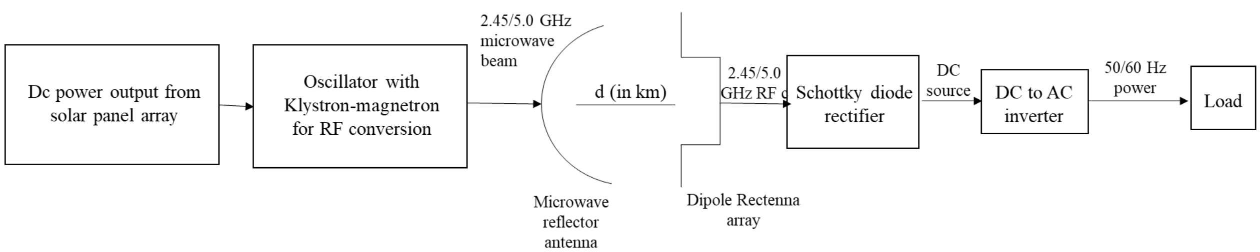

Fig. 1. Operational schematic of a space solar power system

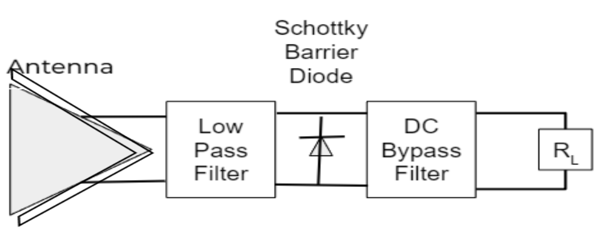

Fig. 2. Block diagram of a single rectenna circuit

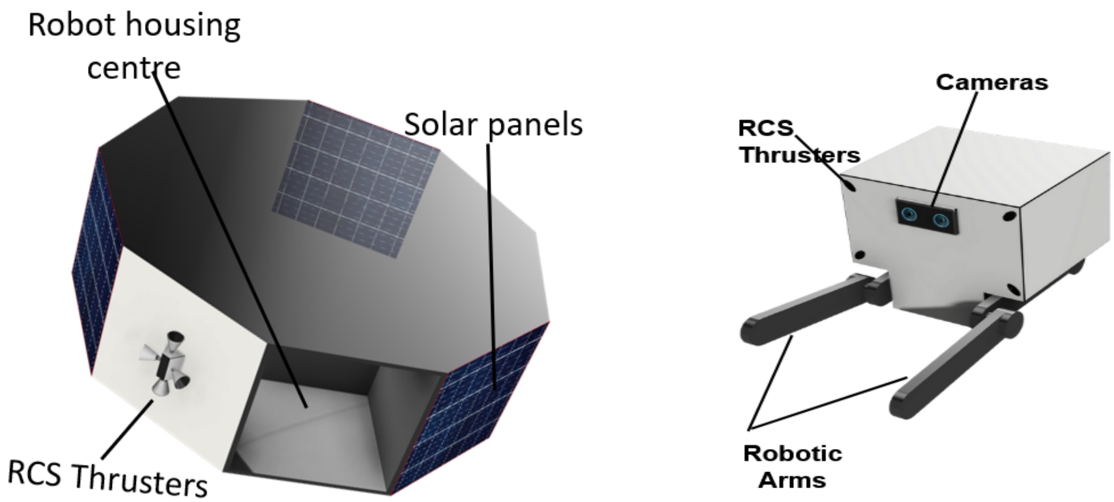

Fig.3. 3-D model of robotic outstation and maintenance bot

AI functionality of the bots:

Trained based on various simulations, the bots system is capable of recognising damaged areas on SSPS using accurate image processing techniques with the help of its cameras.

The bots will be trained on Reinforcement Algorithms that will help it to learn and train itself on dynamic scenarios that will possibly occur in space. These bots will be capable of communicating with each other in order to share data and avoid collision with each during deployment.

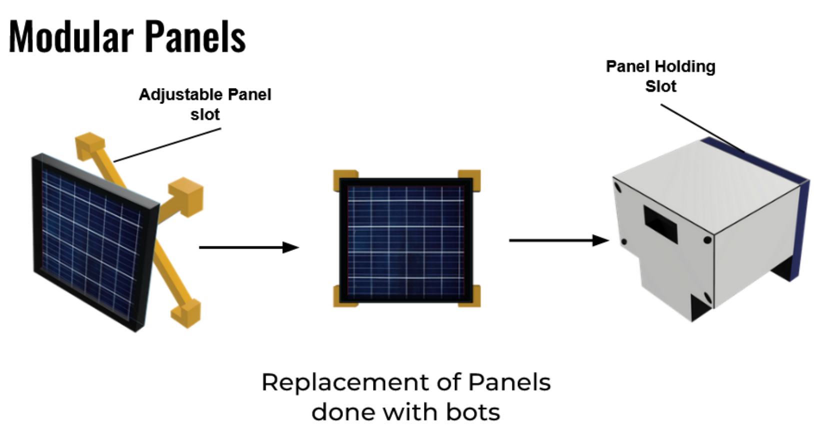

Fig.4. Mechanism to replace the panels with the help of repair bots

Due to modular design of SSPS panels, bots shall be able to replace the panels with ease in case of any wear and tear as shown in figure 4.

3.3 Tables

A detailed efficiency chart for a realistic SPS model with conversion efficiencies[10] are portrayed in Table 1.

Table 1: Efficiency of a space solar power satellite

Component of SPS	**Efficiency**
Solar energy capture	99.9%
Photovoltaic energy to DC power	38%
DC to RF conversion	85%
Microwave beam transmit via antenna	91%
Atmospheric effectiveness with microwave transmission	98%
RF collection by ground station	95%
RF to DC conversion by rectantenna	90%
DC to AC conversion	96%
Grid power distributed supply	95%
Maintenance and monitoring capability in orbit	80%
Repair capability by the bots	65%

Based on Table 1, it is possible to approximate the size of major elements of an SPS system, further of which shall be discussed in the results section.

4. Results

An anticipated 1GW output power generation shall require approximately 3.5-4 square kilometres of solar satellite area and 7-8 square kilometres of rectenna ground receiver setup to effectively supply via power stations.

Certainly, any SPS configuration shall convert solar energy almost the entire time except for eclipses. Almost 85% conversion of DC power to microwaves makes it a zero loss beam transmit platform. It eliminated the need of monitoring and maintenance due to cloud cover, darkness, precipitation and wind speed. The self monitoring and maintenance capabilities via robotic outstation outshows SPS as a long term and independent working power station in space. Additionally, it turns out to be a clean energy source with zero greenhouse gas releases and hazardous waste generation unlike thermal and nuclear power plants. Consequently, capture and collect mechanism in geo synchronous orbit shall be approximately 5 times the maximum terrestrial capture.

Correspondingly, an efficient SPS system requires high cost of construction, assembly and deployment in space. For example, in the microwave transmission technology, reduction of weight per unit of generated power is required to ensure a reasonable cost for a given performance. Maintenance, of course, is fully autonomous but a lot of challenges will be encountered during the process. Alongside, the microwave beam frequency would require isolation from interference with communication satellites. Long Radiation, degradation and satellite heating levels need careful attention before launching into space. Rectenna impact on Earth lifestyle requires close examination. A profound optimisation and evaluation is a must before realising the concept of space solar power to meet Earthly requirements.

5. Discussion

The realisation of a space solar power concept as a large-scale power generation holds massive potential in the near future. The full solar irradiation, unobstructed by atmospheric entities and 5x energy generation invites large scale discussions, both technology amendments and application wise. Certainly, progressive trends towards developing an SPS, followed by optimisation at each level is necessary for a sustainable launch readiness

.

Significant analysis needs to be done on improving the PCE of solar arrays. On calculating, increasing the solar array efficiency by at least 50% can drastically increase the electrical power generated by a factor of two[]. Further increase in solar conversion rates can improve the endlong efficiency of an SPS system. Additionally, an important issue concerning the transmitting antenna is precision monitoring of beam direction to maximise output received at ground segment and eradicate undesired directional microwaves lobes. Emergency calibration has to be employed if there's a slight shift in pre-defined beam angle to rectify and achieve pointing accuracy.

A third generation DSSC has captured interests via displaying themselves as a prime example of utilising organic dyes to absorb sunlight. These cells are comparatively less efficient than inorganic photovoltaic cells. However, they boast cheap fabrication and production, ease in mechanical flexibility and good depth in photon absorption capacity. Surely, DSSC can be a potential candidate for an SPS system if improved efficiency could be achieved with extensive research carried out on them.

Another prospective approach to realise solar energy as the most naturally available source of renewable energy is marching towards the scope of developing a space solar power satellite(SSPS) constellation in the long run. Harnessing power through sunlight with several satellite mediums positioned over prime locations in the orbit, and beam transmitting tons of gigawatt of power to compatible locations on Earth shall possibly solve the issue with energy demand and global warming. However, extensive and detailed oriented studies need to be done before mankind puts resources to justify this mega power plant in space.

6. Conclusions

The escalating global energy demand and depleting fossil fuels in the new millennium straight-away directs towards potential use of space solar power. SPS will receive unbound attraction for its capabilities to harness solar energy at the highest levels. Its environment friendliness including unharmful electromagnetic transmission capabilities, reduction in carbon dioxide emissions and sustainability, significantly awards it as the best green energy source. Alongside, management and repair capabilities delivered by the robotic outstation makes it a fully self-dependent electric power station in space. Possessing such high scope in future, investment in space solar power for its technology readiness, optimisation and effective fulfilment of energy crisis shall definitely be worth it.

Acknowledgements

This work truly represents the efforts of two like-minded young researchers from India. The self-starting of this project and their perseverance in complete remote working is a testament to each and every character involved to get the project to this stage.

We sincerely thank Dr. Ravi Marghasahayam for his timely guidance and belief in us. Partners providing software and technical advice are thanked for their support throughout the project. A gratitude to SpaceOps 2023 and Mohammed Bin Rashid Space Centre for supporting us in presenting our idea on Space Solar Power Satellite and Spacerobotics.

References

[1]Piotr Bojek, "Solar PV", International Energy Agency reports, September 2022

[2]Oscilla en-pages, "Solar Cells: A Guide to Theory and Measurement",Solar cell efficiency tables (version 50). Martin A. Green, Progress in Photovoltaics, Vol 25, p668-676 (2017)

[3]Tony Greicius, "Origami style solar power, NASA JPN news, August 2017

[4]Nishiyama, Yutaka, "Miura Folding: Applying Origami to Space Exploration.",International Journal of Pure and Applied Mathematics 79.2 (2012): 269-79.

[5]Brown., W. C. (September 1984). "The History of Power Transmission by Radio Waves." Microwave Theory and Techniques, IEEE Transactions on (Volume: 32, Issue: 9 on page(s): 1230- 1242 + ISSN: 0018-9480).

[6]Intercommission working group, "URSI White Paper on Solar Power Satellite (SPS) Systems and Report of the URSI Inter-Commission Working Group on SPS",n Radio Science Bulletin, No. 321, pp. 13-27, June 2007;

W.Brown, "Electronic and Mechanical Improvement of the Receiving Terminal of a free space Microwave Power Transmission System, 1977
[7]James O. Mcspadden & John C. Mankins,"Space solar power programs and microwave wireless power transmission technology", IEEE microwave magazine, pp.46-57, Dec 2002
[8]Thorat Ashwini Anil, 2 Prof.Katariya S. S., "Solar Power Satellite", IOSR Journal of Electronics and Communication Engineering (IOSR-JECE), PP: 59-64
[9]Masafumi Yamaguchi, "High Efficiency Ga-As based Solar Cells", Post Transition metals, November 2020
[10]David V. Smitherman, "A Comparison of a Solar Power Satellite Concept to a Concentrating Solar Power System", AIAA 2013-5344, 2013