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SOLAR POWER SATELLITE SOLAR ENERGY HARVESTING

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ABSTRACT

Electronic circuits are currently normally utilized and the requirement for power later on will increment. Sun based energy might be considered an alternative for traditional energy assets due to its inexhaustibility nature. However, the earth gets just 1/100th of complete sun oriented force. There are various satellites in space pointed toward serving numerous applications on the planet. A Satellite with a particular application for producing power from sunlight based radiation is proposed, which is utilized to communicate the put away energy to the ground station as microwaves (RF signal). These satellites are put in LEO/MEO so the sunlight powered chargers of satellite are towards the sun most piece of the day and harvests sun based energy. The Solar boards in the satellite gathers heat energy and changes to DC force and stores in a battery save. This DC power from the battery save is changed to RF energy of required recurrence utilizing a gadget called Magnetron and the changed over power is sent to earth station recieving wire, which is coupled to rectifier circuits that are masterminded as exhibit. Rectifier changes over got power (RF) to energy (DC) that is put away in battery. The thought process behind the proposed sunlight based fueled satellites is to get totally through ecological contamination which is a direct result of the emanation of hurtful gases from nuclear energy stations. The proposed work likewise gives answer for a worldwide temperature alteration and simple energy age utilizing normal asset (Solar Energy).

Keywords

Rectenna, Solar Power Satellites, Photo Voltaic System, Rectifier, Microwave Wireless Power Transmission Technology, Free space loss

1. INTRODUCTION

It is estimated that a total energy of 56000 tera-watt hour is annually required worldwide. Nuclear power plants provide a vast amount of power, but disasters like Chernobyl nuclear accident (1986) in Russia and Fukushima nuclear accident in Japan (2011) **[1]** made the researchers think of an alternative method for power production. Solar power which is renewable and eco-friendly is the better way for producing power safely. Two methods are mainly employed in harvesting power from solar energy.

1) Terrestrial Solar Power system (TSP) and

2) Solar Power harvesting from space (SSP)

More energy is harvested from SSP, since solar flux density in space is much greater when compared to TSP. Solar power satellite is a giant satellite developed as an electrical power plant that orbits the earth using wireless power to transmit solar energy harvested using SSP method. **[13]**

Mainly four operational units are part of this satellite:

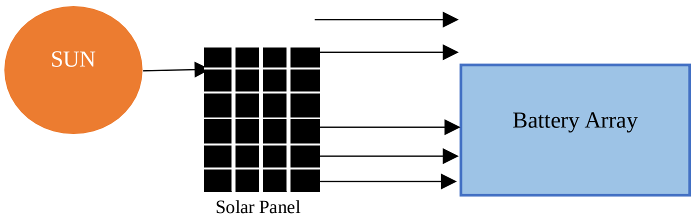
A. Photo Voltaic System used to convert captured solar energy to a DC power

B. System to convert DC power to RF waves.

C. Number of small antenna elements (Array) to transmit the Radio Signals

D. An antenna on the earth station coupled to rectifier circuits arranged as arrays generally known as Rectenna.

This satellite orbits the earth at height of 5000Km (Approximately) from the ground i.e., they are placed in low earth orbit(LEO). The reason for placing the Solar powered satellites in MEO or LEO is that the efficiency of microwave power transmission from Geostationary Orbit to earth surface is extremely low compared other orbits. The converted power is directed as beam to the location where it is needed. At the ground station several rectifiers are linked through series connection which form an array and they perform the conversion of RF to DC and this energy is preserved in the Battery. More recently, the MPT technology is used for wireless charging for mobile phone and electric vehicle. This paper compares the energies harvested by both TSP and SSP. Fig.1 displays the block diagram of proposed concept.



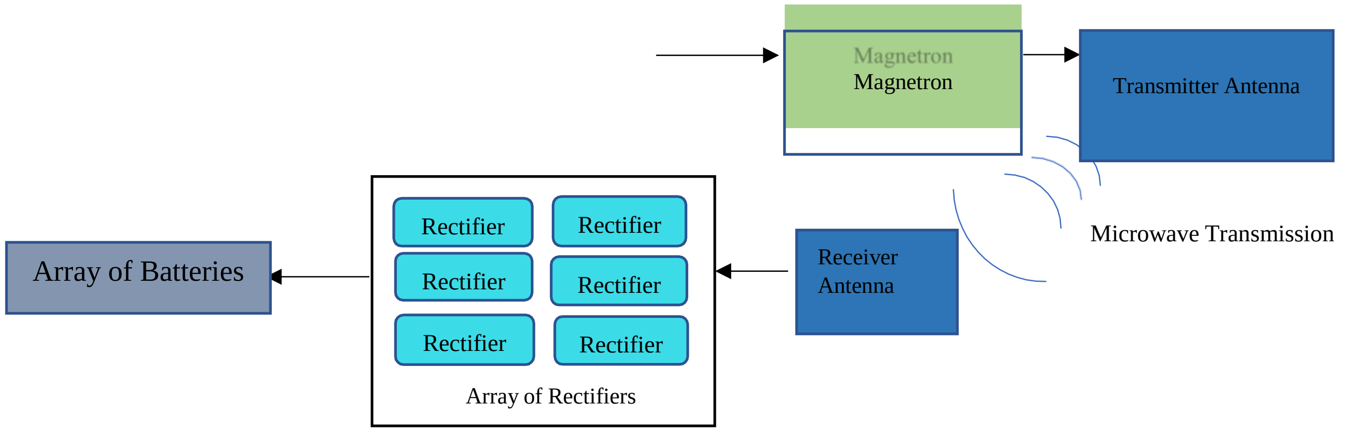


Fig.1 and 2 Block diagrams of proposed SSP

2. LITERATURE SURVEY

Fossil fuels which are non-renewable pollute the environment and increase global warming. But, the energy from the sun is renewable resource. Solar power satellites have been suggested many years back, but these were not implemented because of several practical and technical roadblocks. Compared to the power produced by the photovoltaic system installed on Earth, the power generated from the satellite will be higher as the sun rays are intense in space. SSP concept incorporates a converter to transfer the collected power from space to the Earth station rectenna. The DC power from space is received as microwave beam (RF signal) by the Earth station. The survey on recent power generation techniques and its pros and cons are as follows:

James.C.Maxwell (1865) proves theoretically that electric field(E) and magnetic field(H) can travel together as waves in space at speed of light**[2]**. Based on Maxwell's work, Nikola Tesla (1890) practically proves that E-field and H-filed can travel through space.

Tesla (1891) experiments with the electrical energy transmission using a radio frequency resonant transformer which produced alternating currents of high voltage and frequency that helped in electrical energy transmission for few meters without using wires. The experiment also successfully verified that it is feasible to illuminate vacuum bulbs without the utilization of wires. **[5]**

W.C. Brown (1961) demonstrates a microwave-powered helicopter. The helicopter receives its power in the form of microwave beam for its flight **[27].** Brown (1967-1975) has successfully beamed 30Kilowatts of electrical energy over one-mile distance with an efficiency of 84%. **[3][17]** The proposed work applies SSP based on Brown's validated theory.

Glaser Peter. E (1968), introduces the notion of using a wide array of solar panels to harvest solar energy from space (Several miles in area).This technique of transmitting energy over long distances through microwaves from a very wide antenna (up to 1 km2) on the satellite to the earth antenna[6] is known as microwave beaming. However, the work introduces only the concept whereas practical implementation for energy generation is not proved.

Naoki Shinohara (2013)[23] summarizes the development of Microwave power transmission(MPT) using phased-array techniques on solid-state and magnetron-based power technologies. This paper uses phased-array architecture to present the flight without fuel experiment referred as "Microwave Lifted Airplane experiment".

Xun Li et.al,(2017) proposed the new concept called E-near-zero(ENZ) metamaterial. The author has constructed a metamaterial -cylindrical condenser. Sunlight is collected and sent to the middle of the cylindrical condenser using the refractive index(mu) property. PV system in the shape of hemisphere is fixed at the centre of the condensor and converts the sunlight to DC. Phased array transmitter antenna is employed for microwave beaming to rectenna situated on the earth.

Farhad bagheroskouei, Shahab Karbasian, Maryan Baghban and Reza Amjadifard(2017) designed, implemented and tested a small Solar Power Satellite(SPS) and it is placed in the lower earth orbit with a life time of 40 days. Solar panels used in the satellite is GaAs and the batteries are made of Li-ion to store the energy. The proposed power controller system has five units including battery charging unit, DC to DC converter unit and a power distribution units are installed in the satellite.

Hongxi Yu, Yazhou Dong, Liming Gong, Ying Wang (2013) constructs a concentric disc shaped solar array. The requirements of SPS are placed between the solar panrls array and MPT array in the form of sandwich structure. To trim the dynamic power ranges, solar panels are placed on both side of the satellite and microwave transmission disc rotates to maintain the perfect plane.

From the past survey, the inference is that transmission of power is feasible from satellite to earth station. Therefore, from the theoretical concepts given by past researchers, this paper practically implements the process of conversion of DC power to RF power using magnetron in space. Various power loses during RF power transmission from space to earth, calculation of receiving power and it's loses in groundstation are analysed.

The paper explains the proposed work as follows: Section 1 discuss about Introduction; section 2 details the literature survey of the recent research work; section 3 explains the implementation work flow of the space solar power; section 4 discusses detail explanation of SSP; section 5 gives the details of cost incurred for implementation of SSP; section 6 presents the result discussion of the proposed work; section 7 discuss the conclusion of the proposed work.

3. IMPLEMENTATION PROCESS OF SPACE SOLAR POWERGENERATION

Solar energy is received by solar panels and it is converted to DC power. After converting the Solar radiation to DC power, it is stored in a battery array. This stored DC energy is again converted to RF power for the purpose of transmission to Earth station antenna. To convert the stored DC power to RF power,three sorts of converters areviewed as, for example, magnetrons, klystrons, solid state amplifiers. Among these, magnetrons have high efficiency in terms of power conversion . The magnetron's output power is then provided to the satellite transmitter segment. The transmitted power as RF signal is received by a low loss Half Mode Substrate Integrated Waveguide (HMSIW) rectenna at the earth station. A battery array are used to reserve the received power in the order of Giga watts. The detail process of methodology proposed is discussed in the forthcoming sections.

This paper compares the energy harvested using solar panels on earth and the energy harvested from space solar power system. Also, the proposed work proves that energy harvested using SSP is thrice that of the Terrestrial Solar Power (TSP) system. The amout of losses resulting from the satellite height is also analyzed. The magnetron's output power for different frequencies is also calculated and represented quantitatively. Fig.2 depicts the workflow of proposed SSP

4. SPACE BASED SOLAR POWER SYSTEM

Gallium-Antimony (Ga-Sb) Based Solar Cells for harvesting solar power

A solar cell converts the photons from the sun to DC. Efficiency of solar cell(ɳ) given in equation (1) corresponds to the amount of incident solar energy which can be converted to electrical power in terms of percentage.

$$\eta = \frac{Pout}{Pin} \qquad (1)$$

P_{in} represents no.of photons incident on the solar cell

P_{out} represents the Direct Current (DC) output from the solar cell

Conventional solar cells are comprised of silicon and have a maxmium power generation efficiency of 33.16 percent. Solar cell performance is improved by solar multi-junction cells. A multi-junction solar cell is assumed to be created on a GaSb substrate that is inferred with an improved power generation efficiency of 44.5%. Using equation (2), the number of solar cells and solar panel area is calculated on the basis of the power requirement

$$\text{Number of solar cells} = \frac{Area\ of\ Solar\ pa(Estimation)}{Area\ of\ solar\ cell} (in\ m) \quad (2)$$

Area of a typical PV cell is 0.02233m^2**[7]**. Photovoltaic(PV) systems are typically equipped with components called bypass diodes, which redirect the flow of current around impaired cells. If a single solar cell in panel is shaded, then overall current output of the PV system will decrease which causes power imbalance and may damage entire PV system **[11]**. So, to avoid the shading effect, the PV cells are given series connection for low power loss.In general, a satellite has fewer or more PV cells depending on the power requirement to run the satellite's devices / thrusters. The proposed SSP system do not utilize this harvested power for operation of any sensors or devices as this satellite is dedicated to bring all the harvested power to the ground station. Power obtained from a single solar cell is given in equation (3)

Ps = A x ɳ x H x PR (in watts)

Where Ps = Power from single solar cell

A = Area of single solar cell

ɳ = Efficiency of single solar cell

H = Solar Flux Density (Watts/m^2)

PR= Performance Ratio (Typically 0.75)

The power of entire solar array is calculated knowing the power obtained from single solar cell. The converted solar energy is stored in the array of Lithium-ion batteries(LIB). LIBs are used due to lesser cost, lengthy life cycle and lower weight. **[8]**

DC power to RF conversion

As said above, a device called Magnetron is employed for the process of DC-RF wave conversion because of its good conversion efficiency. The conversion efficiency of magnetron was around 80% .**[4]**

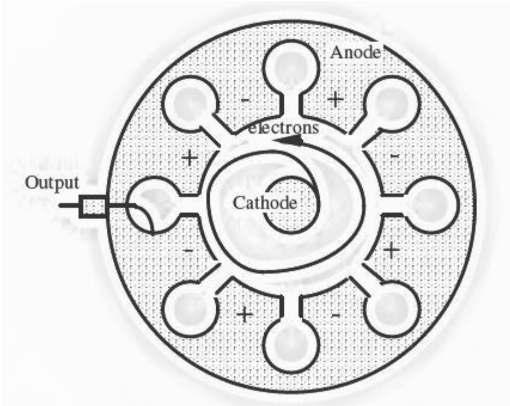


Fig.3 A Magnetron for converting Electric current to Microwave frequency

The working guideline of Magnetron depends on electrons interacting with the H-field. At the core of the magnetron, there consists of hot cathode in the shape of ring. Electrons moving at fast are beamed from the warmed cathode and go through anode.

A resonator which has openings in it for input acts as anode for magnetron. A robust magnet to produce parallel magnetic field to cathode is provided beneath the anode. So, when an electron tries to pass from cathode to anode, they go through both electric field and magnetic field at a similar moment of time. When a particle having charge viz.,electron travels under the impact of a H-field, it takes curved path. The cavities resonate because of rapid movement of electrons in the interior of cavity and discharges microwave radiation. A magnetron is proposed which has power conversion efficiency of 75%. At an operating frequency (F) of 2.465GHz, it produced an output 1.04KW for an applied voltage 4.3Kv and anode current 0.33A. The specifications of the proposed magnetron are as follows: radius of cathode (a) is 0.0065m, radius of anode (b) is 0.0069m, magnetic field (B) corresponding to applied input is 0.19T and the no.of resonators (N) is 5 **[12]**. The power output relies upon the operating frequency, the H-field, the resonator number, the cathode and anode radius. The voltage yielded by the magnetron as output is calculated bu using equation (4)

$$V_o = \frac{2\Pi FB}{N}\,(b^2 - a^2) \qquad (4)$$

where 'a' is the cathode radius and 'b' is anode radius.

The output port of magnetron is connected to a coax cable which acts as bridge between magnetron and tuning waveguide section that is used for impedance matching with transmitter antenna. Fig.3 shows the schematic of a magnetron.

Microwave transmission from satellite to Earth

A 500m (diameter) phased array antenna is considered for microwave transmission from satellite to earth. Since the satellite orbits around earth, phase shifter is used to steer the microwave beam towards the receiver antenna at earth station. Transmitter efficiency is thought to be 80%. Antenna gain(dB) is determined reliant on the necessary efficiency by equation(5).

$$\text{Gain(dB)} = \frac{4\Pi\eta A}{\lambda^2} \qquad (5)$$

A=Area of transmitter antenna in meters ($\frac{\pi D^2}{4}$) (6)

λ = Wavelength at operating frequency = $\frac{C}{F}$

C= Speed of light i.e., $3x10^8$

F=Frequency (2.4GHz)

η = Efficiency of Antenna

The necessary gain for expected transmission efficiency of 80 percent is around 80dB and is accomplished for diameter of the antenna in the range of 400m to 500m as outlined in figure 8

Transmission Losses:

Various losses are considered as power is transmitted from space to earth. Major power loss that occur during microwave transmission is Free Space Loss (FSL), which is calculated by equation (7)

$$FSL(dB) = 20\log(D) + 20\log(F) + 20\log(\frac{4\pi}{c}) - G_t - G_r \quad (7)$$

Where D is the distance between satellite and the Earth station antenna

F is Frequency of transmission of power

G_t is Gain of Transmitter antenna

G_r is Gain of receiver antenna

From figure 9, it is observed that Free space loss is in range of 54dB-64dB for a LEO satellite.

Another loss in microwave transmission is atmospheric loss.Atmospheric loss is caused by energy absorption by atmospheric gases and depends on atmospheric temperatures.Be that as it may, the environment does not have much encounter with the frequencies beneath 10GHz. As mentioned previously, satellite downlink operates at a frequency of 2.45GHz and atmospheric absorption at this frequency is negligible, around 0.006dB/km

Third loss is antena pointing loss(L_p) if transmitter is in asymmetry with receiver. It is necessary to correctly align both the receiver and trasmitter i.e., no misalignment between each other to increase the gain(dB) of transmitting antenna.

Pointing loss can be calculated from the equation 9 as,

$$L_p=12*(\alpha_T/\Theta_{3dB})^2 \quad (9)$$

Where, α_T=offset angle,

Θ_{3dB}=70 x (λ/D) degrees (Half Power Beam Width)

D=Antenna Diameter

Pointing losses are minimized by maintaining approximate offset angle and antenna HPBW. In general pointing losses are around 1dB.

Total Transmission loss (L_{Total}) is determined knowing the free space loss, atmospheric loss and antenna pointing loss from the equation 10 as,

$$L_{Total} = \text{Free Space loss} + \text{Atmospheric loss} + \text{Pointing loss} \quad (10)$$

A specific measure of power is lost during the exchange of power from Space to Earth and it is shown as total transmission losses and the receiver antenna receives the remaining power.The estimated pointing loss value is shown above and the FSL value is pointed in Figure 9.

4.4 Effect of Antenna downtilt on received power

$$A_{dt}=\tan^{-1}(H_t-H_r/D) \quad (11)$$

Where, H_t=Transmitter height

H_r=Receiver height

D=Distance between transmitter and receiver

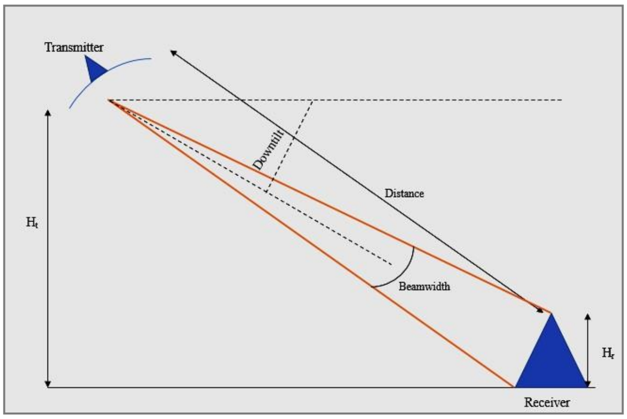
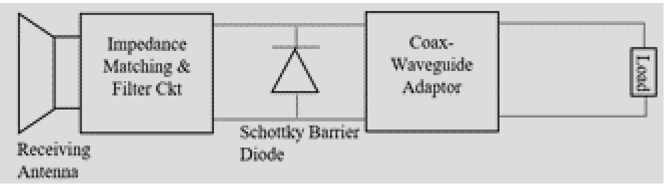


Fig.4 Illustration of Antenna Down tilt

Fig.4 illustrates the antenna downtilt angle i.e, angle between 0o horizon and the 1/2 of beam width. Based on antenna downtilt, transmitter antenna's angle can be adjusted such that the receiver antenna will be in the coverage of satellite transmitter antenna. The transmitter antenna height is designed to cover the receiver on earth for any downtilt angles.

4.5 Receiver Antenna (Rectenna)

Rectenna is a passive component consisting of a circuit-related antenna. Because of its speedier recuperation time and much lower forward voltage drop and good RF characteristics, Schotty barrier diodes (GaAs-W, Si and GaAs) are typically utilized in the rectification circuit. The yield of a solitary rectifier is extremely low. Hence, an array of rectifiers is used based on power requirement. A low profile HMSIW rectenna is used as a receiving rectenna which has a return loss of 26dB and power conversion efficiency of 61% **[10]** at 2.45GHz frequency. At 2.45GHz frequency the measured efficency and calculated efficency of the selected rectenna were 92.5% and 90.5% respectively.**[25]**



Antenna downtilt (Adt) determines the downward angle of the satellite transmitter antenna and it is quantified in degrees. Antenna downtilt angle plays major role in reducing pointing loss. The antenna downtilt requires the transmitter height, the receiver height and the range of transmitter and the receiver.**[20]**. Antenna downtilt angle is calculatedby equation 11,

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Fig.5 Complete rectenna measurement setup

Received power at the Rectenna is calculated by equation (12)

as, Received power = EIRP + G_r – Total Transmission losses

(

12)Where, EIRP (Effective Isotropic Radiation Power) = P_t x G_t

(13)

Pt = Transmitted Power from

satelliteGt = Gain of the

transmitter antenna Gr = Gain of

the Receiver antenna

5.ECONOMIC VIABILITY

The present satellites cost an enormous cost in acspect of the materialsused to manufacture them. So as to make the satellite and space solar power financially savvy, Nano technology is adopted. SPS-APLPHA is the most realistic design to date.It breaks down the solar satellite

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into 8 lightweight, easy-to-start, install and replace modules. This proposed system utilizes materials based on carbon nanotubes**[29]**.Carbon Nanotubes were utilized to lessen the heaviness of modules to significantly diminish costs**[28]**.

A magnetron that produces 2kW expenses around USD 50. Ground systems are expected to cost ~US$50 million. A single launch of satellite costs around US$135 million.The total expenses for launching, maintaining and entire equipment utilized is around US$337.5 million. The satellite can pay for itself within 2years of operation by providing annual revenues more than US$120 million.

6. RESULTS AND DISCUSSION

Table 1. Harvested power comparison: space vs ground

	Altitude		Area	Harvested Energy
Space	5000 Km	1366 W/m^2	200m^2	9Mw/day
		1366 W/m^2	300 m^2	20Mw/day
		1366 W/m^2	400 m^2	36Mw/day
Ground	Location	Sunlight Irradiance	Area	Harvested energy
	Global	3.92kWh/m^{2}day	1 km^2	1.58 Mw/day
	Western Australia	5.90kWh/m^{2}day	1km^2	2.36Mw/day

Table 1 demonstrates that the energy obtained from TSP is much lower than that of SBSP. In space, for 400m^2 area solar panel 36Mw of power is generated per day. On the ground, for 1km^2 area panel, 1.58Mw of power is produced on an average globally

Table 2. Total kilowatt hour power harvested per day

	400m2 Panel	
	In Space (Per Day)	**On Ground (Per Day)**
1000Km	1.31Mwh	541Kwh
MEO	2.90Mwh	1.88Kwh
GEO	3.15Mwh	0.54Kwh

Table 2 shows the power yielded by a 400m^2 solar panel in space and the energy harvested on Earth after transmitting as Microwaves and compares the energy produced for various earth orbits viz.,GEO,MEO and LEO **[15]**

Table 3. Comparison of Energy harvested in space and on Earth for different number of solar cells

No. of solar cells	Power generated in space(watts)	Power generated on earth(watts)
100	1025.8	750.9
200	2051.6	1501.9
300	3077.3	2252.8
400	4103.1	3003.8
500	5128.9	3754.7

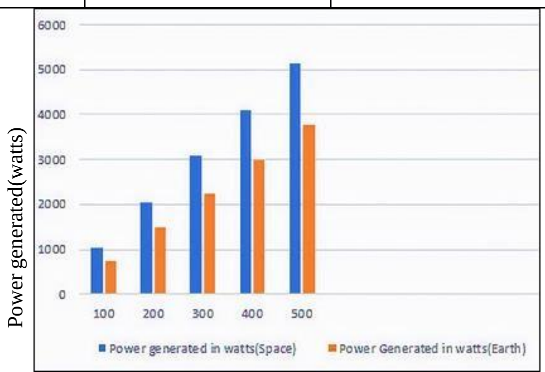

Table 4. RESULTS

Area of Solar Panel	400m^2
Area of single solar cell	0.0225m^2
Efficiency of single solar Cell	44.5%
Type of solar cell used	GaSb based
No. of solar cells in panel (as calculated)	1.7 x 10^6
Power obtained from single solar cell	10.25Wh
Magnetron operating frequency	2.465 GHz
Magnetron Output Power	26.5Mwh
Total Losses occurred during transmission	115.22dB
Received Power (for the entire day)	100Mw
Total DC power stored after conversion (for Day)	91Mw

Table 4 displays various details and results includig the area of solar plate used, category and type of PV cell utilized, power obtained from a single photovoltaic cell, magnetron output frequency, received power at rectenna, total DC power stored in battery after conversion.

Figure 7. Frequency vs Output power graph of magnetron

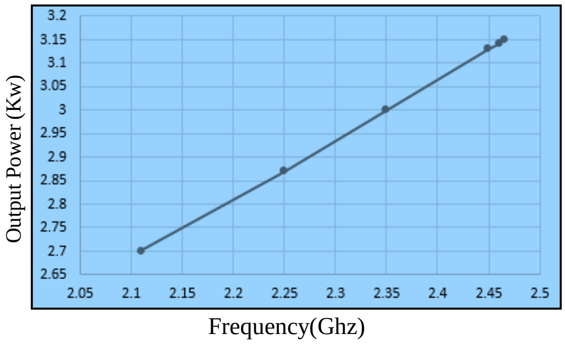

Fig. 7 displays the alteration in magnetron's output power with increasing frequency. It is observed that, as frequency is increasing output power increases linearly. But because of atmospheric losses at high frequencies, frequency between 2.05 GHz to 2.5 GHz is preferred.

Figure 8. Antenna diameter(m) vs Gain(dB)

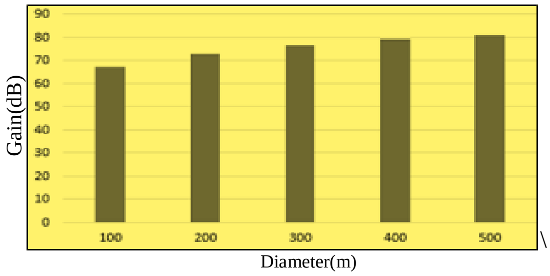

Fig.6 Graphical representation of Power generated on Earth and space for different number of solar cells

No.of solar cells

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Fig.8 shows the variation of the gain (dB) of the transmitter with increasing diameter which helps in choosing antenna diameter based on required gain.

Fig.9 Altitude in km vs Free space loss in dB curve

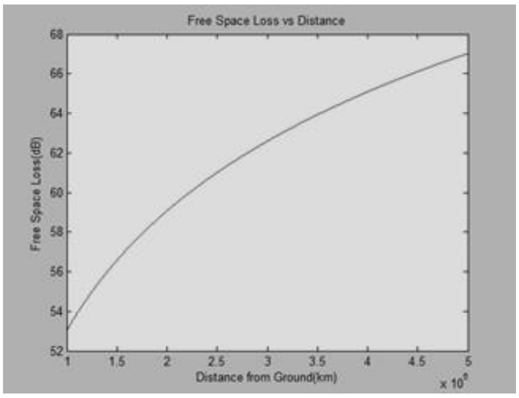
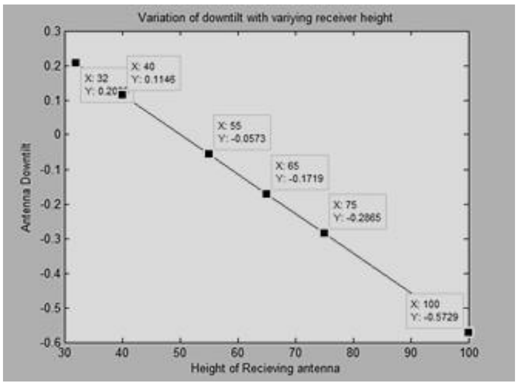


Fig.9 displays the alteration of FSL with increasing altitude which coordinates in choosing the height of the satellite being placed. It is noted that free space transmission loss increases as the height of satellite increases. It is ideal for satellite to be in LEO to have less FSL.

Fig.10 Variation of the downtilt with increasing of Receiving antenna's height



The variation of antenna downtilt with increasing height of transmitting antenna is presented as a graph in Fig.10. It was observed that, with increase in transmitting antenna's height, the downtilt is increasing. The ideal height of receiving antenna is 32m to avoid antenna mismatching. It is observed from the graph that at the ideal height of receiver, antenna downtilt is 0.2deg. Hence, various heights of receiver antenna are considered and their corresponding antenna downtilit angles are shown in the graph for better reception of power.

7. CONCLUSION

The increase of demand for power nowadays and increasing global warming because of traditional methods to generate power is the motive for concept of yielding power using solar energy which is abundant in our outer space and transfer the yielded power to earth wherever it is necessary wirelessly. This proposed and simulated concept offers outstanding prospects for space-to-earth solar power transmission with low power losses. The implementation work flow of power production and transmission from space to earth along with losses during transmission to earth is explained in detail. The calculation of antenna downtilt angle to reduce antenna pointing loss is also presented. Power crisis the world is facing today is solved by the proposed model. The estimated costs for implementing the SSP is presented in the paper. This paper proves that yielding power from outer space through solar energy has greater efficiency than terrestrial solar power harvesting from the outcome of simulation. This idea offers greater transmission power possibilities with losses that can be neglected and simplicity in transmission than other previously made invention or discovery

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