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Space Based Optical Transmission of Solar Energy:

A New Approach to Beam-Down Solar Energy from Space for Terrestrial Use

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Abstract

A new architecture to beam down solar light and distribute it to different regions for the terrestrial use on the host heavenly body is presented. The architecture consist Solar Concentration and Transmission Sub-system placed in geostationary orbit to concentrate the solar light using individually pointable thin optical elements, then using Secondary Solar Reflector to deflect the produced strong intense beam to the Solar Transmission Sub-system that consists the two parallel thin Fresnel lens. The Solar Transmission Sub-system, after producing the strong convergent beam beams down it to the receiver located at the host body. The receiver is again a Fresnel lens that produces the parallel beam and transmits it to the Beam Splitter which splits the beam to a number of narrow beams and with the help of Beam Transmission and Diffuser System directs to different regions and gets diffused for the terrestrial use. A detailed mass budget of the space-oriented part Solar Concentration and Transmission Sub-system is defined. The description of the different elements of the architecture is pointed out and an end-to-end efficiency analysis is performed.

Keywords

Space Based Solar Power, Solar Concentrator, Optical Reflection, Energy Efficiency

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1. Introduction and Background

In contrast to the Space based Solar Power Systems (Mankins, 1997) that use Radio Frequency Waves to transmit solar energy from space for the terrestrial use there is an approach proposed by the space science pioneer Oberth in 1928 (Oberth, 1929) where solar light is transmitted directly to the earth with the help of optical reflectors without any conversion so that to be effectively used for warming and cultivation of Arctic land masses, for keeping shipping lanes ice-free, ''some'' influencing of the weather (incl. night frost prevention and precipitation control), night illumination of large cities and possibly the supply of solar power plants with additional light. In his original proposal he suggested that the reflected mirror would be of $5\mu m$thick with sodium as its reflective layer and orbiting Earth in a 1000×5000 km orbit normal to the ecliptic plane. He calculated the total weight of the satellite would be around $10\ t/km^2$or $10\ g/m^2$and believed that an electric space craft will deliver the construction material of satellite from the moon or any asteroid to reduce its establishing cost.

Similar, concepts were proposed by Lewis M. Frass and Dr. Krafft Ehricke (Frass, 2012; Ehricke, online). Frass' concept *MiraSolar* uses 18-reflector array satellite constellation (Frass, 2012, Frass et al, 2013) with a total system mass of 2.88 x 10^7 kg, in a dawn/dusk orbit at an altitude of 1,000 km creating reflecting spot size of approximately 10 km in diameter with the capacity to produce 5.5 GW of electricity. While Dr. Ehricke's concept uses 10 reflecting satellites each of area 462 km ^{2}, with a total system mass of 2.75 x 10^8 kg to deflect the solar light producing the sun spot diameter on earth of 42 km with a corresponding area of 1385 km^2 to produce 180 GW of electric power.

The pioneering attempts in its development were taken by Buckingham and Watson (Buckingham & Watson, 1968), Billman, Gilbreath and Bowen at NASA (Billman et al, 1977; Gilbreath et al, 1978), and others (Ashurly, 2000; Sistach, 2003; Ehricke, 1977). However, the attempt of its practical establishment was done by the Russian space agency and Energia in 1990 with the development of Russian Space Mirror Project ''Znamya'' developed by the ''Space Regatta Consortium'' (SRC) (Space, 2012). The main goal of Znamya was to illuminate northern Russian cities during the dark winter months to aid economic development (McInnes, 1999) and the development of thin sheet technologies for solar reflection and solar sails.

It was February 4, 1993 when the first SRC "Znamya-2" was tested and successfully deployed in space using a *Progress* vehicle following to its undocking from the MIR space station. The mirror was able to produce spot of light of about 5 km in diameter moving at a speed of around 8 km/s across the earth's surface (starting in France and through Eastern Europe and Asia). The reported brightness of the spot as reported was similar to that of a single full moon ($\langle 1lx$).

Znamya 2 was followed by one more and the last experiment Znamya 2.5 that was deployed on 4th of February, 1999. It was 25-m-diameter reflector with design and construction materials used similar as that of Znamya 2. The main goals of this experiment were to verify the principal improvements and the test operational stability of the film material and structure, to run the new light illumination "*Novey Svet"* experiment, and to operate the new manual attitude control mode of the system and the film structure. However, due to the malfunction in software of mission operations it tangled on an antenna on the Progress spacecraft that was deploying it, therefore the reflector got damaged by the antenna, and the whole apparatus crashed into the ocean. Since then, no attempt was taken to launch any type of space based solar reflector.

Znamya experiments successfully proved the feasibility of illuminating some parts of earth using solar reflectors and handling of thin reflecting sheets in space. However, it also revealed the number of technical challenges we need to ponder about and solve before taking further step for establishing space based solar mirror in the future. The appearing prominent challenges were: (1) for commercial viability of reflected solar light from space it needs very large mirrors to be established in space; (2) a back-up for software if gets malfunctioned; (3) light pollution and associated glitter, and other environmental effects like scattering, reflection of light from clouds, etc; (4) optical reflectors need to be made of very thin film coated polymers (microns thick).

Due to the large rectenna size, less efficiency, technical and feasible issues, and a very large required launching space craft mass of these Space based Solar Energy Transmission Systems 'SSETS' the research intension was given to Space based Solar Power Systems 'SSPS' (Glaser, 1968; Mankins, 1997; Penn & Law, 2000) that possess much higher efficiencies and require small rectenna size than SSETS. In this paper, SSETS concept is reinvented and modified enabling the concept of direct transmission of solar energy from space more feasible and practical to initiate its further development like SSPS. Its architecture possesses very low specific mass, much higher end-to-end efficiency and much better possible applications than the available concepts in the literature.

2. SOTSES Design/Architecture

To transmit solar energy from space to its host heavenly body our design consists mostly optical elements thus we recall our design as Space based Optical Transmission of Solar Energy System (SOTSES). Ground based possible version of the design is shown in figure 1 Unlike other solar transmission concepts our design consists of seven main parts – solar concentrator, Secondary Solar Reflector, transmitter, receiver, beam splitter, transmission pipes and diffuser. However, we have differentiated them into three major sub-systems – Solar Concentration And Transmission Sub-system (SCATS), Beam Receiving And Splitting Sub-system (BRASS) , and Beam Transmission And Diffusion Sub-system (BTADS) - the details of which are given in the below sub sections.

2.1. Solar Concentration and Transmission System (SCATS)

The main purpose of this system is to collect the sunlight, create strong beam of it and beam down it to the host body. To complete the task, it consists the involvement of three major optical elements – Solar Concentrator (SC), Secondary Solar Reflector (SSR) and Solar Transmission System (STS) – the details of which are given in the sections below.

2.1.1. Solar Concentrators (SC)

Our solar concentrator consists of a large array of ultra-light totally optical reflector elements. The number of these reflector elements depends on our need it may be 1000 or 100000 in number. Here in our present design, we are using 850 elements so that to concentrate the solar energy and beam down 1.5 GW of it to the ground. These optical reflectors are configured in such a way that all the radiations falling on them get focused to a particular single point, thus some sort of concave shape is possible by the arrangement of reflector elements. To maintain the constant solar view requirement, the concentrator is placed in GEO in sun-synchronous dynamic orbit.

Since solar concentrator is the element need to orient in space therefore to decrease the weight of the reflector, the material used for construction must be ultra-thin and light weighted, that is, some form of polyimide film is required like solar sail material used in solar sail applications, which is highly reflective and ultra-light in weight. ManTech has prepared such type of material called as LaRC-CP1 polyimide (NASA Technical Reports Service, 1998) that is of the order of a few microns in thickness (Johnson et al, 2011). The material density of this solar sail material is only of order 0.01kg/m^2. This means the total mass of the reflecting material covering 1.36 km^2 of area will weight only 13,600kg. Concentrator using same type of material has also been mentioned in Mirasol concept of SSPS (Dessanti et al, 2013), where the purpose of concentrator is to maximize the concentration of solar power so

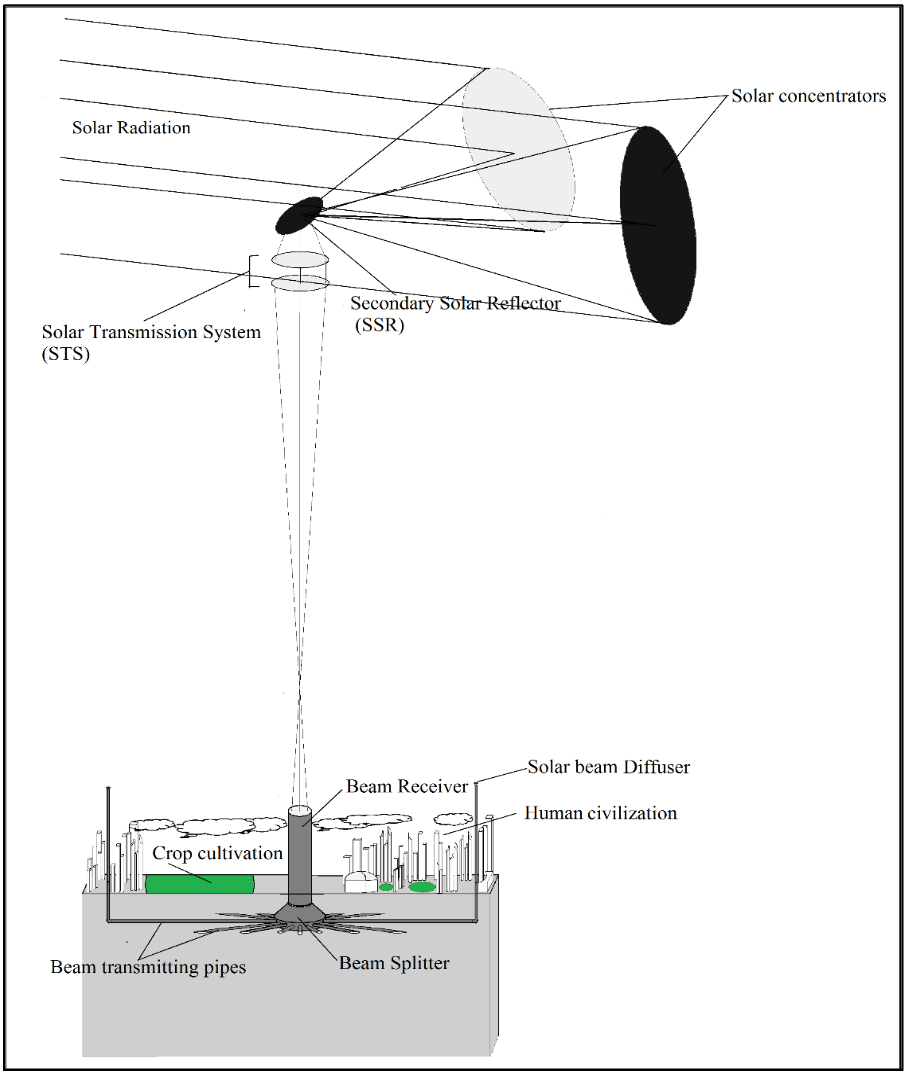

Figure1 Conceptual design of SOTSES

that to get the maximum output of power generation from the solar thermal conversion. However, in our design, however we are not using any type of solar thermal conversion technique.

ADACS

To maintain the necessary sun tracking, required propulsion for guidance, navigation and control, and station keeping for the Platform we need an Altitude Determination and Control system (ADACS). By taking the reference of Mirasol concept (Dessanti et al, 2013) which uses same type of solar concentrators, ADACS bearing weight of around 30 Kg is allotted to each element of concentrator separately which increase the total mass by 25,500 kg.

Propellant Mass to Balance Orbital Orientation

In Halo (Penn & Law, 2000) and Mirasol concept (Dessanti et al, 2013) of SSPS the effect of solar radiation pressure force to dislocate the space craft/concentrators has not been neglected. To counter this pressure some propulsive force is required. For the lifetime period of over 17 years of space craft 32753 kg of the required propellant mass is estimated to maintain the balance of Mirasol structure covering area of 1.536 km^2, which implies the required specific propellant mass estimated for the period using 17 years of time period is around 0.0213. Using this estimation, the propellant mass required to counter the solar radiation pressure falling on the concentrator surface in our design is around 28,968 kg. Like the Mirasol array system, to achieve the goal Krypton thrusters are used that create the specific impulse of 5300 seconds to achieve the balance against the acceleration caused by solar pressure.

Structural Support System

To maintain the required stretch and tension of the reflecting material for each optical element some structural support is required. An equal amount of mass to the solar sail reflective material is allotted to the structural support.

The total mass acquired by solar concentrators is the summation of masses possessed by the solar sail reflective material, propellant mass, ADACS and structural support mass, with a total specific mass averaged over the life time of 17 years valued to about 0.06 kg/m^2 and the total collector mass coming to about 81,668 kg. The mass parameters of the solar concentrator are given in table 1.

The total size of solar concentrators depends upon the need of the area required to be illuminated. In our design we consider the illumination size of the area equal to the size of New York, one of the biggest cities of the world, and the value of solar flux falling on the solar concentrators. Therefore, taking earth as the host planet of the system and the orientation of SCATS at the GEO the value of solar flux is 1 AU. Table 2 summarizes the parameters of solar concentrator array required in our design.

Table 1 Solar Concentrator Mass Summary

Parameter	Mass (kg)
Solar sail reflective material (SSRM)	13,600
SSRM Structural Support System	13,600
ADACS	25,500
Propellant/Thruster	28,968
Total Solar Concentrator	81,668

Table 2 Solar concentrator Design parameters taking earth as the host body

Parameter	Value	Units
Intensity of sunlight at space	1.36	kW/m2
No. of optical elements	850	
Area per element	1600	m2
Specific mass of solar collectors	0.06	kg/m2

2.1.2. Secondary Solar Reflector (SSR)

The collected solar energy by the collectors is focused to the secondary solar reflector that is mounted at some distance at some particular angle to the solar concentrator so that to deflect the concentrated beam to the pair of Fresnel lens for transmitting it to the ground receiver. The reflector consists the same reflecting material and supporting frame as of solar collectors. Since the solar energy that falls the SSR is 99% equal to the amount of solar radiation that falls the solar concentrators, the total amount of solar radiation pressure met by the SSR would be 99% equal to the total summation of solar radiation pressure that fall the surfaces of the solar collectors. Therefore, the mass required to propel the secondary reflector would be closely equal to the 99% of the mass required to propel the solar collectors to maintain the balance against the radiation pressure. There is no physical connection between the elements of solar collector and the secondary reflector and therefore the two parts can be located separately at the any required distance, and at the desired altitudes of GEO stationary region.

Like the Solar Concentrators, SSR need ADACS to maintain the necessary angle between the Solar Concentrators and it, so that the constant divergent beam is deflected horizontally towards the Beam Transmission System (BTS). Like the Solar Concentrator System 30 kg of ADACS is allotted to each optical element of SSR. The mass parameters of SSR are summarized in table 3.

The design parameters of the secondary solar reflector are summarized in the table 4. Since the total radiation falling on the SSR is 99 % of the total radiation falling on the Solar Concentrators and subtracted it with the arbitrary area of SSR, the total intensity of sunlight falling on SSR is calculated. By considering the specific mass of the SSR with the other components of the SCATS, SSR possess highest specific mass density

Table 3 SSR Mass Summary

Parameter	Mass
Solar sail reflective material (SSRM)	32
SSRM Structural Support System	32
ADACS	60
Propeller/ Thruster	28,678
Total SSR	28,802

Table 4 SSR Design parameters

Parameter	Value	Units
Intensity of sunlight	572	kW/m2
No. of optical elements	2	
Area per element	1600	m2
Specific mass	9	kg/m2

2.1.3. Solar Transmission Sub-System (STS)

The reflected beam from the SSR is allowed to transmit through a pair of Fresnel lens placed horizontally parallel to each other at some distance apart. The main purpose of transmitter is to collect the divergent solar reflected from SSR, make it convergent and beam down the same towards the receiver located at the host planet of SCATS. It consists of an ultra-thin and light weighted refractive material made from some form of polyimide material as mentioned in section 2.1. The transmitter is mounted at some specific angle and distance with SSR, and parallel to the beam receiving lens so that the reflected solar power from SSR get fall down vertically to the plane of the Fresnel lens system.

Fresnel lens as refractive concentrator has been extensively studied by O’Neil for use in SSP (O”Neill et al, 2005). In the reference (O”Neill et al, 2015) O’Neill and others gave the comparison of the different materials used in construction of Fresnel lens with the lowest possible areal mass density achieved by FEP Film with silicone prisms of about 0.075 kg/m^2. The transmittance of Fresnel lens can be achieved up to 92% as mentioned in reference (Piszczor et al, 2006).

The addition of Refractive secondary solar concentrators to the solar collecting system has been already mentioned in literature to enable the higher concentration ratios and relaxes the pointing and tracking requirements. Such concentrators are used for ultra-high temperature applications, where the refractive concentrator needs to bear more than 2000 K of temperature (Wong et al, 2000). The Shooting Star Project was initiated by the NASA Glenn Research Centre (GRC) with the collaboration of NASA Marshall Space Flight Centre to demonstrate the thermal propulsion flight experiment using the material Sapphire as refractive secondary concentrator (Wong et al, 2000; Zhu et al, online). In an effort to design and fabricate the secondary concentrator the tests were taken on, 4-inch x 4-inch x 11.7-inch sapphire bar, it was concluded the transmission efficiency of 96% can be achieved with the help of an anti-reflective coating (Wong et al, 2000), and this is what we need for our design.

However, our design needs much wider Fresnel lens than O'Neil's lens system and much thin lens than the sapphire bar, and with temperature bearing capacity of thousands of Kelvin, therefore much research is still required to do before taking the SCATS system in operation. The mass parameters of BTS are summarized in table 5. The special Fresnel lens made of some kind of material as used in sapphire bar with thermal transmission efficiency of about 96%, thickness of about 12.5 micron and the specific areal mass density of about 0.075% as that of Fresnel lens made of FEP film with silicone prisms (O"Neill et al, 2015), is used in the construction of our BTS, although some prior research considerations are required before final fabrication. Like the first two optical elements of SCATS same mass for the construction of Structural support system has been allotted as of its refractive material. However, no ADACS and propellant is required in this element.

Table 5 BTS Mass Summary

Parameter	Mass
Fresnel lens material	2 x 337.5
BTS Structural Support System	2 x 337.5
Total BTS	1,350

Like the SSR the total radiation falling on the BTS is 99 % of the amount falling on the SSR and by subtracted it with the arbitrary area of BTS, the total intensity of sunlight falling on BTS is calculated. The design parameters of the BTS are summarized in the table 6.

Table 6 BTS Design parameters

Parameter	Value	Units
Intensity of sunlight falling on surface	402.84	kW/m2
Arbitrary required Area	4,500	m2
Specific mass of refractive material of lens	0.075	kg/m2
Specific mass of each lens	0.15	kg/m2
Mass of each lens	675	kg

2.2. Beam Receiving and Splitting Sub-System (BRASS)

BRASS is required to receive the concentrated and transmitted strong intensified beam from space and split it into the number of small beams so that to distribute it to different regions of civilization. It consists of two main optical elements – Beam Receiver and Beam Splitter - the details of which are underlined below in this section.

2.2.1. Beam Receiver

Unlike the receivers of other SSPS systems that are located at the ground of earth as their host planet, the receiver of our architecture is located, much above the ground surface of the host heavenly body, at an altitude of around 0.5-3 km above the ground surface level so that to minimize the radiation pollution and other effects caused by the strong beam of solar energy.

In the architecture our receiver is an optical Fresnel lens mounted at the top of the very tall cylindrical hallow construction of concrete of around 0.5-3 km in height above the ground surface level to receive the convergent beam of solar light and converts it into a parallel beam of light so that it could split into a number of smaller beams easily. For the host body earth, the height of the structure of receiver will appear above the height of clouds so that to reduce the effects caused by this strong beam of solar light on habitation in surrounding region. The base of the construction is attached with the top of the beam splitter at few meters of separation between them. By constructing the strong concrete beams horizontally attached to the base of the construction the weight and position of the construction is lifted and maintained.

The same Fresnel lens is used in receiver as used in BTS. Therefore, the specific mass of the receiver is almost the same as of transmitter. The basic design of the receiver consisting the tall cylindrical hollow construction is shown in the Figure 2, with the slice cut in architecture shown so that to reveal the inner hollow construction.

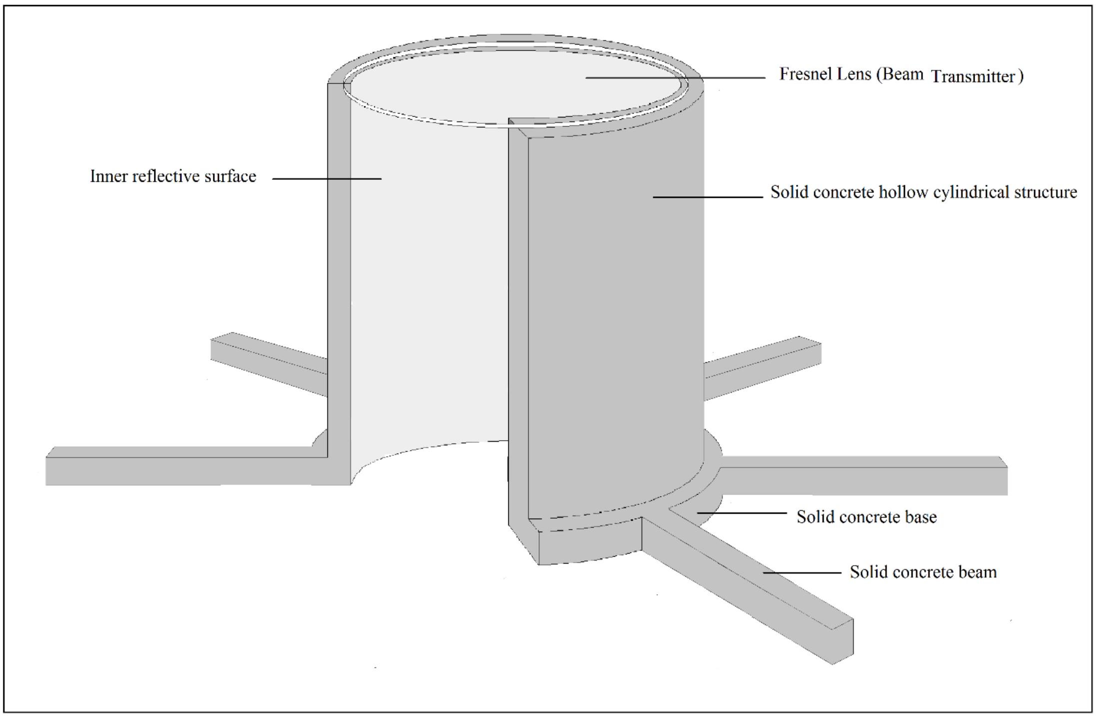

Figure 2 Conceptual design of Receiver

To totally reduce the impact of radiation effect on the living creatures in the habitat it is convenient to construct the structure far apart from the region of habitation, like on earth in any ocean or remote and mountainous region.

2.2.2. Beam Splitter

This is the underground part in the architecture of our design. It is a highly sophisticated and innovatively built reflecting junction of a number of concaved triangular reflecting surfaces joined to each other in a cone shaped arrangement as shown in Figure 3. Further details about it have been given by the author in reference (Dar, 2019), however due to its larger size than the former Beam Splitter, solid concreate beams have been added in the structure to firmly hold the structure in the ground.

2.3. Beam Transmission and Diffuser System (BTADS)

This system is required to transmit the splitted beams using specially designed solar pipes and solar diffusers for illumination purposes. The system uses two main optical elements – Beam Transmission Pipe and Beam Diffuser - to accomplish the task, the basic details of which are given in the reference (Dar, 2019).

However, like the other ground based optical elements of the architecture, the construction of the solar beam pipe system is made of solid concrete with the cross-sectional area ranging between arbitrary 50-300 m^2, and travelling to distances in thousands of meters, where from the reflector of joint diverts the beam at 90 degrees to upward direction for illumination purposes.

Meanwhile, unlike Beam Diffuser described in the reference (Dar, 2019) the Diffuser used here in the architecture has different optical configuration, the basic details of which are shown in the Figure 4. While passing through this optical element the light beam gets bend to different directions appearing like the huge source of light scattering its light in all required directions.

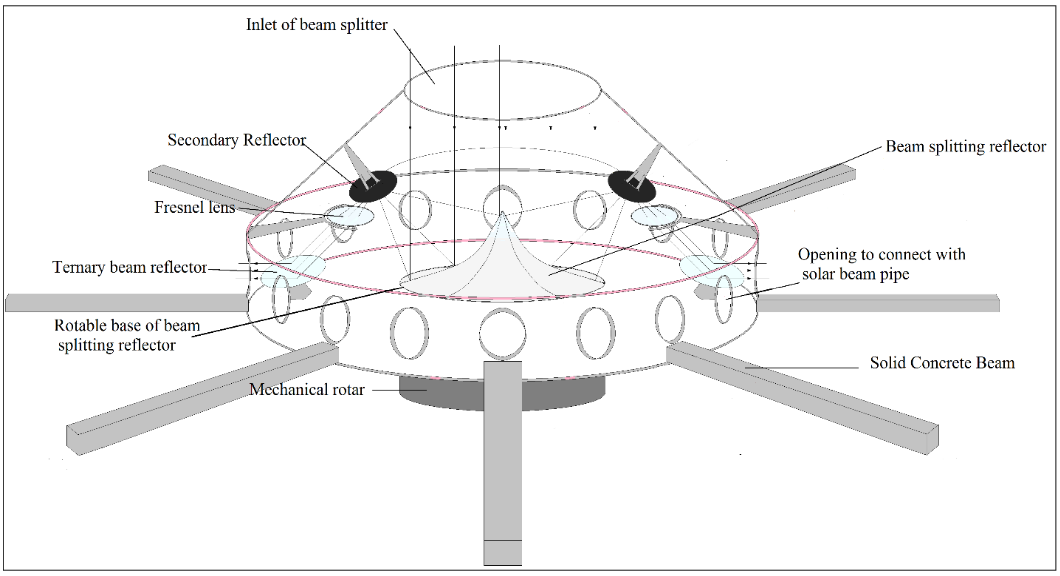

Figure 3 Conceptual design of Beam Splitter

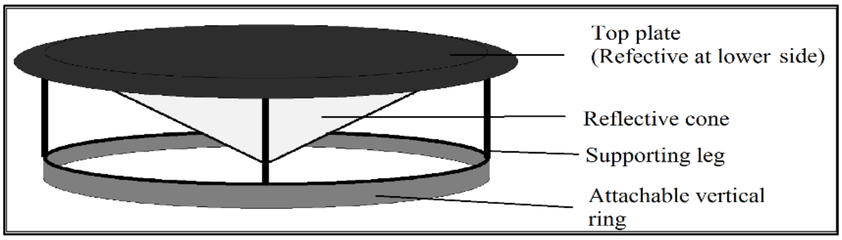

Figure 4 Basic design of Diffuser

3. Comparison with other proposed Concepts

As per the purpose and working principle of our SOTSES is considered it is totally different than SSPS concepts. In sense our system transfers the solar energy directly from the space to its host body in the same form it hits the solar collectors. While there have been proposed similar concepts in the history of science as already mentioned in the section 1 that transmits the solar energy directly to the host planet from the space using some optical method.

SOLARES

SOLARES concept (National Space Society, 1981) was proposed to meet the global need of power system sufficient enough to produce 810 GW of power from six individual sites. It consists of about 916 mirrors each of size 50 km^2 accounting total area covered by mirrors equal to 46,000 km^2. The principal features of the SOLARES concept is that it could be used for any energy use where enhanced sunlight would be used to advantage. There are both LEO as well GEO versions of the concept where its LEO version at an altitude of 2,000 km with 15 smaller ground stations (Solar Power Satellites, online) seems more feasible and desirable. Some of the main differences between the *SOLARES* and our *SOTSES* concept are figured out in table 7.

Soletta 1978

Dr. Krafft Ehricke (Ehricke, online; Ehricke, 1979) proposed the idea using constellation of satellites to beam sunlight down to earth for terrestrial solar electric power generation. 10 reflecting satellites each of area 462 km ^{2} are used to deflect the solar light producing the sun spot diameter on earth of 42 km with a corresponding area of 1385 km^2. The main goal of Soletta was to produce an intensity of sunlight on earth equivalent to the normal daylight intensity of sun. Using solar farm this redirected solar energy is able to produce 180 GW of electric power for terrestrial use. One of the main problems of this concept lies in the distribution of generated power and the vast required rectenna size on earth. Some of the main differences between our concept and Soletta 1978 are figured out in table 7.

MiraSolar

Lewis M. Fraas from JX Crystals Inc, USA**,** uses the same idea of beaming down solar energy for terrestrial power generation using 18-reflector array satellite constellation (Frass et al, 2013; Frass, 2012) in a dawn/dusk orbit at an altitude of 1,000 km creating reflecting spot size of approximately 10 km in diameter with the capacity to produce 5.5 GW of electricity. The concept assumes the use of 40 terrestrial solar farms each generating 5.5 GW of electrical energy. Unlike 180 GW power level of Soletta concept, 5.5 GW is easier to "ramp up" using already being built ground infrastructure. However, 40 rectenna sites are required and only for two hours per day sunlight view on those sites is enhanced, producing the power of only 160,000 GWh per year, which is not quite enough for the vast infrastructure of the concept using area 4,617 km^2 for redirecting sunlight. SOTSES concept seems much promising in many regards than the MiraSolar due to the prominent factors as mentioned in table 7.

Znamya Experiments

As already mentioned in the section 1 the sole purpose of the Znamya experiments was to see the feasibility of illumination of some parts of earth using reflecting solar light from the space and the research related development of thin sheet technologies for solar reflection and solar sails. Practically, two attempts Znamya 2 and Znamya 2.5 were taken to conclude the feasibility but only the first one succeeded. Unlike the SOLARES and our concept it was

Table 7 Comparison with other similar proposed concepts

Item	SOTSES	Znamya Experiments	SOLARES	MiraSolar	Soletta 1978
Orbital orientation	GEO	LEO	2,000 km in altitude	LEO	4200 km in altitude
No. of optical reflecting elements/reflectors	850 optical elements each of 1600 m2	1 reflector	916 Reflectors	18 satellites each of 78 km^2	10 satellites each of 462 km^2
System mass	111,820 kg	Znamya 2 = 69080 kg, Znamya 2.5 =107932 kg, Znamya 3 = 621720 kg	2.72 x 10^8 kg	2.88 x 10^7 kg	2.75 x 10^8 kg
Iluminated area size on earth / rectenna size on earth	Rectenna size ~ 4,800 m^2	Znamya 2 = 19.6 km^2, Znamya 2.5 =38.5 km^2, Znamya 3 = Not specified (intensities in lunette)	Rectenna size = 1000km^2	Rectenna size = 78.5 km^2 (each rectenna)	1,385 km^2
Total area of reflecting/collecting surface of sunlight	1.36 km^2	Znamya 2 = 314 m^2, Znamya 2.5 =490.6 m^2, $^{\text{Znamya}}$ 3 = 2826 - 3846 m^2	45,800 km^2	1,404 km^2	4,617 km^2
Power Level	1.5 GW	Not Specified	810 GW	5.5 GW	180 GW

only meant for illumination not for other energy conversions. The main differences between the Znamya and our concept are figured out in table 7.

4. End-to-End Solar Power Efficiency Analysis

The end-to-end efficiency is defined as the total amount of solar energy that came out from the diffusers per the total amount of solar energy that fall on the solar collectors. By taking efficiency values of different elements of SCATS from different references an end-to-end efficiency was calculated to account for various losses present in the system. The highest possible efficiency values, as per the available data, of all the optical elements used in the construction of SCATS is presented in the table 8.

The ultra-light optical reflector used as solar concentrator can achieve solar reflectivity of 99.5 % as is achieved by current commercially available heliostat reflector element produced by Practical Solar (Rohr, 2009). SSR, all reflectors of BS, inner surface of BTP and reflective surface of beam diffuser all elements possess same value of efficiency since all the elements use same reflective material used for the manufacture of Solar concentrators.

The maximum light transmission efficiency of all elements using Fresnel lens as the refractive medium on the basis of theoretical basis is 96% that is achieved using sapphire material (Zhu et al, online) in its construction.

The 91.2 % efficiency of SCATS comes from the multiplication of efficiencies of its components which include two reflecting surfaces and a pair of Fresnel lens as illustrated in equation 1. Similarly, 94.5 % efficiency of beam splitter is the product of efficiencies of its components as is given in equation 2. By the improvements in the manufacture of Fresnel lens the efficiencies of both SCATS and Beam Splitter can be enhanced. The total end-to-end efficiency 81.5% of the design SOTSES is calculated by the relation 3.

Table 8 End-to-end efficiency analysis

Parameter	Efficiency (%)
Solar collecting array efficiency	99.5
Solar reflecting array efficiency	99.5
Solar transmitting lens efficiency	96
End-to-end efficiency of SCATS	91.2
Transmission efficiency through atmosphere	≈100
Receiving lens efficiency	96
Beam splitter efficiency	94.5
Transmission efficiency through pipe system	99.5
Diffuser efficiency	99 – 99.5
End to end efficiency of SOTSES	81.5

$$\eta_{E-E(SCATS)} = \eta_{SC} + \eta_{SSR} + \eta_{BTS} \quad (1)$$

$$\eta_{E-E(BS)} = \eta_{BS} + \eta_{SR} + \eta_{F} + \eta_{TR} \text{ (Dar, 2019)} \quad (2)$$

$$\eta_{E-E(SOTSES)} = \eta_{E-E(SCATS)} + \eta_{ATM} + \eta_{BR} + \eta_{E-E(BS)} + \eta_{P} + \eta_{D} \quad (3)$$

Where in the equations [1, 2 and 3] $\eta_{E-E(SCATS)}$,$\eta_{E-E(BS)}$ and $\eta_{E-E(SOTSES)}$are the end-to-end efficiencies of SCATS, BS and SOTSES. η_{SC}, η_{SSR}, η_{BS}, η_{SR}, η_{TR}, $\eta_{P}$and $\eta_{D}$are the reflecting efficiencies of SC, SR, TR, solar pipe system and diffuser, while η_{BTS},η_{ATM},η_{BR} and $\eta_{F}$are the transmission efficiencies of BTS, atmosphere, BR and of Fresnel lens used in BTS.

The normal solar light that falls to ground of planet earth faces many losses while its transmission through the atmosphere. However, in our system the intensity of solar light gets multiplied thousand times which exceeds the pressure and temperature of the light beam sufficient enough to vaporize the water molecules and move apart the dust particles and other molecules that come in its path. Thus, the transmission efficiency of atmosphere for the beam becomes equivalent to the 100% transmission efficiency of vacuum.

5. SCATS Mass Summary

The total mass of SCATS is the summation of all masses possessed by its components, the details of which are summarized in table 9. Based upon the SCATS mass the launching cost of it can be estimated.

Table 9 SCATS mass summary

Parameter	Mass (kg)
Total Solar Collector mass	81,668
Total SSR mass	28,802
Total BTS mass	1,350
Total mass of SCATS	111,820

6. Conclusion

An innovative optical architecture for the direct transmission of solar light from space and its receiving cum distribution system at its receiving host planet was introduced. The SOTSES architecture offers the potential to reduce the Rectenna size at the receiving station and helps in uniform distribution of intensified beam at different locations. Using optical energy efficiency analysis, it was estimated that in SOTSES concept 81.5 % of concentrated solar energy in space is transmitted to the receiving station for terrestrial use. Due to the improved end-to-end energy efficiency, a very big reduction in Rectenna size and a much lesser mass of the space components to launch in space SOTSES architecture opens a new way to reconsider further research and development of the SSETS as is carried for SSPS concepts. The architecture offers potential to meet all the terrestrial required needs of sunlight like illumination, crop cultivation, electricity, etc. Meanwhile, the design offers the large improvement in specific solar power, the amount of solar power that can be transmitted to terrestrial ground per unit mass required to be launched into orbit (~18.5 kW/kg of solar power).

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Appendix:

The total transmitted solar power ‘P_S’ is calculated from the fact that power from the sun per area in space is 1.36 kW/m^2 in space. Calculating it over the area of space occupied by our concentrator ‘A’, which is the product of number of optical elements ’N’ used in the construction of solar concentrator and the area of each element, that is

$$P_S = 1.36 \times A \times N = 1.36 \times 1600 \times 850 = 1{,}849{,}600kW \approx 1.85GW \qquad (4)$$

After considering the 81.5 percent of end-to-end efficiency of the whole system, that is 19.5 percent of the loss in total solar power received by the concentrators, the total solar power ‘P’ that get emitted from diffusers can be calculated as;

$$P = P_S \times \eta_{E-E} \times 100 = 1{,}507{,}424 \approx 1.5GW \qquad (5)$$

Where ‘η_{E-E}’is the end-to-end efficiency of the system, that is 81.5.

우주 기반의 광학적 태양 에너지 전송:

지상에서의 사용을 위한 태양 에너지 하향 빔에 대한 새로운 접근

자항기르 아마드 달 인도 아미티 대학 하르야나 아미티 응용과학 학교
인도 국제 혁신 재단 셀 혁신가, 인도 풀뿌리 혁신 및 증강 네트워크 혁신가

초록

본고에서는 태양열을 빔(beam)으로 만들어 위에서부터 지상으로 쏘아 모 천체 상 서로 다른 지역의 지상에서 이용하는 새로운 설계가 제시된다. 본 시스템은 크게 태양열 집광(Solar Concentration) 시스템과 태양열 전송 하위 시스템(Transmission Sub-system)으로 이루어져 있는데, 집광 시스템은 정지 궤도 상에 위치하였으며 개별적인 얇은 광학 요소를 이용하여 빛을 집광시키며, 이렇게 생성된 강력한 빔은 2 차적 태양열 반사기(Secondary Solar Reflector)를 통해 2 개의 평행하는 프레넬(Fresnel) 렌즈로 구성된 태양열 전송 하위 시스템으로 반사된다. 태양열 전송 하위 시스템은 강력한 융합 빔을 만든 후 모 천체 상에 위치한 수신기로 이를 전달한다. 수신기 또한 프레넬 렌즈이며 평행 빔을 생성해 빔 분열기(Beam Splitter)로 전송하는데, 분열기에서는 빔 전송 및 분산 시스템(Beam Transmission and Diffuser System)을 통해 여러 개의 얇은 빔으로 빔을 분열하여 서로 다른 지역으로 보내 지상에서의 이용을 위해 분산한다. 본고에서는 우주 지향적인 태양열 집광 시스템과 태양열 전송 하위 시스템의 상세한 질량 버짓(mass budget)을 정의한다. 설계의 서로 다른 요소가 설명되어 있으며 전체적인 효율성에 대한 분석이 이루어졌다.

키워드

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