Space-Based Power Grids Introduction: Feasibility Study

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Abstract—This paper introduces a viable alternative for space-based power transfer that is called space-based solar power grid (SBSPG).[1][2] The SBSPG is a solar power network that consists of hybrid wire-wireless formations. Each formation has four units: (1) a solar power harvesting unit (SOPHU) located on a solar power station in a medium altitude orbit (MEO), (2) a low earth orbit (LEO) satellite, (3) a transmission line structure (TLS) that connects the SOPHU to the LEO satellite; and (4) a power collecting base station (PCBS) on the earth. The paper discusses the details of its structure, and compares it with the traditional Geostationary space-based power transfer in terms of the harvested power on the earth. The pointing accuracy of the LEO satellite has an important impact on the power transfer efficiency of the proposed system. Thus, the paper also studies its mechanical implementation feasibility.

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1. INTRODUCTION

The Sun has the capacity to be Earth's primary source for renewable energy. The Sun radiates 2.3 billion times more energy than currently received on the Earth; therefore, the energy propagated by the Sun in just one hour could provide all of Earth's population the energy it needs for an entire year. However, reliable solar energy of this magnitude cannot be created simply by installing more solar cells on Earth due to impeding cloud, rain, or snow coverage. Space-based solar power (SBSP) research is driven by the promise of sustainability [1]-[5]. Unlike earth-based solar power stations, space-based stations can collect and transmit solar power, using microwave energy, regardless of weather conditions. This is a key factor in northern climates with minimal sun exposure. In addition, the higher altitudes of space-based power stations experience shorter eclipse periods which allows higher energy collection.

Since 1968, scientists have researched methods for collecting the Sun's energy in space and converting it to usable power [6]. Japan, one of the technological giants of the 21st century, has committed to the development and installation of a space-based system by 2020 [7]. Similarly, the US has announced that by 2016 a "Solaren" power station will be lofted into geostationary orbit (GEO) and begin collecting 200 megawatts of sunlight under a 15-year contract with San Francisco-based Pacific Gas and Electric Company (PG&E) [8]. The solar energy from this station will be converted into radio waves, beamed to a ground station in Fresno, transformed back into electricity, and fed into PG&E's grid. Corporations, government agencies, and associations like SPACE CANADA all have been formed to research SBSP.

To date, the main method proposed for harvesting and transmitting solar energy has been via space structures in GEO orbit, at about 37,000 Km altitude, equipped to transmit accumulated energy to the earth via microwave [9]. Earth receivers are then proposed to collect the transmitted energy and convert it to usable electricity. However, SBSP satellites in GEO have certain limitations: 1) GEO is congested; 2) the launch cost to GEO is very high compared to lower orbits [10], [11]; and 3) the transmitted energy is subject to high path loss due to the 37,000Km distance [12], [13]. In addition, part of the transmitted energy is absorbed or reflected by the ionosphere and atmosphere layers through which it must pass [11].

As a viable alternative, we propose an approach called space-based solar power grid (SBSPG). The SBSPG is a solar power network that consists of hybrid wire-wireless formations. Each formation has four units (see Figure 1): (1) a solar power harvesting unit (SOPHU) located on a solar power station in a medium altitude orbit (MEO), (2) a low earth orbit (LEO) satellite, (3) a transmission line structure (TLS) that connects the SOPHU to the LEO satellite; and (4) a power collecting base station (PCBS) on the earth. Therefore, the SOPHU will have a physical link – a light-weight super conductive TLS – to the LEO satellite. Transmitting signals through a TLS will reduce the path distance and ionospheric losses.

The units (1) – (3), i.e., SOPHU, TLS, and the LEO satellite form a long rigid space-based MEO-LEO formation (MLF). The overall MLF orbit is determined by its center-of-mass. Preliminary results depict that MLF can be designed to point to the earth's center-of-mass at all times. Placing solar cells in higher altitudes of MEO will utilize the unfiltered energy of the sun while reducing the orbital eclipse period. The harvested power will ultimately be transmitted wirelessly via high-gain antennas to the earth. The altitude of the LEO satellite will reduce aerodynamic drag perturbation.

Compared to the traditional GEO SBSP, the proposed method: (1) will reduce launch expenses through use of smaller harvesting units that will be used at lower altitudes but will still generate equivalent power; (2) will decrease the challenge and cost of construction as the size of transmit

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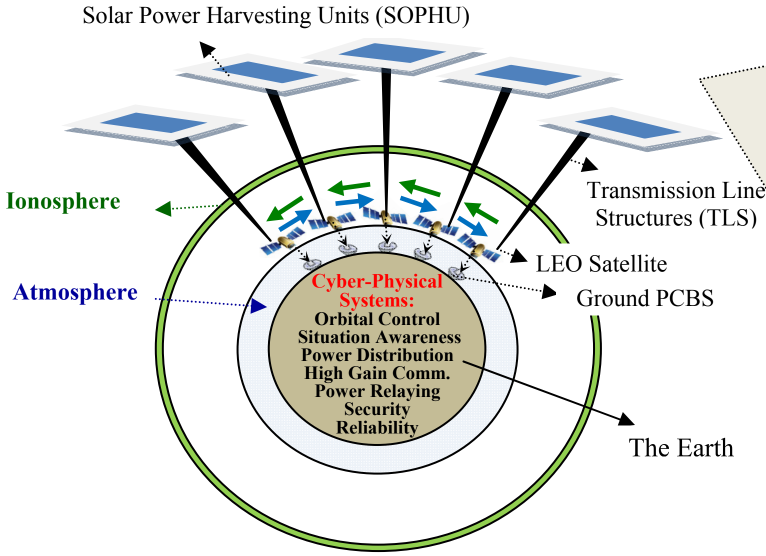


Figure 1 - Space-Based Solar Power Grid (SBSPG) formation.

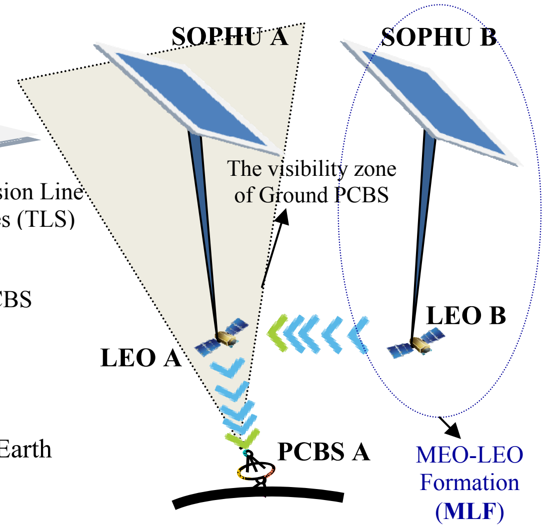


Figure 2 - Relaying the collected energy by SOPHU B to the PCBS through LEO A.

antenna reflectors will be smaller; (3) will increase power distribution across a greater number of earth PCBS by optimally designing the MEO and LEO orbits (a) to fully cover the earth's surface, (b) to reduce loss and expenses of ground energy transfer via ground-based transmission lines, and (c) to allow for the transfer of energy to remote areas without using **ground-based** power grids; and (4) will have lower power; and thus, less environmental effects [14]-[18]. The permissible power density is 100mW/cm^2. Now, to capture 100MW power on the ground, GEO SBSPs need to produce more than 1GW to distribute over a *Kilometer wide* beam. This produces higher power than 100mW/cm^2 (mainly at the center of the coverage area), which has the potential to impact satellites if they cross the beam. However, the proposed SBSPG uses only a *meter-wide* TLS. Thus, the likelihood of TLS collision with other space objects is minimized.

Sensors will be implemented on the TLS to create situation awareness, and sustain autonomous collisions avoidance. In addition, LEO satellites will function as *smart* nodes in the SBSPG system. The three main challenges of the proposed SBSPG are: 1) the construction of a super conductive TLS, 2) the design and implementation of cyber signal processing schemes to support operations such as handoff, situation awareness, multi-satellite synchronization, and 3) power control across LEO satellites as detailed below.

Because the MEO harvesting station and the LEO wireless transmission satellite below will not be moving in sync with the Earth, a number of PCBS receiving units will be required on the earth to ensure that at any given time, a given MLF will be able to transfer the harvested energy to one PCBS. The process of disconnecting from one PCBS receiver and connecting to another one on the ground will be similar to the handoff process in cellular systems. Moreover, multiple satellites may simultaneously fall within the visibility zone of a given PCBS. Thus, maintaining a firm synchronization, across the LEO satellites that transmit the collected power simultaneously to one PCBS, is vital to achieving power efficiency.

The proposed formation orbit will be designed such that each PCBS receives energy through at least one LEO satellite, either directly or indirectly, by relaying energy through a nearby LEO satellite (see Figure 2). Space-to-space (over the same orbit) signal transmission is efficient; it results in only a small amount of power loss. This plan will help prevent blackouts throughout the whole system even when an MLF is in the earth's eclipse. For example, in Figure 2, LEO satellite B which is not in the visibility zone of any PCBS can transmit SOPHU B's harvested energy to the PCBS A through LEO satellite A. Moreover, if SOPHU A is in the earth eclipse, and PCBS A needs power resources, even if LEO B is in the visibility zone of a PCBS, it can still relay (part of) the harvested energy of SOPHU B through LEO A to PCBS A to fulfill PCBS A's energy needs. LEO satellites, functioning as a power distribution unit, will be designed to maintain continuous control of the energy transmission process at all times – in density, in direction, and in handoff. Therefore, LEO satellites have two important roles: (1) to transmit the energy harvested by their associated SOPHU to an earth PCBS if they are in the visibility zone of a PCBS; and (2) to relay the energy harvested by the SOPHU to another nearby LEO satellite.

The SBSPG system shown in Figure 1 is a combination of distributed physical systems and intelligent networks to control and coordinate the operation of the system. The cyber control will have two aspects: (1) an intelligent control scheme for individual components, and (2) cooperative strategies among distributed elements in the SBSPG. Major mission scenarios of this Cyber-Physical System (CPS) include power relay management among LEO satellites, LEO satellite power transmission control, handoff process across earth PCBSs, and autonomous collision avoidance maneuvering by controlling satellite thrusters, and monitoring the status of power harvesting units. The situation-awareness control decisions of each MLF (SOPHU, TLS, and LEO satellite) will be made based on information collected by sensors distributed across the MLF.

The proposed technique ensures higher efficiency compared to the MEO satellites whose solar panels transmit their power wirelessly to the earth. This efficiency is attainable when the MEO solar collector and the LEO transmission satellite orbit the earth as a single unit, linked via a low-loss transmission line. Efficiency is also related to the pointing accuracy of the unit. Section 2 Analyses the harvested power on the earth. The pointing stability accuracy of the proposed SBSPG unit toward the PCBS on the ground is discussed in Section 3. Section 4 concludes the paper.

2. POWER EFFICINCY ANALYSIS

Satellite communication channels are affected by the ionosphere's layers, water vapor, oxygen, and reflectors located in the proximity of the PCBS (e.g., hills and buildings). The reflectors located in the proximity of the PCBS impact received signal statistics; however, the signal pathloss is mainly a function of free space pathloss, as well as, ionosphere and atmosphere attenuations which vary with frequency, time of the day, and the position of spacecraft.

Many studies have been conducted on the effects of the ionosphere [22]-[24], which depict how ionosphere characteristics vary with time and position. This variation impacts the received signal strength and creates signal fading. Ionosphere impacts High Frequency (HF) ranges the most. However, studies also show frequency-selective effects for high bandwidth signals even at higher frequency ranges including very high frequency (VHF), ultra high frequency (UHF), and microwave [24].

Studies have shown that if the frequency is selected beyond 1GHz, polarization errors will be minimal and ignorable [25], [26]. These results are confirmed by studies conducted on polarization effects of the ionosphere. Studies also depict that low-bandwidth signals reduce polarization errors [27], and have confirmed that water vapor, clouds, and oxygen attenuations do vary with frequency [25], [28], [29].

This section explains the advantages of the power efficiency of the proposed technique. The proposed system is compared with a system which transfers the harvested energy wirelessly from medium earth and geostationary orbits. The wireless transmission loss from any level above the ionosphere F-Layer is:

$$L_{Direct} = 32.45 + 20log(d_{Km}) + 20log(f_{MHz}) + L_{Ion} + L_{Atm} + L_{Ecl} \quad (1)$$

Here, d_{Km} is the altitude measured in Km, f_{MHz} is the frequency measured in MHz, L_{Ion} represents the ionosphere overall loss, L_{Atm} is the atmospheric loss, and L_{Ecl} is the eclipse loss: the percentage of the time that the harvesting unit is located in the earth eclipse. Eclipse loss impacts the overall accumulated power and it is in the order of

$$10log\left[\pi/\sin^{-1}\left(\frac{6370}{(d_{Km}+6370)}\right)\right].$$

Note that the power loss due to that eclipse period of a LEO satellite can be compensated through nearby LEO units if the formation orbits are properly designed. The total loss of the SBSPG system that is due to the hybrid transmission from MEO to LEO through TLS and then wirelessly from LEO to the earth PCBS corresponds to:

$$L_{SBSPG} = L_{TLS} \times \frac{(d_{Km,MEO} - d_{Km,LEO})}{100} + 32.45 + 20log(d_{Km,LEO}) + 20log(f_{MHz}) + L'_{Ion} + L_{Atm} + L_{Ecl} \quad (2)$$

In (2), L_{TLS} denotes the TLS loss in dB/100Km, and $L'_{Ion} < L_{Ion}$ is the loss due to all ionosphere layers except the F-layer (300Km). Moreover, $d_{Km,MEO}$ and $d_{Km,LEO}$ are the altitudes of the SOPHU, and LEO satellites measured in Km, respectively. In general, TLS loss increases with frequency.

Table 1 represents the received power captured at the ground PCBS assuming a receiver equipped with a reflector antenna with the aperture of 1Km, efficiency of 95%, and frequency of 5GHz; hence, the PCBS antenna gain would be about 94dBi. Moreover, the power harvested by solar cells is assumed to be 1400W/m^2. In addition, atmosphere and ionosphere losses are assumed to be 1dB, LEO satellite altitude in SBSPG is assumed to be 200Km, and TLS loss is 0.1dB/100Km. Accordingly, using a 100m×100m harvesting unit at the altitude of 1000Km, 1GWatt power is attainable on the ground. If the TLS loss is higher, SOPHU altitude should be lowered, or its area should be increased. Currently, researchers are working to improve the efficiency

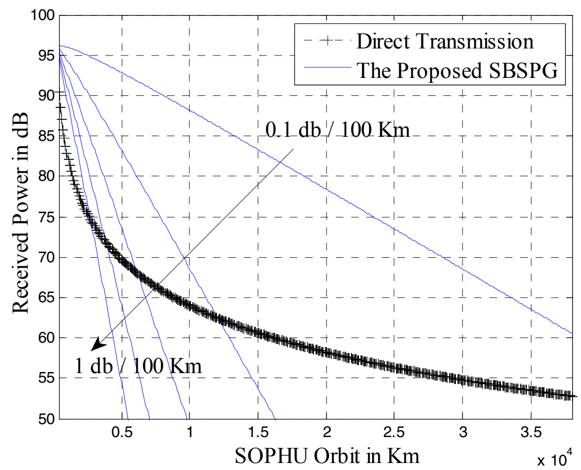
Table 1. The Captured Power on the Ground.

TX Antenna Aperture	Area (Km^2)	P_t(dB)	Captured Power GEO Direct	SBSPG Captured Power for SOPHU Altitude of:			
				GEO	20000Km	5000Km	1000Km
500m (88dBi)	4	98	100 MW	500 MW	30 GW	1 TW	3 TW
	1	91	20 MW	100 MW	6 GW	200 GW	600 GW
	0.01	71	200 KW	1 MW	60 MW	2 GW	6 GW
250m (82dBi)	0.01	71	33 KW	165 KW	10 MW	340 MW	**1GW**

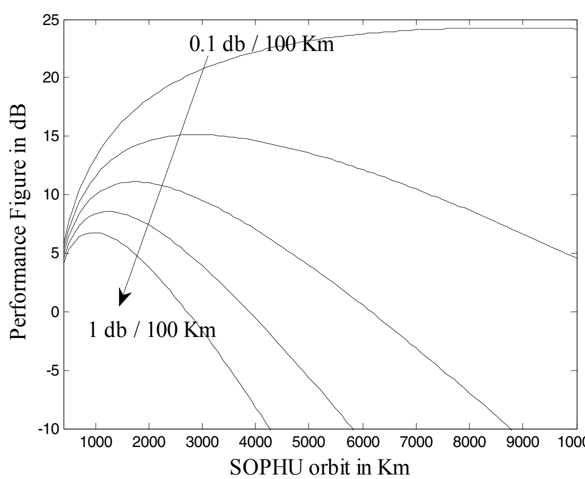
of solar cells to values higher than 1400 W/m^2 in space.

Figure 3(a) sketches the received power at PCBS for full wireless transmission from MEO calculated using Equation (1) based on the same assumptions as the last row of Table 1. This figure presents the total received signal power at the PCBS for the proposed hybrid system, assuming the LEO satellite has been installed at 200Km. The corresponding cluster curves have been sketched based on Equation (2) for different TLS losses. Here, we achieve up to 25dB performance via the proposed SBSPG. Thus, we assume a performance figure in dB based on the excessive loss of the fully wireless transmission in (1) compared to the proposed wired-wireless system in (2), which corresponds to:

$$PF = 20log\left(d_{Km,High}/d_{Km,low}\right) - L_{TLS} \times \left(d_{Km,High} - d_{Km,low}\right)/100 \quad (3)$$



(a)



(b)

Figure 3 - (a) Received Power, and (b) Performance Figure.

Figure 3(b) sketches the PF. If PF increases in the positive direction, the proposed hybrid system would be efficient. Note that the transmission effects of the atmosphere are the same in both MEO and LEO. Thus, atmospheric effects are cancelled in (3). In addition, because in (2) $L'_{Ion} < L_{Ion}$, PF portrays an upper bound on the performance. In (3), maximum efficiency is achieved at an altitude of $870/L_{TLS}$. Thus, if it is desirable to install SOPHU above 400Km, L_{TLS} should be designed to be less than 2dB/100Km to maintain the desirable efficiency. Figure 3(b) confirms that PF has a maximum that is shifted toward higher altitudes as the TLS loss decreases. In addition, as the TLS loss increases, the attenuation tends toward negative magnitudes for lower altitudes.

In general, the proposed hybrid transmission will be efficient if PF is larger than a threshold, e.g., $PF > 10dB$. This threshold will be characterized to ensure lower launching and installation costs and higher harvested power for the proposed system compared to that of the traditional one. The design and the structure of the TLS and the selected frequency of transmission are vital for the implementation of this system. A typical PF of about 10dB at an altitude of 1000Km is achievable.

3. MECHANICAL DESIGN ASPECTS

Figure 4 represents a proposed structure for the MLF unit. The SOPHU structure can be modeled as a huge square plate with the area of 100m^2 (about the same as that of the International Space Station). The altitude of the plate is about 5000Km. The plate is connected to a small box-shaped body of mass 500Kg and dimensions $1\text{m} \times 1\text{m} \times 1\text{m}$. The whole structure acts as a single body.

The center of mass of this body is at altitude 4750Km. The whole structure will orbit around the Earth as a single rigid body; the altitude of the orbit is the altitude of the center of mass. The orbit period (the period in which the SOPHU unit completes one revolution around the earth) depends on the altitude of the center of mass. The orbit of each SOPHU dictates the ground track. The ground track is the trace of the sub SOPHU point on the earth surface, as the SOPHU is moving in orbit. The ground track of an orbit will be the locus for all the PCBS units that will receive power form all the SOPHUs in that orbit. At the selected SOPHU altitudes (1000 km ~ 10000km), the ground track covers all longitudes on the earth surface. The range of earth latitudes covered by the ground track depends on the inclination of the SOPHU orbits. High inclination orbits cover high latitudes. The SOPHU orbits design parameters include: the number of PCBS units, the locations of the PCBS units, the power downlink time budget for all PCBSs and SOPHUs, and the desired repetition period (the period after which a SOPHU return above a PCBS unit again).

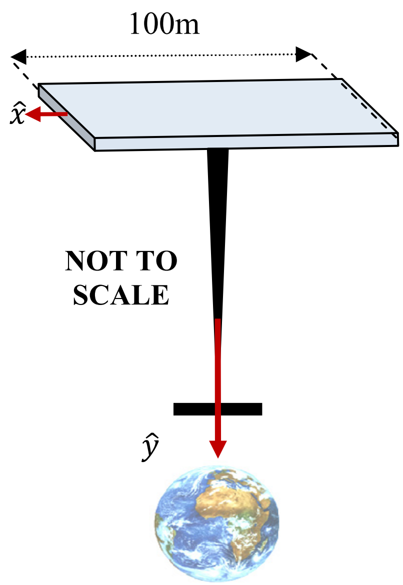


Figure 4 - MLF Unit.

Another aspect of the SOPHU motion is the attitude (orientation) stability of its structure. The SOPHU needs to be always pointing towards earth center (the sub SOPHU point which is the locus for the PCBS units, the y-axis in Figure 4). The attitude stability depends on the ratios of moments of inertia for the SOPHU structure. In general, the proposed shape for the SOPHU structure guarantees attitude stability about the desired orientation. The pointing accuracy budget depends on the orbit of each MLF unit. A control system is needed to achieve the required pointing accuracy. To sustain this structure in space, an orbit control system is required to compensate for perturbations like aerodynamic drag and solar radiation pressure and to maneuver MLF units within the operation period (see Sections 3.4 and 3.5).

The proposed attitude control system consists of control moment gyros (CMGs) [30] along with thrusters. Star sensors will be used for attitude measurements [31]. The system, however, must be stable at approximately the required attitude even in the absence of a control system. The configuration of the LMF unit is symmetrical with respect to its main axis. Thus, in the absence of control, it will be gravity gradient stable about the nadir [32]. The long distance between LEO and SOPHU causes the satellite to be susceptible to the torques caused by the gradient of the Earth's gravitational field. The gravity gradient torques act as stabilizers for the space structure since the mass moments of inertia of the satellite about the x and z axes are larger than the z axis [33]. The torques cause a decaying oscillation about the x, y, and z axes at the frequencies of $\pm 1.9\times 10^{-4}$, $\pm 2.2\times 10^{-4}$, and $\pm 1.9\times 10^{-4}$ radians per second, respectively. These torques help maintain the satellite's desired orientation. The vibration of the MLF unit impacts its pointing accuracy. A vibration damping system will help to guarantee the pointing accuracy.

4. CONCLUSIONS

A novel approach of space-based power transfer was introduced in this paper. The potential of this technique to harvest power from space was investigated. Typically, it was shown that if the harvesting unit of the proposed system is installed at the same orbit as GEO SBSP, then we can attain up to five times higher power compared to GEO SBSP. Moreover, if the proposed system is installed at the GEO orbit and we use a 100m by 100m harvesting unit, up to 1GWatt energy can be harvested on the ground. Finally, the pointing accuracy of the proposed technique was investigated and it was shown that a high pointing accuracy is achievable.

The proposed system can be implemented through a network of satellites. In some situations when a number of satellites are communicating with one ground station, synchronization across those satellites is required to ensure efficient power transfer. In addition, the whole satellite system need full orbital control. Moreover, satellites need to sense the possibility of collision with outer space objects and in some situations they need to change their orbit mildly to avoid collision. In addition, in some situations, for example when one space-based harvesting unit is in the eclipse of the earth, the energy may need to get relayed to the ground through other units in order to maintain a reliable source of energy. Thus, a smart system needs to control the whole structure that is a cyber physical system. Accordingly, the implementation of this system needs research and investigation in different areas that include (but not limited to) orbit control, multi-agent systems, and synchronization and beamforming techniques.

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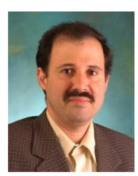
BIOGRAPHY



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