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Solar Power Beaming: From Space to Earth

A. M. Rubenchik, J. M. Parker, R. J. Beach, R. M. Yamamoto

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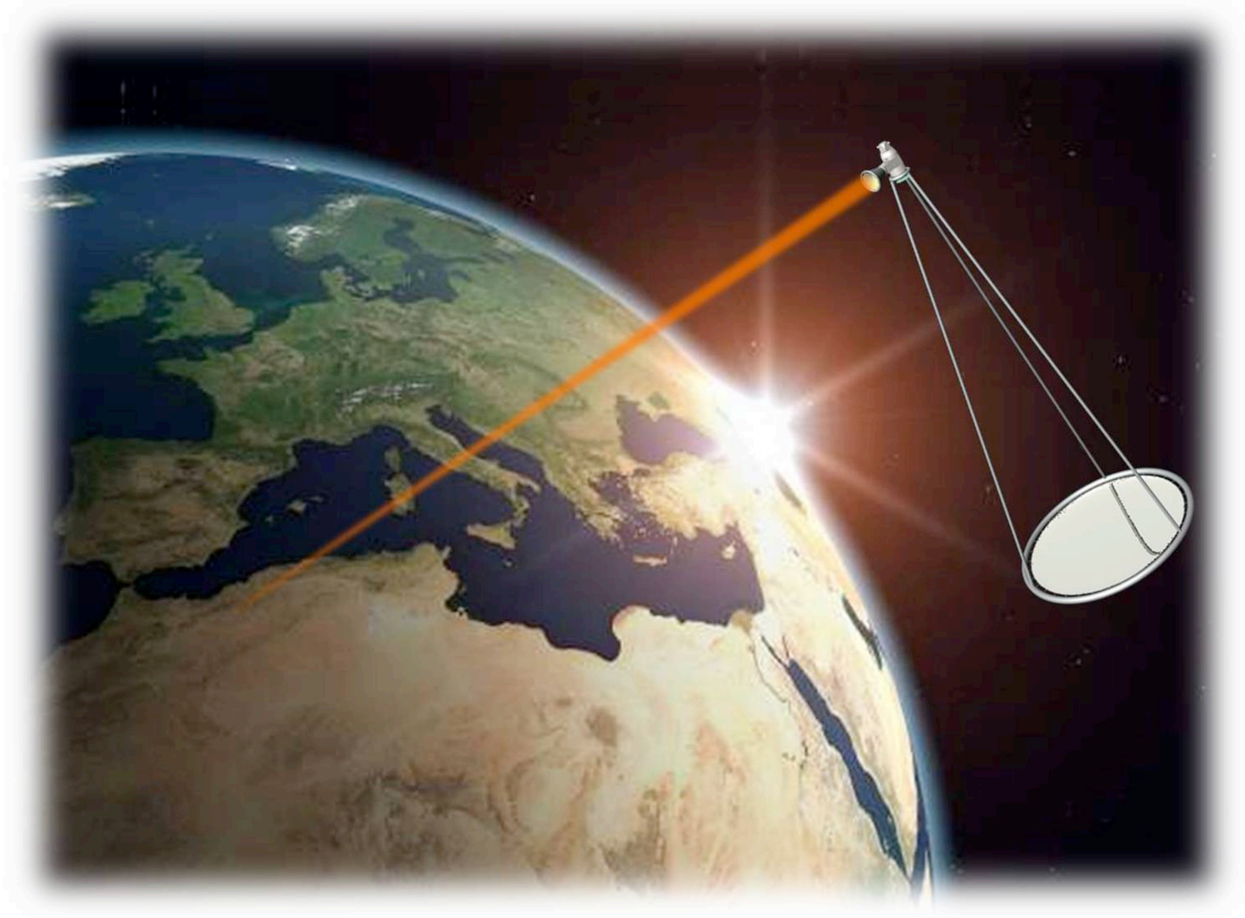

Figure 1: Solar Power Beaming System Concept

I. ABSTRACT

Harvesting solar energy in space and power beaming the collected energy to a receiver station on Earth is a very attractive way to help solve mankind's current energy and environmental problems. However, the colossal and expensive "first step" required in achieving this goal has to-date stifled its initiation. In this paper, we will demonstrate that recent advances in laser and optical technology now make it possible to deploy a space-based system capable of delivering 1 MW of energy to a terrestrial receiver station, via a single unmanned commercial launch into Low Earth Orbit (LEO).

Figure 1 depicts the overall concept of our solar power beaming system, showing a large solar collector in space, beaming a coherent laser beam to a receiving station on Earth. We will describe all major subsystems and provide technical and economic discussion to support our conclusions.

II. INTRODUCTION

The Need for Space-Based Solar Power

Over the years, there have been many excellent papers written on the need for the world to invest in clean renewable energy sources. Estimates have been made on the total amount of energy needed worldwide as populations increase, and the need for more and more energy is desired. These discussions include the need to look for alternatives to fossil fuel, as the scarcity of hydrocarbon-based fuels is ever increasing, and with it, increased political and social unrest. Pollution control and issues associated with climate change also support the need to develop clean renewable energy sources. An obvious solution is the development and use of solar energy. Solar energy is plentiful, clean, and for all practical purposes provides a limitless source of power.

Large-scale collection of solar energy on the surface of the Earth is problematic for several reasons. First, solar radiation has low energy density, and consequently very large areas of solar collectors are required. This equates to an excessive amount of materials and infrastructure needed to build such a terrestrial-based solar energy collection system. In addition, these solar collectors would block sunlight from hitting the ground, causing potential ecological impacts, as well as changing the local thermal balance. Cloud cover also has an impact on the effectiveness of solar energy collection at the Earth's surface, making it an inconsistent and unreliable energy source. The collection of solar energy in space mitigates many of these problems.

The idea of harvesting energy in space and then transporting it to the ground was suggested at the dawn of the space age [1]. Initial proposals made use of converting sun-generated electricity into microwaves, which would then be power-beamed to the ground. The arguments in favor of the microwave concept were high conversion efficiencies in space and on the ground, with good transmission through the atmosphere, even during periods of heavy cloud cover. The main problems with using a microwave-based system were the huge size of the required receiver on Earth, and the stringent performance requirements of the focusing system. Later on in the seventies, scientists at the Lawrence Livermore National Laboratory (LLNL) suggested using laser light instead of microwaves, thereby reducing the requisite focal spot size; which in turn reduced by a thousand fold the overall size requirements for the receiver and focusing optics. Nevertheless, start up costs of billions of dollars prevented any serious consideration of this solution to the problem [2]. Two significant factors contributing to the huge cost of deploying a space-based solar power system are; its large volume and weight - requiring multiple vehicle launches, and the need for human participation to activate the system in space orbit.

Recently, the National Security Space Office (NSSO) published a report emphasizing the demand for local energy supply in the megawatt range for remote bases and villages, etc. [3]. The main showstopper, as indicated in the NSSO report, is that astronauts would be required to assemble the system while in orbit, making the project economically infeasible.

In this paper, we will show that modern advances in laser and optical technology have greatly reduced the weight and complexity of the power beaming system, making possible the development of a system that can be delivered into orbit at low cost, and which will deploy and operate automatically. A key attribute of our solar power beaming system is that due to its extremely light weight, the entire space-based system can be put into Low Earth Orbit (LEO) using a single, commercially available heavy lift launch vehicle. In addition, the system requires no human intervention for deployment and activation in space, and is brought to full operational mode remotely from Earth. These two advances overcome significant cost challenges that have prevented development of space-based solar power concepts from a practical perspective.

The key element of the suggested system is a highly efficient, electrical diode pumped laser presently being developed at LLNL [4]. The laser efficiency from electricity to light is approximately 50% with a 5kg/KW weight-to-power ratio and very good beam quality, which is a key requirement for propagating the laser beam from space to the collection receivers on Earth.

Another breakthrough technology developed at LLNL, and included in our system, is lightweight diffractive optics, used to focus the laser light onto the ground receiver. The unique design of the optic provides a very compact packaging for launch, and allows it to unfold automatically when deployed in orbit [5] [6].

For the solar panel, we are considering a cell concept developed for space applications by the National Renewable Energy Laboratory (NREL) [7]. This thin, lightweight cell transforms (300 X) concentrated solar radiation into electricity with an efficiency of around 40%.

To concentrate the solar radiation onto the solar panel initially, we suggest using an inflatable, rigidizable and lightweight reflector such as that manufactured by L'Garde, Inc. of Tustin, California [8]. Details of their inflatable space structure system follow in Section IV, *Major Subsystems*.

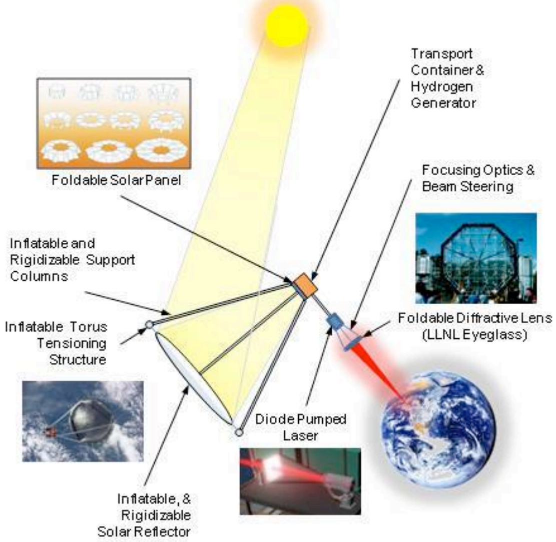

Figure 2: Overview of the Solar Power Beaming System

Collection of solar energy in space is continuous, with very high-energy flux intensities, correlating to high efficiency gains. Conceptually, the space-based solar power system is quite simple. A modest sized solar reflector is used to capture and focus the solar energy onto a solar collector. This energy is transformed into a high intensity, coherent laser beam and transmitted via a set of focusing optics to select locations on Earth. Figure 2 provides a top-level overview of this entire process.

<u>*Reasonable Next Steps*</u>

One can easily be overwhelmed by the magnitude of a program to develop and deploy a space-based solar power system. The amount of R&D perceived to be required, corresponding to huge costs, could be considered a "show-stopper". Our plan is very straightforward: use as much existing technology as possible, keep it simple, and take reasonable steps by not going for too much too soon. We will build on our successes and learn from our miscues.

An example of this philosophy is to leverage those technologies that have already been developed and proven. This would include the launch vehicle, the inflatable solar reflector, etc. Companies identified in this paper have worked on these technologies for many years and we plan to utilize their expertise and certainly not reinvent the wheel. In addition, the technologies developed at NREL and LLNL are well suited for our application.

The technology requiring the most development is the laser itself, which transmits the collected solar energy from space to receivers on Earth. The laser of choice is a diode pumped laser being developed at LLNL. It is extremely compact and lightweight, simple in design to promote long-term reliability and capable of transmitting megawatt class power levels. One of the key attributes of this type of laser is its high efficiency, critical to having a viable way to transmit the collected solar energy from space to Earth. LLNL has an aggressive timetable to develop this laser system.

The other major focus area is the integration of all of the major subsystems into an effective and coherent working system. This will take a concerted effort, utilizing a wide range of capability. The expertise required is not only technical in nature, but includes the logistics of putting such a system into space, the safety aspects of a high power laser beam propagating from space to Earth, etc. All of these challenges will have to be addressed before this type of system is realized.

III. CONCEPT OVERVIEW

The proposed system is straightforward in concept (see Figure 2). The inflatable reflector focuses solar light onto a solar panel, transforming it into electricity. An electrically pumped laser then produces a high-power laser beam, which is directed to the receiver on Earth's surface via a diffractive lens. A steering system of optics and automated hardware controls the beam direction.

As previously mentioned, due to the extremely lightweight nature of our space-based solar power system, the entire package can be put into Low Earth Orbit (LEO) utilizing a single heavy lift launch vehicle, such as the Falcon 9 manufactured and fielded by Space Explorations Technologies, (SpaceX) of Hawthorne, California [9]. The Falcon 9 is capable of lifting 10,450 kg (23,050 lb) into LEO, having more than enough payload capacity for our system. The entire space-based solar power system is deployed into orbit remotely, without the need for any human intervention, giving rise to significant cost and timesaving.

Let us estimate the system parameters. First, we consider the 1 Megawatt diode pumped laser. An electrical efficiency of about 50% is expected for this kind of laser system. For the solar panel, we consider the cell developed at NREL for space applications, having efficiency of approximately 40%. Using the above stated values, the solar energy flux incident on the cell must be about 5MW. Since solar energy flux in space near the Earth is approximately 1.4 KW/m^2, the area of the solar collector must be at least 3600 m^2, and the solar panel area must be 12 m^2.

An inflatable space structure is used as the solar reflector for our system. The solar reflector has a diameter of 70 meters and is made out of thin, highly reflective material, such as aluminized mylar. It utilizes three inflatable and rigidizable support columns (tripod-like configuration) and a torus tensioning structure that links the solar reflector to the solar collector system, providing good thermal contact between the component parts. L'Garde has demonstrated a proof of principle inflatable antenna via an actual space based experiment utilizing this technology [10].

The solar collector system includes a very efficient array of solar panels, totaling approximately 4 meters in diameter. In addition, a solar transport package is included, being comprised of a hydrogen gas generator used to inflate the support structure of the solar reflector, power supplies for the hydrogen gas generator, etc.

The laser system takes the collected solar energy and beams it down to the receiver stations on Earth. This laser is capable of megawatt-class power levels, providing a coherent laser beam in the near infrared wavelength that is suitable for efficient transmission through Earth's atmosphere. The laser is focused onto the receiver via a 5-meter diameter, foldable diffractive lens. This type of large, lightweight optic has been designed and built with success at LLNL, specifically for space-based applications.

In our system, a ground receiver, 5 meters in diameter, captures the energy in the laser beam at the Earth's surface. For a focusing lens in space with a diameter *(D)* of 5 meters, the spot size diameter *(d)* of the laser on the ground is given by the expression:

$$d = \frac{4\lambda F}{\pi D}$$

where λ is laser wavelength and F is the distance of the receiver on Earth to the orbiting focus lens. Our laser system has a wavelength (λ) of ~0.8 µm and a relatively low orbit height *(F)* of ~400 km, corresponding to a minimal laser spot size *(d)* of ~0.1m for ideal beam quality. When the receiver will be on horizon, the distance from the orbiting focus lens to the receiver will increase by $\sim\sqrt{2RF}$, or ~2200 km where *(R)* is the radius of the Earth. In this situation, the footprint of the laser *(d)* at the receiver will be ~0.5 m. To be conservative, and to take into account inefficiencies in the transport of the laser beam (jitter, etc.), we have chosen a receiver with a diameter *(d)* of 5 meters. For this case, effectively aiming the laser from space orbit to the receiver on Earth requires a pointing accuracy of about 2.5 µrad, a value that has been demonstrated on projects having similar long distances of travel.

The power generation station on Earth uses molten salt as the medium to capture and store the received energy, and is incorporated into a generator system utilizing steam turbines and an electrical generator. The electricity is then sent via transmission lines to its intended destination.

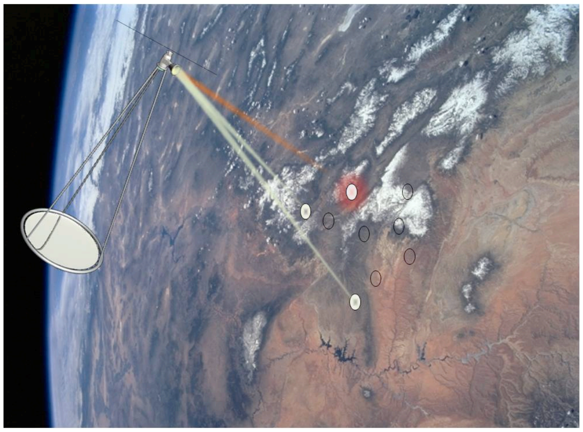

Figure 3: A Single Solar Power Beaming System Can Beam to Multiple Receiver Sites During Orbit

As previously mentioned, our space-based solar power concept utilizes solar collectors in Low Earth Orbit (LEO), approximately 400 kilometers above the surface of the Earth. We have chosen this orbit for several reasons:

- the payload to cost ratio is much less expensive for LEO packages versus geosynchronous orbits (GEO: 36,000 kilometers) having a cost differential of at least a factor of two, if not more.
- the maximum allowable payload for a single launch into LEO using the SpaceX Falcon 9 is over double that of a GEO launch.
- the distance the laser beam has to travel is approximately 90 times less for a LEO versus a GEO; in addition, the pointing and stability accuracy of the laser system is much reduced for a space-based system orbiting in LEO.
- a system orbiting in LEO (versus GEO) however does experience more atmospheric drag, due to its closer proximity to Earth; because of this, small rocket motors (such as the gas generators used to inflate the solar collector) will be required to fire intermittently to keep the space-based solar power system from losing altitude.

A fully operating space based solar power system will have multiple solar power beaming stations orbiting the Earth, and multiple power receiving stations on Earth, as shown in Figure 3. This concept allows power beaming to continue during times of inclement weather at some receiver stations, and increases the total area to which the collected solar energy can be supplied. The solar power beaming stations will be in Low Earth Orbit (LEO) at an altitude of 400 kilometers, and will orbit the Earth every 90 minutes or so. For any given receiver station on Earth, the solar power beaming station will be able to illuminate that specific receiver for approximately 9 minutes at the megawatt power level. After the 9 minutes, the solar power beaming station will not be able to "see" that particular receiver, and will therefore "switch" to another receiver on Earth. This scenario can happen continuously as desired. Assume that 10 stations were all positioned correctly, you can imagine power beaming quasi-continuously to each of the these 10 stations, 9 minutes at a time, using a single solar power beaming station in space.

IV. MAJOR SUBSYSTEMS

Launch Vehicle

Our Solar Power Beaming System requires a minimum launch payload capacity of 9125 kg, and is intended to deploy in a single launch. We have chosen the Falcon 9 launch vehicle from SpaceX, Inc. as the preferred launch vehicle, due to its breakthrough advances in reliability, time-to-launch and cost; offering the lowest available cost per kilogram (pound) to orbit. The current price for a single launch into LEO for a 10,450 kg (23,050 lb) payload is $36.75 million, roughly equating to $3516/kg ($1600/lb). Long-term plans call for a $1,100/kg ($500/lb) cost within a decade, or $11.5 million for future launches.

Falcon 9 presently launches from Cape Canaveral, Florida with plans for a future launch facility at Vandenberg AFB, California. Initial flights have been scheduled for 2009 and 2010. Their facilities include a state-of-the-art Class 100,000 clean room for system assembly and payload processing. As shown in Fig. 4, there exists ample room for our system's transport and deployment package within the Falcon 9 payload bay. Dimensions are in meters, with inches inside the parentheses.

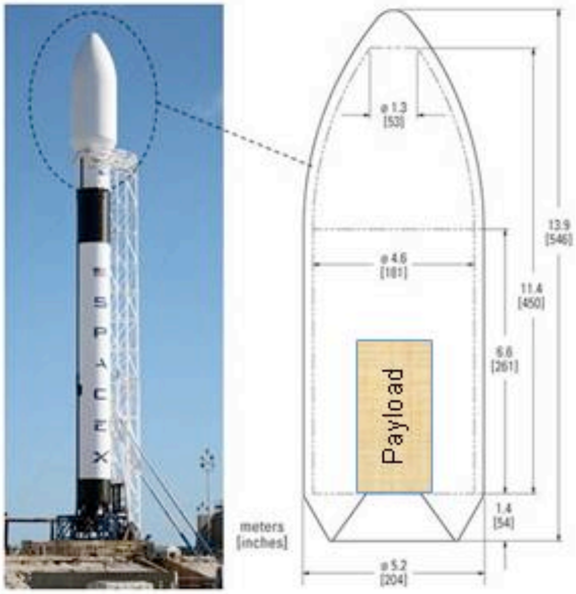

Figure 4: The SpaceX Falcon 9 Launch Vehicle and Payload Fairing Dimensions

Solar Reflector

The development of large, inflatable, and deployable space structures by L'Garde, Inc. has tremendous potential for use in our Solar Power Beaming System, due to their low cost, lightweight and demonstrated high deployment reliability.

L'Garde successfully demonstrated a 14-meter version of this type of structure as part of the Inflatable Antenna Experiment (IAE) in May, 1996 (see Figure 5). Results indicate good scalability of the concept to accommodate our system's larger 70m diameter requirements.

The entire structure is fabricated from thin flexible membrane materials and consists of:

(a) the reflector surface and a transparent canopy, used to form a closed cavity so that inflation gases put tension on the two membranes

(b) a multiple layer torus structure that supports the reflector/canopy assembly through a large number of attachment points around its perimeter (see Figure 6), and

(c) three multiple-layer struts that interface the torus with the transport package containing the remaining system components.

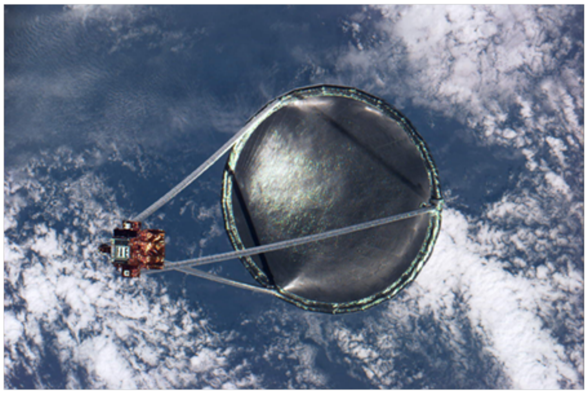

Figure 5: Still Camera Image of the IAE in Orbit during Testing, Taken from the Space Shuttle *Endeavour*

Good thermal contact between these inflated components and the laser system package will provide a mechanism for the removal of heat from the other system components through conduction, then via radiation to space.

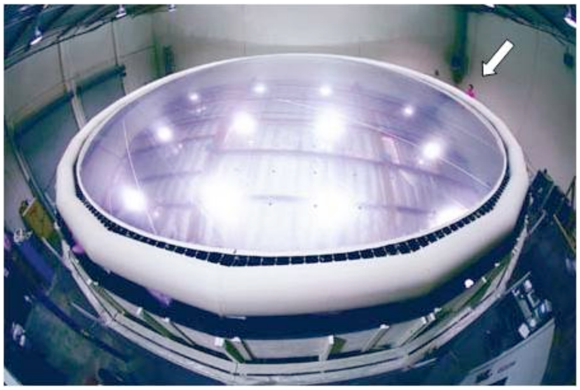

Figure 6: Inflatable Antenna Experiment reflector during ground tests. For scale, note the person on the right wearing a red shirt.

Deployment is accomplished by sequentially introducing inflation gas to the stowed struts, torus and reflector/canopy, as shown in Fig. 7.

Once LEO is reached, the stowed inflatable structure ejects from the transport package (1) via a spring-loaded plate (2). Next, the resultant strain energy from stowage of the inflatable struts initiates their deployment, with completion by inflation (3). Shortly thereafter, deployment of the torus initiates by release of its strain energy, then again completed by inflation (4). After the support structure has been completely deployed, the reflector and canopy are inflated (5) to their proper pressures.

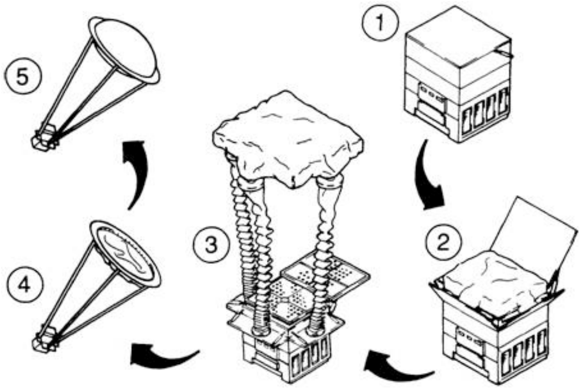

Figure 7: Solar Reflector Deployment Sequence [10]

Strain from completed pressurization of the struts and torus will cause their Sub-Tg membrane material to "rigidize", thus forming a stiff support structure for the rest of the system. The reflector membrane will also rigidize upon pressurization, after which, the clear canopy will remotely disengage from the deployed Solar Reflector.

The structure is relatively inexpensive, as it is constructed entirely of readily available membrane materials and does not require any high-precision mechanisms, complicated structures or electro-mechanical devices. In addition, the structure is very light, with a membrane thickness approximately 6 to 8 microns for the reflector and canopy, and a few hundred microns for the torus and struts. High deployment reliability is realized since the structural elements simply unfold from the stowed configuration as they are pressurized sequentially. The deployment is similar in fashion to that of an escape chute deploying from an airliner.

The Solar Reflector is packaged by systematic folding, in a manner to accommodate the appropriate sequence for deployment. L'Garde has gained valuable experience in this area from their efforts on the Inflatable Antenna Experiment (IAE). Our packaged structure is designed to fit within a 2m x 2m x 1m deployment volume. The hydrogen generation system used for inflation will be located in a separate container.

The total weight of the packaged Solar Reflector, including the inflation system, is estimated at 3425 kg.

Solar Collector

We propose using the Concentrator Photovoltaic (CPV) cell concept of the National Renewable Energy Laboratory (NREL), developed for space applications. This thin, lightweight cell will transform (300 X) concentrated solar radiation into electricity with an efficiency of approximately 40%. EMCORE Corporation of Albuquerque, New Mexico currently manufactures multi-junction cells using NREL's technology [11].

EMCORE's high efficiency Multi-Junction cells have a significant advantage over conventional silicon cells in concentrator systems because considerably fewer and smaller solar cells are required to achieve the same power output.

Using a Solar Reflector, as in our system, we can direct the sunlight onto a very small, highly efficient Multi-Junction solar cell array. This allows for the substitution of the costly and heavy semiconductor PV cell material, for the more cost-effective Solar Reflector. The high-energy output from this more efficient system, and the savings in costly semiconductor area, make the application of CPV technology economically advantageous. For example, under 300-sun concentration, 1 cm^2 of solar cell area produces the same electricity as would 300 cm^2 without concentration. This is particularly significant considering the general cost and weight constraints inherent to LEO launches.

Our Solar Collector (CPV cell array) will utilize the same compact, foldable design as the diffractive optics lens described in the *Focusing Optics and Beam Steering* section later in this document. Once unfolded, the Solar Collector will have an effective solar collection area of 12 square meters.

The estimated weight of the Solar Collector, including energy conversion hardware, is 300 kg.

System Transport Package

The System Transport Package will serve as the packaging container for deployment of the Solar Power Beaming System into LEO, as well as provide a backbone for the system structure once deployed.

In general, the entire Solar Power Beaming System must be packaged compactly enough to fit within the payload hold of the launch vehicle (see Figure 4), yet allow for straightforward, remote deployment. Once in orbit, the System Transport Package serves as the anchor point for all subsystems to provide a sound structure. The actual container that houses these subsystems will be constructed from strong, lightweight materials that are resistant to solar radiation and extreme temperature swings.

Subsystems contained in the System Transport Package include; the Solar Reflector, the Solar Collector, the DPAL laser system, the Focusing Optics and Beam Directing system, and a general, non-deployed utilities package, which includes a hydrogen generator, components for power conversion and the communication/positioning systems. All subsystems will be packaged for ease of remote, sequenced deployment.

The packaging container, with the incorporated utilities package, will weigh on the order 450 kg.

Laser System

- Diode Pumped Laser

Since the advent of lasers over four decades ago, solid state and gas lasers have followed largely separate development paths, with gas lasers being based either on direct electrical discharge for pumping or luminescent chemical reactions, and dielectric solid-state lasers being pumped by flash lamps and semiconductor diode laser arrays. Our diode pumped laser is a new class of laser system that has been under development at LLNL for the past several years.

One of the characteristic features of the diode pumped laser is its very small quantum defect, only 2% in this case, allowing almost elastic conversion of pump photons to high beam quality laser photons. Our laser is unique among diode pumped lasers in utilizing fully allowed electric-dipole transitions for both pump excitation and laser extraction. This gives high optical efficiencies, and also very high cavity gains ideally matched to simple and robust unstable resonator geometries, providing a pathway to very high beam quality. Based on experimentally validated first-principles physical models, we predict that power-scaled systems will achieve unprecedented optical-to-optical efficiencies of 65-70% using today's diode arrays, and enable fully packaged systems at <5 kg/kW (system mass to power output). This value is consistent with another laser under development, the High Energy Laser Area Defense System (HELLADS) being supported by the Department of Defense [12]. Figure 8 shows the essential features of the approach, transforming diffuse low-beam-quality diode laser radiation into high-beam-quality output laser radiation, with very high conversion efficiency. Using high-efficiency (65%) diode laser pump arrays, overall laser system efficiencies (wall-plug) of ~ 50% are possible.

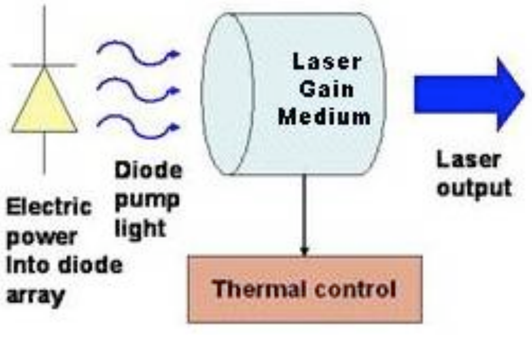

Figure 8: The diode pumped laser system is an "optical converter" that transforms low-beam-quality diode radiation into high-beam-quality laser output with very high efficiency.

The total weight for the 1 MW diode pumped laser system is estimated at 4550 kg.

Focusing Optics and Beam Steering

Focusing the laser radiation onto a small spot size over an extended distance (~2000 km) is in itself a huge challenge, requiring a large diameter mirror (~5 m diameter) having ultimate optical quality. As a reference, it should be mentioned that the Hubble telescope mirror has a mere 2.4 m diameter. Fortunately, the technology to construct lightweight, high quality, large diameter mirrors based on the use of diffractive optics has recently been developed by LLNL.

The 5m diameter prototype shown in Fig. 9 was built and tested at LLNL in 2003. The large mirror is composed of 72 diffractive optics segments, which are initially folded into a compact package using origami techniques.

In orbit, the packaged lens can be unfolded remotely and is immediately ready for operation. Ground tests of the Eyeglass lens [5][6] demonstrated a high optical quality output for the unfolded system, without any required adjustment.

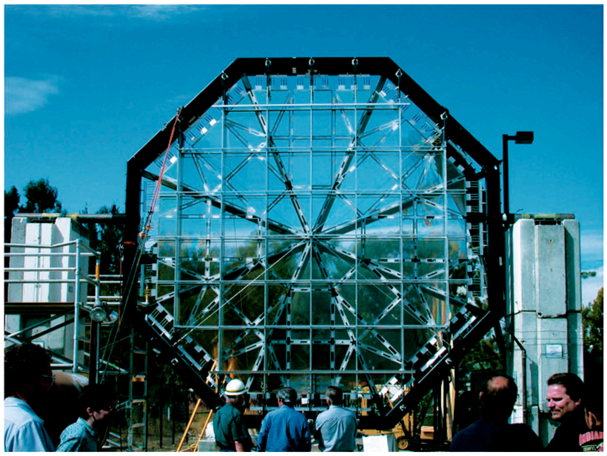

Figure 9: LLNL's 5-meter "Eyeglass" diffractive lens prototype, shown mounted in a steel and aluminum frame, ready for optical testing.

The required thickness of the fused silica optical segments is on the order of 1 mm, giving a total weight for the 5 m mirror of only 43 kg.

Taking into account the mass of the frame, the total weight of the lens should fall below 400 kg.

The following table summarizes the weights of the individual subsystems and provides a total Solar Power Beaming System payload weight and volume. It can be seen that our proposed system will easily meet the SpaceX Falcon 9 payload weight and volume restrictions of:

Maximum weight to LEO = 10,450 kg

Maximum Payload Volume = ∅ 4.6m, 6.6m Ht.

Subsystem	**Weight** (kg)
Solar Reflector	3425
Solar Collector	300
Packaging Container w/Utilities	450
Diode Pumped Laser System	4550
Focusing and Beam Director System	400
Total System Weight	**9125**
Total Packaged Volume	**2m square x 4m tall**

Ground Receiver and Power Generator Station

A molten salt generator configuration (as shown in Figure 10) is one of the options available for the terrestrial Power Generation Station. Due to the monochromaticity of laser light, the electronic structure of the converting elements for such a device can be optimized for specific photon energy, and according to Hyde, et al [2], the achieved efficiency of transformation to electricity can reach 70%.

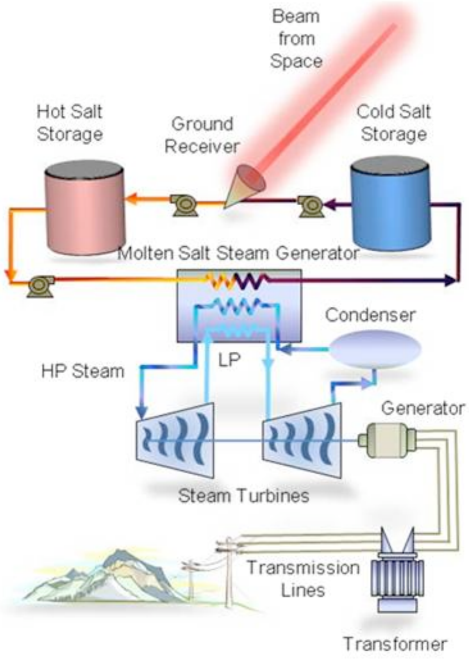

Figure 10: Molten Salt Generator Station Configuration

Thermal Management

Thermal management is a crucial problem for our proposed space-based solar power station, since the only available cooling mechanism will be losses via radiation to outer space. The high efficiency of the solar panels and our efficient laser system greatly helps to resolve the problem.

For our system, we must rid as waste heat approximately 4 MW of energy. The only practical way to do this is by thermal radiation from the surfaces of the subsystem components and structure. The advantage of the diode pumped laser is not only its high efficiency, but also in its robust operation at high temperatures (T~440K), which we consider will be the approximate temperature for the entire system, assuming good thermal contact of the components. The blackbody radiation flux at this temperature is:

$$P = \sigma T^4 \approx 10^5 T_{eV}^4 W/cm^2 \sim 0.2W/cm^2$$

If we consider only the concentrator area of 3600x2 m^2 (where we take into account the radiation from the rear surface), the total radiated energy will be ~14 MW. Hence, if all elements of our system are connected using aluminum-coated inflatable columns, the radiative losses will be sufficient to support steady-state system operation.

Station to Station Power Beaming

Our proposed space laser system has a high (~50%) efficiency of electricity conversion to laser radiation. The conversion of laser energy back to electricity can be done with an efficiency reaching 70%. As a result, it can also be attractive to use the laser system for ground energy transmission. Another possible application of this technology would be in conjunction with wind energy. For the most part, large wind farms are situated in remote places having good wind patterns, but frequently surrounded by rugged terrains. The construction of transmission lines to retrieve the harvested power is expensive and invasive to natural habitats, quite often leading to a stream of environmental objections. Laser-based energy beaming is flexible, noninvasive, and can be an integral part of a transmission system (see Figure 11). Though power beaming can be weather sensitive, it remains consistent with the intrinsic intermittency of wind energy.

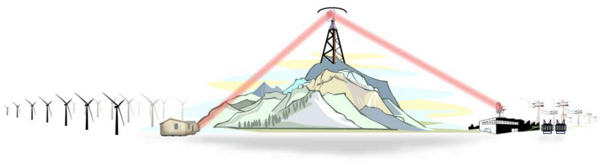

Figure 11: Remote Power Beaming Using Mirror Stations

V. ECONOMICS

- Cost

The cost to deploy the first space-based solar energy system is estimated at approximately $500 million. A significant percentage of this cost is attributed to the laser, the solar reflector/collector systems and the ground receiver/power generation station on Earth. This cost includes a single space-based power beaming system and a single receiver station on Earth. Multiple industries would be engaged supporting their areas of expertise to comprise the total required system. A rough order of magnitude cost for a first system is shown in the following table:

Subsystem	**Cost** ($M)
Launch Vehicle	37
Solar Reflector	80
Solar Collector	50
Packaging Container w/Utilities	55
Diode Pumped Laser System	100
Focusing and Beam Director System	70
Ground Receiver & Power Generation Station	100
Total ROM Cost	**~ 500**

Subsequent systems would cost significantly less. The cost to launch future additional vehicles into LEO is estimated to be several times less than the initial launch, and the cost of the laser system is also estimated to be several times less than the first deployed unit. Since a first article is yet to be designed and built, it is difficult to estimate with strong confidence the actual cost of our proposed system. However, the attributes of the system as explained in previous sections, strongly support significant cost reductions for future deployments and the total initial system costs as described.

- Schedule

The time required to deploy the described space-based solar energy system is dependent upon the required development time of the laser system. The laser system is the key technology advancement required to bring this concept to fruition. Based upon the current rate of progress, we believe this megawatt class laser will be available approximately five years from this whitepaper's publication.

The other major systems that comprise the total space-based solar energy system are much more mature in their development, and most have already been demonstrated at some significant engineering level. Obviously, their development will continue in parallel with the development of the laser system, and thus, will be even more mature and robust as the laser itself evolves to a level of working hardware. We believe that within a six to seven year time frame, the first complete space-based solar energy system can be deployed at LEO and begin power beaming operations to receiver stations on Earth.

Barriers to Entry

With all of these fundamental attributes, why then has space-based solar power not been developed? The simple answer is one of economics. The initial cost estimates show that investments on the order of billions of dollars are required to develop and deploy a functioning space-based solar energy system. Included in these costs is the development of some key technology items, such as the laser system. The buy-in cost is just too high for anyone to seriously consider this type of business venture.

However, when looking at long-term energy needs, the development of space-based solar power is certainly an option worth considering. The recent feasibility study conducted by the National Security Space Office emphasized the need for megawatt class systems, which would supply energy to remote locations and small villages worldwide. However, even in this initial, rather low throughput case, the start-up costs look prohibitively high. We believe that our proposed system can be deployed and begin power-beaming operations at a cost of a few hundred of millions of dollars. Although this initial system may be far from economical, it certainly can stimulate the technological development (as an example, the solar power beaming lift vehicle) to reduce costs, such that space-based solar power can be an economic realization in the not too distant future.

Although the extremely high cost of a space-based solar power system is the most prevalent "barrier to entry", there are additional issues that should be mentioned. These issues include the perception that these systems orbiting in space could be and would be used for military purposes, engaging airborne targets and land based installations worldwide with its high intensity, coherent laser beam. One minute the system would be beaming coherent laser light to a power generation receiver station and the next minute, it would be shooting down a ballistic missile or satellite in a military application. One way to mitigate this concern is to control the size of the focusing mirror. The mirror must be large enough to produce effective operation of the receiver, yet small enough to limit the focused laser power to less than military requirements.

In our example of a 1 MW laser system with a focal spot size of about 4 m in diameter, the maximum irradiance will be about 10 W/cm^2 and therefore insufficient for military applications.

The laser itself is a key system that is still in the research and development phase. The laser needs to be both lightweight and small in size to be consistent with this space-based application, yet have the capability to transmit megawatt class power for hundreds of kilometers under maintenance-free operation. Although there is no physics reason why this is not possible, this type of laser system is not presently available.

Another "barrier to entry" addresses the issue of safety, and in particular laser safety. The logistics of sending a megawatt class, coherent laser beam from space to a receiver on Earth 400+ kilometers away conjures up several interesting scenarios. What if the transmitted high power laser beam hits an unintended object crossing its path, an airplane or a bird? In addition, what if the laser's beam direction control system malfunctions, and the high-powered laser beam is misdirected, away from the power generation receiver and onto buildings, cars or even people? Moreover, what about the possibility of having the transmitted megawatt class laser beam reflecting off a surface and blinding a person from the glint of the reflected beam.

All of the above potential issues are just the "tip of the iceberg" with regard to the logistics that need to be resolved, such that actual deployment of a space-based solar power system can be realized. However, we believe that the development of clean, renewable energy sources is critical, and although the "barriers to entry" are important factors to consider, each will be addressed and viable solutions found on a case-by-case basis.

Viability during periods of inclement weather

The use of Low Earth Orbit (LEO) for our space-based solar power system provides us with the ability to pick and choose which receivers on Earth we send the power to. This is especially significant when inclement weather prohibits the beaming of power to Earth as receivers are hidden from direct view of the orbiting space-based solar power system. The ability to acquire, point and engage a multitude of receivers on Earth provides increased probability that the power can be transmitted from space to locations of interest on the planet.

VI. CONCLUSION

We have described a fully self-contained space-based solar power system capable of efficiently beaming collected solar energy from space to receiver stations located at the Earth's surface. The key technological advancement that supports this concept is the development of a simple, lightweight laser system that can effectively transmit a coherent laser beam from space to Earth with high efficiency and reliable operation. The laser's near infrared wavelength (795 nanometers) supports efficient transport through the Earth's atmosphere, with the related attribute of requiring a correspondingly very small receiver on Earth, of merely a few meters in diameter. A Low Earth Orbit (LEO) has been chosen to facilitate the use of current launch system capabilities, as well as reducing the laser beam and optical system pointing and alignment requirements.

A rough order of magnitude cost of $500M for the first space-based solar power beaming system is estimated. Significant cost reduction factors include: that the entire space-based solar power system can be deployed into space via a single launch vehicle, and that the system requires no human intervention to set-up and activate. Subsequent systems are estimated to cost several times less. A deployment timeframe of six to seven years for this initial system is proposed.

Although many engineering details need to be resolved to make this system a reality, we believe that all of the major subsystems and components are mature enough to warrant serious support of this concept. Our philosophy is to take a reasonable first step, make a simple system initially, learn from our experience, and build on our successes over time to gain increased performance and capability in subsequent systems.

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