Towards an Early Profitable PowerSat, Part II

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Abstract

Development of space solar power (SSP) suffers from the extremely large dimensions and mass of traditional designs driven by the size of on-orbit microwave antennas (typically a kilometer or so) necessary to deliver power to Earth from geosynchronous orbit. This large size leads to huge up-front capital requirements and long, complex development cycles, typically including multiple launches and on-orbit assembly. Critics claim these difficulties are impossible to overcome and block investment in SSP research and development. To counter this view, we investigate technologies and designs that, following a reasonable R&D effort, may be able to deliver small, operational, single-launch PowerSats suitable for niche markets. Part I of this series described an SSP design based on low-mass, thin-film solar cells such as those already proven in space combined with infra-red power beaming. Since infra-red wavelengths are approximately 30,000x shorter than microwave and the product of the diameters of the transmitting and receiving systems is a linear function of wavelength, the on-orbit power beam radius can be a few meters, making small PowerSats practical. This paper, Part II, contains a design sketch of a power beaming system using fiber lasers integrated into the power-collection system. Based on this design sketch, we quantify some of the improvements in the state-of-the-art necessary to develop a 120 m radius PowerSat, launched by a single Falcon 9, that delivers up to 6.2 MW to the grid. We also investigate using a Falcon Heavy as the launch vehicle. Although there is significant risk, we conclude that a reasonably sized, reasonable length R&D program could lead to small, practical SSP PowerSats and perhaps jump start a vigorous SSP industry. This would have enormous positive implications for energy markets, the environment, and nations with strong aerospace industries.

Introduction

Successful development of space solar power (SSP, aka SBSP) would provide vast quantities of clean electrical power to Earth for the next few billion years. Such a prize is worth considerable effort and risk. Indeed, it seems obvious that our energy development research should aim not only for near-term, relatively easy targets that can be incorporated into the world's energy systems within a few years, but also long-term, risky targets that would have a transformative impact if achieved. Fusion and SSP fall into this second category.

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Any SSP system requires four major systems:

1. a system for solar power collection, called the sail here for reasons that will become clear.
2. a system for power beam generation.
3. a system to direct the beam to Earth.
4. a receiver on the ground to convert the power beam into electricity.

Most SSP proposals involve kilometer-scale dimensions for the first two components, leading to enormous up front costs and long development times. This has prevented SSP from making much progress. In particular, kilometer-scale satellites have never been built and would require many launches plus a system to assemble the gigantic final product. Indeed, some observers believe that SSP is so difficult that there is little or no point in research or development (Fetter, 2004), even though SSP's enormous potential would seem to justify a great deal of risk.

One argument against any SSP research and development (R&D) funding is a comparison with ground solar, which receives less energy less consistently than PowerSats and requires much more land than SSP systems. However, Earth is a much easier and cheaper environment to work in. First, it should be noted that solar systems optimized for the ground are much different than those optimized for space, so direct comparison is misleading. Second, there are niche markets, such as in Alaska, where there is essentially no sun six months of the year making ground solar completely impractical, at least in the winter. Finally, to get started, SSP need not compete with every ground option. It only need compete with one commercially successful energy source. For example, in very remote locations diesel generators are routinely used for power. Thus, were SSP cost competitive with diesel in the most remote regions of the world; there would be a niche market for SSP.

This paper describes a target PowerSat design and examines the research and development necessary to make it profitable. Our investigations suggest that the target PowerSat *may* be competitive with nuclear fission and/or diesel generation in very remote locations.

It should be noted that although SSP is certainly difficult, it is much closer to fruition than nuclear fusion. Solar arrays are in routine use for satellites and power beaming has been demonstrated. In spite of tens of billions of dollar of research, nuclear fusion has never produced a positive watt of power. Today, U.S. federal funding for fusion is around $400 million/year[1] whereas the SSP budget is zero.

The total global energy market is measured in trillions of dollars per year. If a small, relatively inexpensive, SSP PowerSat for niche markets can be profitable, then experience will be gained, more PowerSats will be built, and the launch rate will increase; all of which will drive down costs and widen the markets in which SSP can compete. Eventually, of course, we would like to see very large PowerSats filling the same role of providing 24/7 power as nuclear, coal, oil, and natural gas are

[1] http://www.cfo.doe.gov/budget/10budget/Content/Highlights/FY2010Highlights.pdf retrieved on 27 January 2011

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today. However, there is little likelihood of getting there in a single step. What we need is a small step in the right direction.

Of the major space powers, only Japan has invested significantly in SSP R&D. Japan has a 30 year program to build a one gigawatt system (Suzuki, Kisara, Niino, & Mori, 2009). A one gigawatt system is necessarily large, kilometer scale in fact. To gather one gigawatt requires a 750,000m^2 collector even if sunlight is converted into power at 100% efficiency, which is impossible so actual spacecraft will be larger. If microwaves are used to transfer power to Earth, then the minimum size space antenna is kilometer-scale in any case (Department of Energy, 1978) because of unavoidable wave properties when transmitting between Geosynchronous Orbit (GEO) and Earth. Given an enormous antenna, only a large solar collection area makes sense. We need a smaller on-orbit power beaming system.

This paper suggests one such path based on infra-red power beaming and a thin-film solar cell array stabilized and perhaps deployed by the beam generating system! Infra-red power beaming systems are smaller than microwave beaming systems for long transmission distances because the product of the diameters of the transmitting and receiving systems is a linear function of wavelength (see equation 1), and infra-red wavelengths are tens of thousands of times smaller than microwaves. As the on-orbit radius of an infra-red power beam can be as little as a few meters, smaller PowerSats make sense.

$$D_t\, D_r \propto\; r\, \lambda \qquad (1)$$

Where:

D_t is the diameter of the transmitter

D_r is the diameter of the receiver

r is the distance the beam must travel

λ is the wavelength

We approach the problem of justifying funding for SSP R&D by sketching the design of a small, relatively inexpensive, single-launch target SSP system suitable for niche markets. The target system design relies primarily on technology either demonstrated in space, such as the thin-film solar arrays for energy collection, or available in the commercial market, such as infra-red fiber lasers for power beam generation. The target PowerSat has a mass budget of 100 g/m^2 which means a 120 m radius disc can be launched by a single Falcon 9. This system delivers up to 6.2 MW to the Earth's electrical grid assuming an end-to-end efficiency of 10%. Meeting the efficiency target will require significant, but plausible, improvements in the efficiency of the subsystems.

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Part I of this paper series focused on the solar collection system, which will be summarized here. The focus of this paper is infra-red power beaming generation based on fiber lasers. Fiber lasers are optical cables doped with rare-earth elements to lase.

Important note: throughout this paper quantitative data are rounded off and approximated. The state of this design is much too preliminary for anything resembling high precision. Also, throughout, optimistic but, we hope, reasonable numbers are used. There is no claim that this system could be built today and generate a profit, but rather that profitability may be the other end of a reasonably sized R&D program. In particular, an R&D program that may be significantly smaller than that necessary to bring fusion to profitability.

The next section discusses infra-red power beaming in general, followed by a discussion of using thin-film solar cells for solar energy capture. We then sketch the design of an infra-red power beaming system based on fiber lasers and integrated across the entire solar energy capture surface. Finally, we quantify the R&D improvements necessary to develop a one-launch SSP system, followed by a discussion of potential customers and future work.

INFRA-RED POWER BEAMING

Most SSP proposals use microwaves to deliver power to the ground. Unavoidable physics limits efficient transmission of power in the microwave from GEO to Earth to kilometer scale on-orbit antennas (Department of Energy, 1978) regardless of power levels. For example, the 1978 DOE

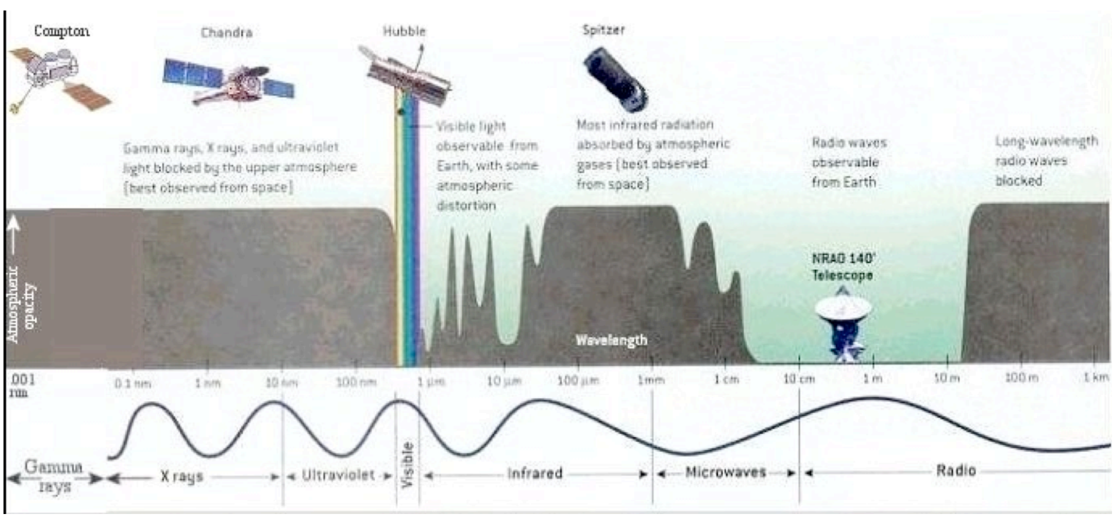

Figure 1: Atmospheric absorption of power over many wavelengths. Notice the depth of the transmission windows around 12 cm vs. 1 μ.

reference design (Department of Energy, 1978) featured 2.45GHz (12.2cm) transmission with a one km diameter on-orbit antenna and a 10 km diameter ground antenna to achieve an estimated 63% efficiency. As noted above, such large on-orbit antennas make small PowerSats impractical, thus requiring many launches and on-orbit assembly.

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However, the product of the sending and receiving system minimum diameters is linearly dependent on wavelength (see equation 1). There are narrow transmission windows in the atmosphere around 1– 2 μ which, if exploited, could reduce the minimum antenna diameter product by a factor of 30,000-120,000. At 1μ this would permit a five meter on-orbit beam transmitting to a minimum 32 m receiver on the ground. This enables small PowerSats, at the cost of much higher beam density and associated problems. Limiting a 6.2 MW-to-the-grid facility to 10x the power of sunlight with 42%[2] conversion efficiency implies the receiver must be roughly 50 m in diameter. This is orders-of-magnitude smaller than microwave systems to accomplish the same end. Of course, as the near 1μ windows do not survive cloudy conditions, such PowerSats may be most suitable for desert-like locations, where, fortunately, there are substantial electrical power markets such as Los Angeles, San Diego, Las Vegas, parts of Australia and North Africa.

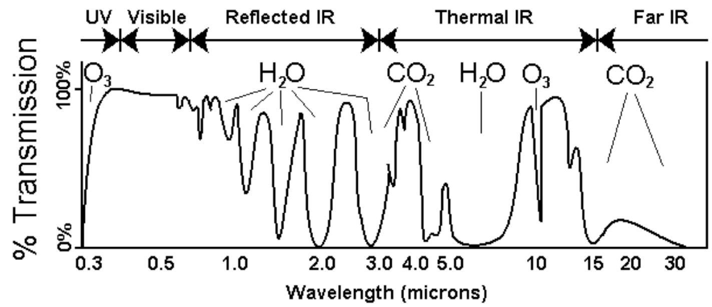

Figure 2: Atmospheric windows for power transmission in the micron range. Notice the narrow bands of high transmissivity near one micron.

Infra-red power beaming has been demonstrated by, among others, LaserMotive, which won first prize in a NASA sponsored power beaming competition. This involved a vehicle climbing a one km tether using power beamed from the ground. LaserMotive delivered 500 w at 0.808 μ with around 10% efficiency over one km using off-the-shelf lasers, custom optics and custom solar cells. High efficiency was not essential to the project. The LaserMotive chief scientist suggests that 25% transmission efficiency could be achieved today and perhaps 40% with near-term technology (Jordin, 2010). Our target is around 30%.

Coming from another angle, Alfalight, Inc., a diode laser manufacturer, recently demonstrated 65% power conversion efficiency as part of the DARPA Super High Efficiency Diode Sources program. This program has a goal of 80% efficiency. Spire Semiconductor LLC produced a concentrator photovoltaic solar cell measured by the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) at 42% peak efficiency. These results also suggest that something near 40% end-to-end efficiency may be achievable with sufficient development. While this is less than the 63% estimated for microwaves, massive reduction in system size provides ample compensation.

The low efficiency of solar cells is in part due to the difficulty of capturing energy at many wavelengths. As lasers produce energy at essentially one wavelength, it may be possible to develop very high efficiency receivers to convert this laser light to electricity. Kotter et al. (Kotter, Novack,

2 42% conversion has been achieved for sunlight to electricity in the lab. It may be possible to do better with laser light as it is a single frequency and easier to convert. See discussion below.

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Slafer, & Pinhero, August 10-14, 2008) report a 92% simulated receiver efficiency at 10 μ based on arrays of very small antennas, called nantennas, that work like radio or TV antennas but at much shorter wavelengths. This contrasts with conventional solar cells where photons push electrons across the band gap. Kotter et al. also report fabricating such devices with electron beam lithography and suggest approaches to mass production.

While the preceding analysis suggests that in principle there should be some suitable infra-red power beaming system, it does not immediately suggest an implementable design. It appears that fiber lasers may be an excellent choice for the power beaming system because the fibers can be quite long, up to at least 100m, so they can be spread across the back of the sail to ease thermal management and to add stiffness to the sail. Fiber lasers are in routine commercial use and have many of the key properties necessary: high efficiency, high power, and high reliability.

To understand why fiber lasers are an excellent choice, it is first necessary to understand the architecture of the target satellite. The architecture is driven by the solar energy collection approach. Our design sketch uses thin-film solar cells due to their low mass.

Thin-Film HelioGyro Power Generation

Assuming a relatively small infra-red beam, the physical architecture of a PowerSat is driven by the nature of the power collection area. For low mass per unit area, a heliogyro is an excellent choice (Globus, Towards an Early Profitable PowerSat, 2010). Heliogyros are solar sails where the sail is stabilized and shaped by rotation rather than structure, leading to very light-weight designs. Solar sails generate thrust by reflecting photons, which have finite mass and therefor impart a tiny push when reflected due to Newton's Third Law. The difference between a solar sail and a PowerSat is the coating applied to the sail material: reflective for propulsion and power-producing for PowerSats. For this reason, we call our solar power collection system the 'sail.'

An integrated in-space test of a heliogyro with thin-film solar power has been successfully conducted by the Japanese Ikaros satellite (Westlake, 2010). Launched on 21 May 2010, Ikaros is a solar sail currently en route to Venus. The 14 m on-a-side square sail is made of four triangular blades spin-stabilized at 1– 2 rpm. 5% of the sail area is covered with thin-film solar cells to produce about 500w for the satellite, suggesting about 4% efficiency. The sail material is 0.0075mm thick and the solar cells 0.025mm thick making for an extremely low mass per unit collecting area; assuming density comparable to commercial ground thin-film solar cells[3], perhaps 45g/m^2.

[3] The Big Frog Mountain PowerFilm MPT4.8-150 module: length x width 94x77mm, thickness 0.2mm, mass 2.9g was used for this calculation.

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The amount of energy a PowerSat can generate in orbit is a function of the collecting area and the efficiency of the solar cells. Solar insolation is about 1,366 w/m^2. Commercially, Kaneka Solar (Kanaka) sells thin films cells that are approximately 14% efficient, which would generate about 190 w/m^2 in space, or 8.7 MW for a 120 m radius PowerSat. In the lab, Ramanathan et al. (Ramanathan, et al., 2003) report 19.2% efficient thin film cells based on $ZnO/CdS/CuInGaSe^2$, about 260 w/m^2 in space, or 12 MW generated for a 120 m radius PowerSat.

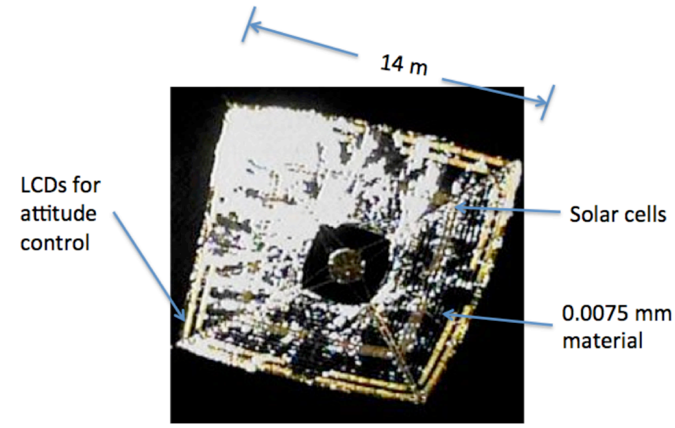

Figure 3: The Ikaros solar sail. Note the inner ring of faintly yellow materials. These are thin-film solar cells. A PowerSat might employ this same design but extend the power production area to the entire sail. The more prominent yellow around the edge of the sail are liquid crystal devices used to control the satellite by electronically changing their reflectivity. Image courtesy of JAXA.

In Part I (Globus, Towards an Early Profitable PowerSat, 2010) our analysis suggested that a 5 MW-to-the-grid system might be launched by one Falcon 9 with a mass budget of 100 g/m^2 for a 210 m on-a-side square satellite. After accounting for power generation, the rest of the system had a mass budget of 55 g/m^2. However, there was no power beaming design, only analysis suggesting that it should be possible. After examining several options for infra-red power beaming, fiber lasers appear to be the strongest candidate. To keep all the fiber lasers the same length, a circular sail is preferred and, in a surprising result, it appears that the fiber lasers may be sufficiently stiff to dispense with spacecraft rotation. All this leads to a target system somewhat different than that presented in Part I.

FIBER LASERS

Fiber lasers are optical fiber doped with rare earth elements to lase. Lasing is induced by pumping lasers that can be distributed along the fiber. Fiber lasers are commercially available today for high power applications such as cutting. Fiber lasers are a strong candidate for infra-red power beaming from PowerSats because they:

1) can lase at about the right frequency ($1-2\mu$).
2) have high power output.
3) are efficient.
4) have excellent thermal properties (high surface to volume ratio and operate at high temperatures).
5) provide their own waveguides.

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6) can run from the outer edge of the sail all the way to the center, like the stays of an umbrella, where the beams can be combined and directed to Earth by a system of mirrors.
7) can be pumped at many points along the fiber.
8) may add enough stiffness to the sail to dispense with rotation and thus significantly simplify the system to direct the beam towards Earth.

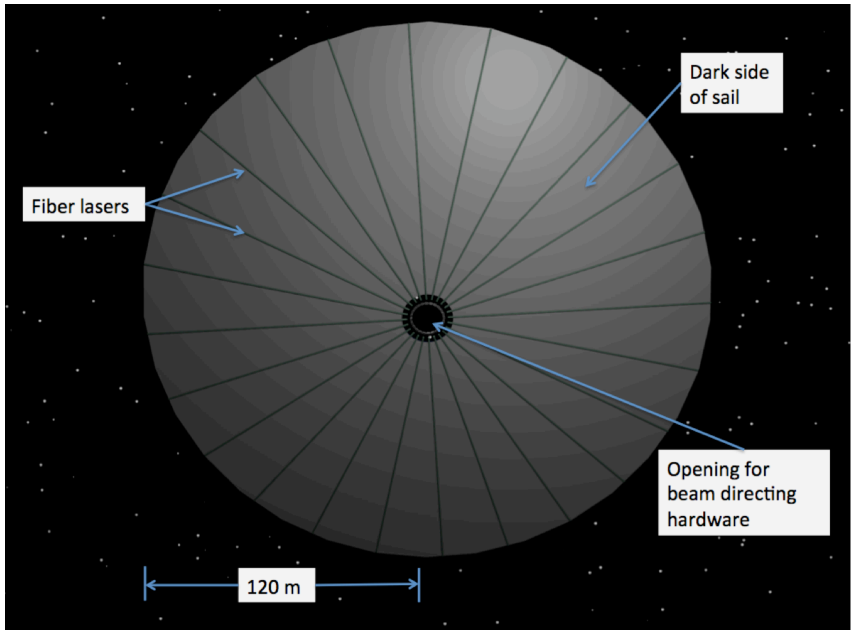

Figure 3: Sketch of a small number of fiber lasers on the dark side of a circular sail. If all 376 fiber lasers were drawn the image would distort. Laser beams are emitted into the hole in the center. The hole is for a not yet designed mirror system to direct the beam to Earth.

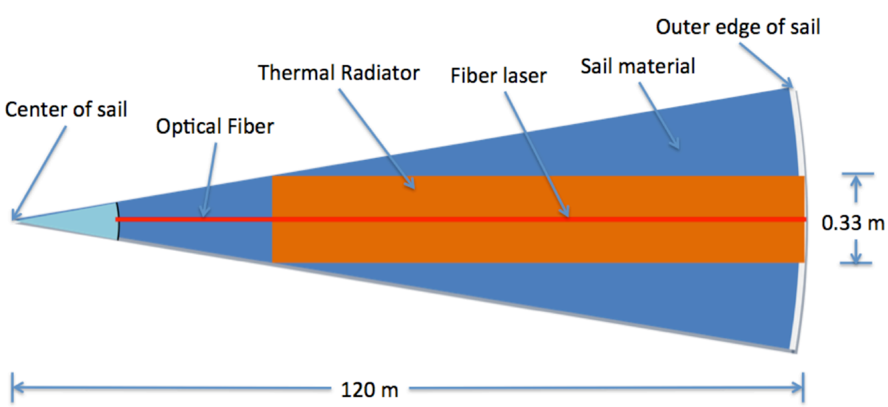

Figure 4: Sketch of fiber laser, optical fiber, and radiator for one pie piece of the sail. *Not to scale*. The light blue represents the hole in the center of the sail where the beam directing hardware goes. 376 such pie pieces make up the entire sail.

IPG Photonics advertises continuous wave fiber lasers with up to 50 kw power, wall-plug efficiencies greater than 30% and fiber lengths up to 100m (IPG Photonics, 2011). For a 120 m radius sail with fibers running from the outer edge to the center of the sail, each fiber laser could be coupled with an optical fiber the last 20 m to the center of the sail where the fibers are too close together to cool if they are actively lasing. Assuming 60% efficient fibers 2 m apart at the out edge of the sail, the target 120 m radius 6.2 MW-to-the-grid system would require

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376 fibers each delivering about 35 kw – very near the parameters of the IPG commercial product except for the efficiency.

Fiber lasers emit heat all along their length. For 35 kw output per laser, assuming 60% wall-plug efficiency, about 23 kw of heat must be rejected along 100 m of laser fiber, or roughly 230 w/m. At 300k, a black body radiates 459 w/m^2. At this temperature each laser would require a heat radiator roughly 0.5 m wide, which is more than the 0.33 m space available between lasers near the center where the optical cable starts. Fortunately, raising the operational temperature reduces the size of the heat sink as a function of ΔT^4. At 340 K the radiator must be only 0.3 m wide, which is consistent with the available space. Thus, developing high temperature fiber lasers is a priority. Fortunately, fiber lasers have an unusually high tolerance for high temperature operation.

To calculate the mass of the radiators, assume the density of aluminum foil, 700 kg/m^3 (SI Metric), and an average radiator thickness of 0.01mm, which is significantly thicker than the thinnest aluminum foil[4]. Assuming 340 K operation, or 0.3 m wide radiators, that gives us a mass of roughly 7 g/m of fiber laser.

While the details of combining 376 laser beams efficiently are not obvious, there is at least some evidence that incoherent laser beams can be combined effectively. In 2008 Sprangle et al. reported combining incoherent laser beams with approximately 90% efficiency (OptoIQ, Sprangle, Ting, Penano, Fischer, & Hafizi, 2008). This obviates the need for a difficult phase-coordination of hundreds of separate beams.

Eliminate the Spin

There is a potential opportunity in arranging the fiber lasers like the stays of an umbrella. If the fiber lasers are stiff enough the satellite need not rotate to maintain shape. This would substantially simplify the mirror system that directs the beams to Earth, which must otherwise be despun. It would also simplify many other aspects of satellite construction, deployment and operation. While optical cable and the associated heat radiators are not very stiff, the major force on the sail is sunlight, which very weak.

A simple, conservative model was used to calculate the maximum deflection of the sail due to light pressure. Specifically, a beam fixed at one end with equal pressure all along the beam. The formula for the deflection of such a beam is:

$$\delta = (F\ len^3)/(8EI) \quad \text{(Granata Material Intelligence)} \qquad (2)$$

where

δ is the deflection in meters,

len is the length of the beam,

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[4] Aluminum foil with a thickness down to 0.003mm was available without support backing at http:www.goodfellowusa.comATin-Foil.html in March 2011.

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E is the Young's modulus, a measure of the stiffness of the material,
I is the second moment of area, the contribution of the cross-sectional shape to stiffness.

Assume len = 120m (we include the optical cable). The force of sunlight at Earth orbit is 9×10^{-6} N and we assume conservatively that the force all along the fiber is equivalent to the solar pressure on a 2 m wide swath[5]. E for optical fiber is 50 GPa (The Engineering Toolbox). I is $\pi r^4/4$ for a circular cross section of radius r. With these assumptions and a 2 mm fiber radius the deflection is 6.2 m, perfectly acceptable. With those parameters and the assumption that the fiber laser is entirely glass, the fiber laser will weigh roughly 25 g/m assuming a two ton/m^3 density of glass.

If we assume an average of a meter of optical fiber (fiber laser or optical cable) for every square meter of sail and a 2 mm cross-section for the fiber, we get 25 g/m^2 of sail for the fiber. Including the thermal radiators and making a conservative estimate by ignoring the fact that the last 20 m of the fibers are optical cable with minimal cooling requirements, this gives us 32 g/m^2 of sail for the infra-red system including 7 g/m^2 for cooling radiators. Combined with the mass of the thin-film solar cells (45g/m^2) we have 77 g/m^2 of sail for power collection and beam creation, leaving 23 g/m^2 of our 100 g/m^2 mass budget for all other spacecraft systems, or roughly one ton for a 120 m radius circular sail. Most of this mass may be needed for mechanical systems, mirrors to direct the beam to Earth, and orbit maintenance hardware, but this analysis must wait for the next paper.

More accurate and detailed design is necessary to validate this approach, but the calculations suggest that by adopting fiber lasers for the beam generation technology we can eliminate sail rotation. There may be better (lower mass) approaches as well. Eliminating the rotation simplifies operations and vastly reduces the complexity of the system to direct the beam to Earth, which need not be despun. It may be also possible to drive sail deployment with the force of coiled laser fibers as well, but this will probably require zero-g experimentation to determine.

It should be noted that fabrication of the proposed sail will be quite challenging. The sunward side is covered with thin-film solar cells and the electronics to distribute power to the closest pumping laser. The shadowed side attaches to the fiber lasers, including the pumping lasers, and their heat sinks. All of this must be rolled up, launched, deployed in orbit and operate in the space environment. Furthermore, the sail is very large so manufacturing must be efficient and testing will be difficult.

A One-Launch PowerSat

A simple spreadsheet was developed to see how capable a PowerSat could be if launched with a single vehicle, given optimistic but reasonable assumptions for performance following a reasonably-sized precursor program of research and development. The Falcon 9 launch vehicle was chosen because prices are readily available. According to the SpaceX website in early 2011, a Falcon 9 can deliver 4.54 tons to Geosynchronous Transfer Orbit (GTO) for around $56 million (Space Exploration Technologies Corporation). This assumes that the satellite can fly the rest of the way to

[5] The actual width of the swath of sail attached to each fiber is two meters at the outer edge of the sail tapering off to zero at the center.

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its final orbit. Assuming around 6.2 MW can be delivered to the grid, this works out to around $9/w capacity for the launch vehicle, which is less than nuclear construction costs[6]. A few years ago SpaceX was willing to reduce launch prices by a factor of 3.6 for orders of 1,000 launches (Globus, In Defense of Space Solar Power, 2009). At 6.2 MW per system, 1,000 launches would generate 6.2 GW. This is a very small fraction of global electrical demand. If the launch discount is still available and the PowerSat and ground system are within a factor of about four of launch costs, then PowerSats deployment may be cost-competitive with nuclear power construction. Operations should be much less expensive as there is no fuel or waste and there are no catastrophic failure modes comparable to those that drive nuclear power costs.

Looking from another angle, assume a mass target of 100 g/m^2, which at 45 g/m^2 for the thin-film solar cells and 32 g/m^2 for the fiber lasers leaves about on ton for all other systems. This leads to a circular PowerSat 120m radius. Assuming 10% sunlight-to-grid-power efficiency this system would deliver roughly 6.2 MW to the grid. Achieving this efficiency will certainly be challenging. Current and target efficiencies are:

System	'Current' efficiency (%)	Target (%)
Thin film solar cells	19.2 (lab)	35
Fiber lasers	30 (commercial)	60
Beam combining	90 (lab)	95
Transmission	90 (judging from figure 2)	90
Ground receiver	42 (lab) 92 (simulation)	60
Total efficiency	1.9	10.7

This suggests something resembling the current state of the overall sunlight-to-grid efficiency is a little less than 2%, or 1.2 MW for a 120 m radius PowerSat. If the targets can be reached, efficiency is around 10%, or 6.2 MW for the target PowerSat. While these targets are challenging, they do not require the multiple-orders-of-magnitude improvement SSP opponents claim is necessary.

Furthermore, even at 2% sunlight-to-base-load efficiency, at 100 g/m^2 the system is less than 4 kg/kw, well below the 5 kg/kw target proposed by Fetter, a major SSP critic, and assumed to be well-nigh impossible (Fetter, 2004). If 10% efficiency can be achieved we get 0.72 kg/kw. There is a long, dismal history of incorrect technical predictions of impossibility. The anti-SSP predictions could well be added in the reasonably near future.

Recently, SpaceX has announced the Falcon Heavy, a larger vehicle with roughly five times the payload capacity of the Falcon 9 to LEO (53 vs. 10.4 tons) at only double the cost per launch ($125 vs. $56 million). One could take advantage of this additional capacity to build a larger PowerSat, but then the sail would have a 271 m radius. To avoid rotation would require then thicker, more massive fiber lasers or some other system to avoid excessive bending under solar pressure.

[6] Considering only nuclear power plant construction, costs are near $10/w. This does not include fuel, insurance, operations, waste storage, or decommissioning.

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Alternately, one could launch five of the target satellites together for only twice the cost. For this analysis, we will assume the latter.

Potential Customers

It is clear that the proposed SSP system cannot compete financially with current U.S. base load power providers, which charge perhaps $0.05−0.1/kwh. Thus, to be economically viable, our system must exploit niche markets that are willing to pay significantly more. There are at least three candidates[7]:

1. A recent DOD report (Rouge, 2007) suggests that the U.S. military is willing to pay at least $1/kwh for power beamed to forward bases in Asia. Trucks transporting diesel can be ambushed, power beams cannot. Football-field sized receivers could fit on the larger bases. Five 6.2 MW systems at this price could provide up to $270 million per year revenue for five PowerSats, enough to pay for a Falcon Heavy launch in less than six months.

2. For commercial customers, the highest price this author could find world-wide was $0.29/kwh for industrial users in Italy in 2008. This could provide up to $75 million per year for five PowerSats – requiring a year and a half to pay for a Falcon Heavy launch.

3. There are many remote locations that depend on diesel generation for electricity. The highest priced diesel fuel by country appears to be Malawi, at 1.67/liter[8]. Assuming 0.25 liters/kwh, this is $0.42/kwh, meaning the target PowerSat could provide up to $110 million per year Falcon Heavy launch, requiring a year to pay for launch. There may be places smaller than whole countries that pay even higher rates for diesel. For example, diesel fuel in Antarctica costs $3.17/liter or more (National Renewable Enerergy Laboratory). This works out to as much as $0.79/kwh. Unfortunately, orbital constraints make SSP in Antarctica impractical. The recent increases in oil prices are not included in these figures. These and likely future crude oil price increases will, of course, only improve SSP financial viability.

Of course the cost of the satellite, ground station and operations are unknown, so the payback times can be expected to be quite a bit longer. Still, this is not a system that is many orders of magnitude from feasibility. Furthermore, one can expect that as more PowerSats are built manufacturing costs should drop dramatically.

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[7] Costs are for the years to pay for the launch, not for the entire system. This is because we know the cost of the launch and it is too early to make a sensible estimate of the cost of satellite construction, ground receiver construction, and operations. Estimating cost would be difficult, time consuming, and very inaccurate. At this point, time is better spent reducing mass, increasing efficiency, simplifying the system and completing the design.

[8] Diesel costs per country may be found, at least in March 2011, at http://www.gtz.de/de/dokumente/gtz2009-en-ifp-part-1.pdf

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FUTURE WORK

There is a great deal of future work to do: completing preliminary design, improving component and subsystem performance, and determining the highest-priced electrical energy markets worldwide. Specific tasks include:

1. Design a mirror system to direct the power beam to Earth. It appears this will not need to be despun. However, it must take power beams coming from a 360 degree circle, combine them and redirect the resulting beam to the receiver on Earth. This direction will rotate a full 360 degrees each day relative to the sail, which must face the Sun.
2. Search the world for the remote locations requiring power and determine the cost of diesel fuel delivered there.
3. Develop higher efficiency, higher temperature fiber lasers.
4. Work out the details of the heat radiators for fiber lasers.
5. Improve the efficiency of all parts of the system.
6. Find a way to add stiffness to the sail with less of a mass penalty than simply making the fiber lasers thick. This is particularly important for larger PowerSats because a Falcon Heavy can launch one 271 m radius system.
7. Manufacture pieces of the sail.
8. Study sail packing and deployment. In particular, ground test sail deployment feasibility using optical fiber stiffness as the driving force. For very small sails, this could be accomplished in parabolic-flight aircraft.
9. Perform safety and environmental analysis.

SUMMARY

Although critics have suggested that SSP is multiple orders-of-magnitude from profitability, this does not seem to be the case. Specifically, given a relatively modest precursor R&D program, infra-red power beaming based on fiber lasers and very light-weight solar power collection based on thin-film solar cells seems to bring single-launch SSP within a small factor of financial feasibility in certain high-energy-price niche markets. It should be noted that fusion power development, which is at least as problematic as SSP, receives $400 million per year from the federal government whereas SSP receives zero. Once a few PowerSats for niche markets have been successfully deployed, prices will drop and additional markets will open up.

There are enormous benefits to successful development of SSP. Specifically, essentially unlimited quantities of clean electric power for billion of years. Furthermore, SSP will most likely be dominated by nations with strong aerospace industries, such as the U.S., rather than those located above large pools of oil. Thus, as there seems to be a reasonable chance of success, a vigorous program to develop SSP is warranted.

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