Towards an Early Profitable PowerSat

Al Globus*

I. Abstract

For initial development of almost anything, small systems are preferred over large for obvious reasons. Unfortunately, development of space solar power (SSP) suffers from the extremely large dimensions and mass[1] of traditional designs making small scale tests and initial operations difficult. So difficult that SSP is perceived to be orders of magnitude away from profitability, requiring new launch vehicles, remote teleoperated assembly, and much else to make financial sense. The physical dimensions of PowerSats are driven by the need for very large antennas for power transmission from geostationary orbit in the microwave band. In addition, the mass is driven by solar collection and conversion hardware, the area, and thus mass, of which is proportional to the power produced. If the antenna must be very large, a small solar collection area makes no sense. This paper examines three technologies:

1. Power transmission in one of the atmospheric windows near $1-2\mu$, reducing the minimum product of the power transmission emitter and receiver radius by a factor of up to 120,000 over traditional designs.[1]
2. Thin-film solar-to-electric conversion systems that can be made in large sheets, rolled up, launched, unrolled, and function in the space environment.
3. Heliogyro design for PowerSats, eliminating most of the structural mass associated with energy collection.

If developed, these technologies could enable substantial reduction of the size and mass of PowerSats and, perhaps, spark development of a profitable industry.

While there are substantial uncertainties and many unknowns, reasonable assumptions regarding improvements in these areas suggest that it may be possible to deploy a $5MW$ operational SSP system with a single launch of an existing vehicle. Furthermore, it may be possible to pay for this launch within one or a few years by selling power in high-priced niche markets.

II. Introduction

Successful development of space solar power (SSP, aka SBSP) would provide vast quantities of clean electrical power for the next few billion years. Such a prize is worth considerable effort and risk. However, the technical difficulties and the huge scale of proposed systems, requiring enormous up front costs and long development times, have prevented SSP from making much progress. If a way could be found to field a small SSP system profitably, even if limited to niche markets, operational progress could be made with relatively small investments over short time scales. This paper suggests one such path.

A. IR Power Beaming

Unavoidable beam spreading limits efficient transmission of power in the microwave from Geostationary Orbit (GEO) to Earth to kilometer scale on-orbit antennas,[1] regardless of power levels. For example, the 1978 DOE reference design[1] featured $2.45GHz$ $(12.2cm)$ transmission with a $1km$ diameter on-orbit antenna and a $10km$ diameter ground antenna to achieve an estimated 63% efficiency. Such large on-orbit antennas make small PowerSats impractical, thus requiring many launches and on-orbit assembly.

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*San Jose State University Research Foundation

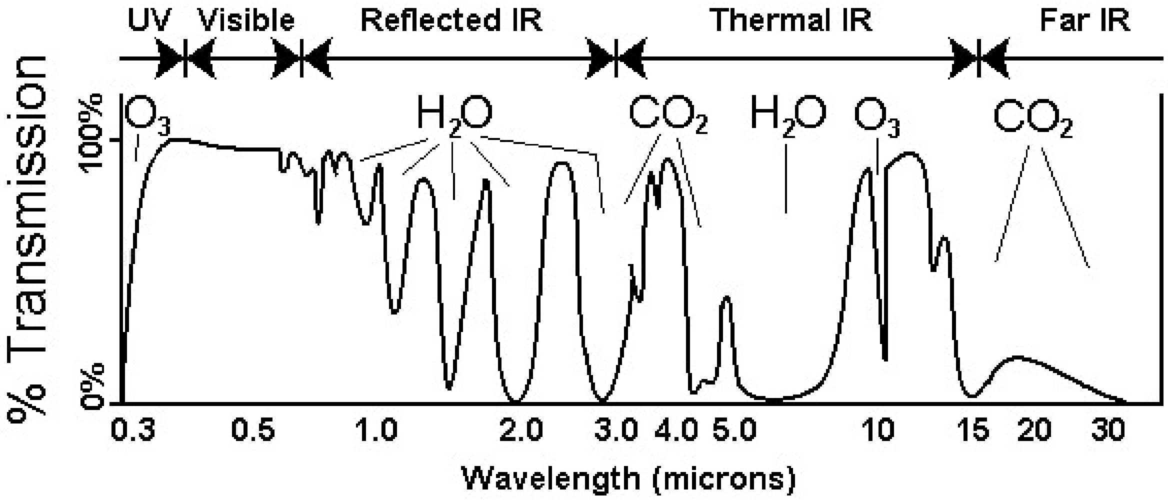

Figure 1. Atmospheric windows for power transmission in the micron range. Notice the narrow bands of high transmissivity near one micron.

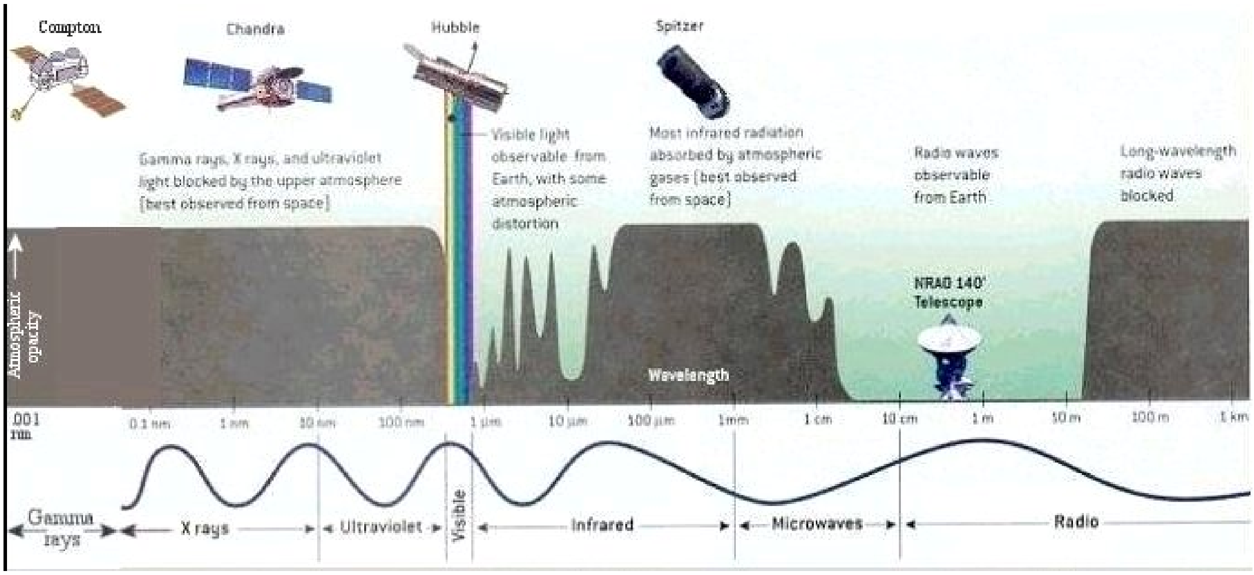

Figure 2. Atmospheric absorption of power over many wavelengths. Notice the depth of the transmission windows around $12cm$ vs 1μ.

However, the product of the sending and receiving system minimum diameters is linearly dependent on wavelength. There are narrow transmission windows in the atmosphere at around $1-2\mu$ which, if exploited, could reduce the minimum antenna diameter product by a factor of around 60,000-120,000 at the cost of some efficiency. At 1μ this would permit a five meter on-orbit beam transmitting to a minimum $32m$ receiver on the ground. This enables small PowerSats, at the cost of much higher beam density and associated problems. Assuming the best conversion efficiencies demonstrated in the lab, for a $5MW$-to-the-grid facility with a beam at 10x the power of sunlight the receiver must be about $45m$ in diameter. Also, 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.

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 $500w$ at 0.808μ 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% could be achieved today and perhaps 40% with near-term technology.[2]

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. As lasers produce energy at essentially one wavelength, it should be possible to develop high efficiency 'solar' cells to convert this laser light back to electricity. The low efficiency of conventional solar cells is in part due to the difficulty of capturing energy at many wavelengths. 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. While this is less than the 63% estimated for microwaves, massive reduction in system size provides ample compensation.

B. Thin-Film HelioGyro

Heliogyros are solar sails where the sail is stabilized and shaped by rotation rather than structure, leading to very light-weight designs. A heliogyro was a finalist in the JPL competition for a mission to Halley's Comet. It was narrowly defeated by a solar-electric system, and the whole mission was subsequently cancelled. The Halley's comet heliogyro was a solar sail, whereas we are interested in power production. 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. The JPL design was a spin-stabilized craft with a central core attached to many blades of thin-film material with stays to maintain shape. The blades were to be kept normal to the sun by rotation-related forces which replaced the structural mass of traditional designs. Blades could be turned to control spacecraft pointing.[3] Blades were rolled up to fit within a launch vehicle fairing and unrolled on orbit, a significantly simpler and less error-prone deployment than other solar sail designs.

An integrated in-space test of a heliogyro with thin-film solar power has been successfully conducted by the Japanese Ikaros satellite.[4] Launched on 21 May 2010, Ikaros is a solar sail currently en route to Venus. The $14m$ on-a-side square sail is made of four triangular blades spin-stabilized at $1-2rpm$. 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 $0.0075mm$ and the solar cells $0.025mm$ thick making for an extremely low mass per unit collecting area; assuming density comparable to ground thin-film solar cells[a], perhaps $45g/m^2$ or $0.8kg/kw$. Note that Fetter[5] in his critique of SSP considered $5kg/kw$ for the whole system a nearly unattainable target. Converting the Ikaros design to a small PowerSat involves simply covering the entire sail area with thin-film solar cells. This would produce about $9.5kw$ on orbit. Power beaming equipment would also be necessary to distribute the energy. The Ikaros satellite cost $16 million and weighs $300kg$ suggesting that such a demonstration satellite might be quite inexpensive by aerospace standards.

III. A One-Launch Operational PowerSat

A simple spreadsheet was developed to see how capable a PowerSat could be if launched with a single vehicle. The Falcon 9 was chosen because the prices are readily available. According to the SpaceX website,

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[a] Big Frog Mountain PowerFilm MPT4.8-150 module: length x width $94x77mm$, thickness $0.2mm$, mass $2.9g$.

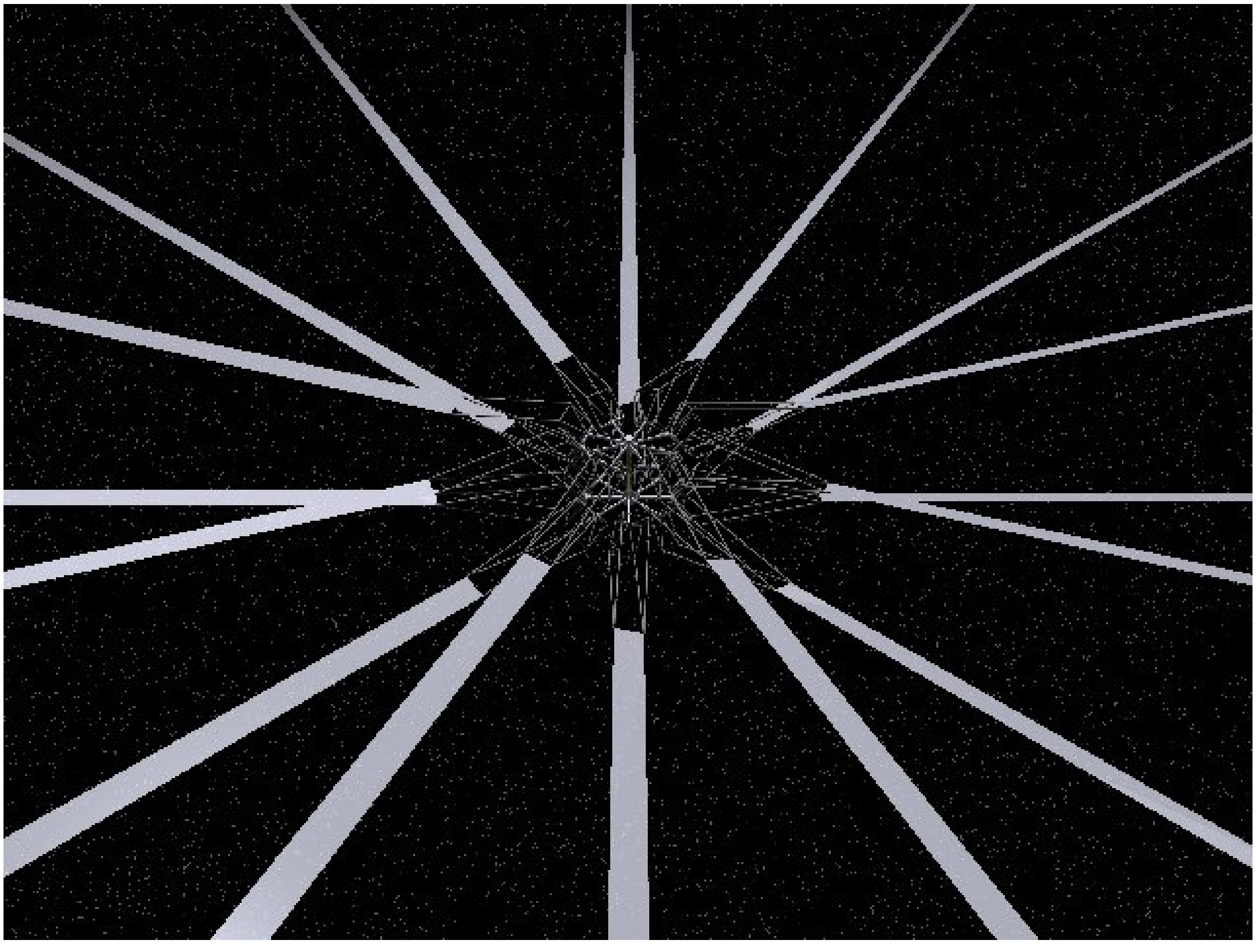

Figure 3. Artist conception of the JPL heliogyro Halley's Comet spacecraft design. Note multiple layers of blades. Image courtesy of CalTech.

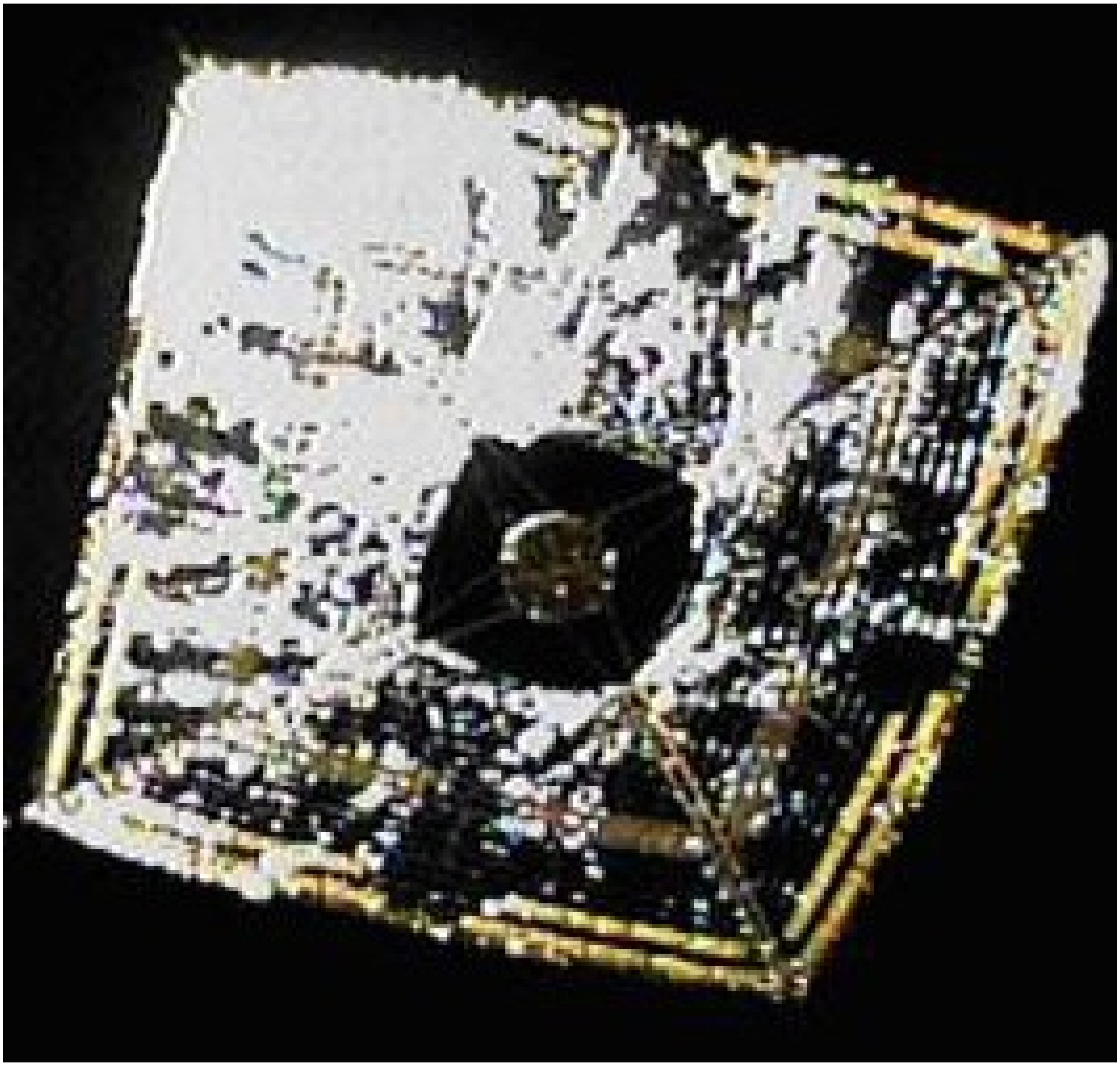

Figure 4. The Ikaros solar sail. Note the inner ring of faintly yellow materials . These are thin-film solar cells. A PowerSat might employ this same design but extend the power production area to the entire sail. The more prominent yellow around the edge of the sail are liquid crystal devices used to control the satellite by electronically changing their reflectivity. Image curtesy of JAXA.

a Falcon 9 can deliver $4.8 tons$ to GTO (Geosynchronous Transfer Orbit) for $56 million. This assumes that the satellite can fly the rest of the way to its final orbit. Assuming around $5MW$ can be delivered to the grid (see below), this works out to around \$11/w capacity for the launch vehicle, which is comparable to nuclear life-cycle costs (near \$14/w). A few years ago, SpaceX was willing to reduce their launch prices by a factor of 3.6 if one ordered 1,000 launches (100 would probably be sufficient to receive the discount). At $5MW$ per system, 1,000 launches would generate $5GW$. This is a very small fraction of global electrical demand. If the launch discount is still available and the PowerSat, ground system, and operations cost within a factor of four of launch costs, then such PowerSats would be cost-competitive with nuclear power.

Looking from another angle, consider a PowerSat launched by a Falcon 9 assuming a mass of $100g/m^2$, which at $45g/m^2$ for the collection area leaves $2.6tons$ for all other systems. This leads to a square PowerSat $210m$ on a side. Assuming 8% sunlight-to-grid-power efficiency (20% solar cell and 40% transmission efficiency) this system would deliver roughly $5.28MW$ to the grid. A recent DOD report[6] suggests that the U.S. military is willing to pay \$1/kwh for power beamed to forward bases in Asia. Trucks transporting diesel can be ambushed, IR power beams cannot, and football-field sized receivers could fit on the larger bases. A $5MW$ system at this price would provide up to \$46 million per year revenue, enough to pay for the launch in a little over a year. 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 deliver up to \$13.4 million per year – requiring a little over three years to pay for the launch.

Of course, there is considerable uncertainty and more than a little optimism in these numbers. However, it is clear that an SSP system based on advanced but reasonably near-term IR power transmission and a thin-film solar cell heliogyro is no more than a factor of a few more expensive than nuclear power, not multiple orders of magnitude from profitability as asserted by Fetter[5] based on traditional designs. Indeed, given the right market one might be able to build a profitable PowerSat in the relatively near future. It is interesting to note that one commercial company, Solaren, has a contract with Pacific Gas and Electric to deliver $200MW$ of space solar power to California beginning in 2016 and their design is based on thin-films.

IV. What Is Not Needed

What is perhaps the most important part of this design is not what the system needs, but rather what it does not need. No new launch vehicle is necessary, although a significantly larger and cheaper one would help. No teleoperated robotic assembly system need be developed. Enormous expanses of land need not be covered with antennas, something roughly the size of a football field may be sufficient. And lest we forget, IR does not interfere with communication systems so no internationally-recognized frequency band need be reserved after lengthy and difficult negotiations with most of the world.

Indeed, deployment of the first operational SSP system might look like a fairly normal space mission: develop the spacecraft, integrate with the launch vehicle, launch, deploy, then send photons to and from the ground.

V. IR Power Beaming Research

Clearly, improvement in infra-red power beaming would greatly benefit the proposed system. The U.S. military is working vigorously to increase the power (Northrop-Grumman recently demonstrated a $100kw$ solid state laser) and generation efficiency (65% achieved, 80% is a near term goal) of lasers, as mentioned in the IR Power Beaming section. DOD has substantial resources and it would be difficult for a small organization such as the Space Studies Institute (SSI) to make a contribution. However, there are areas where relatively small efforts may bear fruit.

First of all, it may be possible to substantially increase the efficiency of converting laser light to electricity. LaserMotive used custom cells provided by Spectrolab of Sylmar CA, a subsidiary of the Boeing Company. The light impinging on the receiver will be nearly a single frequency, so energy conversion should be much easier than for sunlight which is relatively wide-band.

Perhaps the easiest and most profitable research area is system design; which has received very little effort so far. There are a wide variety of issues to be addressed, from efficiency, scalability and reliability to environmental effects and safety that must be considered. The thermal design is particularly important since even at 80% efficiency the lasers will generate a great deal of heat. However, a single brilliant insight can make large improvements and have a substantial impact on the potential profitability of the system.

Such studies, at least at the preliminary level, can be quite inexpensive.

There are a number of environmental and safety factors that require attention. Careful choice of wavelength may reduce danger to the eye, which could be particularly important for a demonstration satellite. It is also possible that a sufficiently strong beam can punch its way through a light cloud cover, making the system applicable to more than just desert areas. Finally, as the beam is much denser than microwave designs, it may heat a column of air producing localized weather effects which must be understood. Again, a preliminary study may be quite inexpensive and appropriate for an organization such as SSI.

VI. Collector Research

The most ambitious pre-operational development would be to build and fly a version of the Ikaros satellite with more area devoted to power production. This could produce about $9kw$, sufficient to prove the technology. The Ikaros satellite is reported to have cost only $16 million, and a second similar satellite should cost far less. Covering the sail with solar cells will increase the cost, as would development and integration of an infra-red laser, optics and the ground system. However, this may be an extremely cost-effective approach to demonstrating SSP. While such a mission is probably well beyond the financial capabilities of SSI, phase A studies may not be.

The Ikaros demonstrated packing and deployment of an operational thin-film solar array $14m$ on a side. It may be that the same techniques will not work well for a $200m$-on-a-side sail. Preliminary studies of various options should be relatively inexpensive.

Finally, the proposed system weighs only $100g/m^2$ and will respond substantially to light pressure from the sun. While this pressure sums to zero over the course of a year, other perturbations, such as lunar gravity, can amplify changes to orbital parameters and cause the system to drift over long periods of time. Preliminary simulations with AGI's Satellite Toolkit suggest that a $100g/m^2$ spacecraft in GEO will oscillate around its initial location and the orbital parameters will drift, but at the end of a year the spacecraft will return to nearly the same orbital parameters it started with, suggesting that minimal stationkeeping fuel will be needed. However, a $20g/m^2$ satellite will become very unstable, with large changes in orbital parameters that do not return after a year. The minimal reasonably-stable mass per unit area is not known. This is a relatively easy study to undertake.

VII. Conclusion

Although critics, such as Fetter,[5] have suggested that SSP is orders-of-magnitute from profitability, this does not seem to be the case. Specifically, using IR power beaming similar to that which won the NASA-sponsored power beaming contest, very light-weight solar power collection based on the Ikaros solar sail heliogyro and thin-film solar cells may bring SSP within a small factor of financial feasibility. Indeed, total system cost may be less than a few times greater than life-time nuclear power cost per watt of installed capacity; and high end markets, such as forward military bases, are willing to pay such high prices for power that profitable space solar power may be within our grasp.

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[2] Kare, J., "personal communication," September 2010.

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