Satellite Communications Class Project:
Space Solar Power

ECE 6390 – Fall 2011

Synopsis:

Your newly-formed SunSat team/"company" will respond to the request for proposal (RFP) at the end of this project description, designing a revolutionary new space solar power system to deliver clean-energy to the earth grid.

Team-Member Assignments:

I will assign teams with 4-5 members each to constitute a "company". Once formed, the teams must elect a team-leader, choose a company name, and submit an 80 x 80 pixel icon for their web link. I expect everyone to contribute to the final design and documentation and will solicit internal rankings of team-member efforts.

System Components:

Due to the multiplicity of talents within each group and the "systems"-nature of the class, *all* aspects of the mission design should be explored in the final proposal. The systems for microwave power transfer should receive the most design focus, but the final project should address all of the following systems:

- SunSat Orbital Parameters – Spacecraft used to collect solar power and transmit it back to earth, including orbit parameters.
- Microwave Power Transfer Hardware – How the energy is harvested, converted to microwave power, and sent back to earth with an antenna dish or array.
- Earth Station Collector Design – Design of the array of energy-harvesting antennas used on earth to collect the power. Clearly calculate the end-to-end conversion efficiency.
- Resiliency of Electronics – Discuss strategies for space-hardening the electronics for the duration of the voyage. Identify the likely points of failure.
- Budget and Timeline – total research and development costs broken into materials, equipment, supplies, people costs, space resources, and other miscellaneous costs. A final estimate of $/kilowatts should be included as a culminating figure of merit for the team design.
- Communications Systems – Design a basic two-way communication link between the Earth collection station and the SunSat to exchange all relevant diagnostic, telemetry, and control information. Choose carrier frequency, bandwidth, antennas, modulation

schemes, and coding schemes with an emphasis on **security** and **anti-jamming** attributes.

This list is not necessarily exhaustive. The level of detail for each system is left up to the groups. However, increased descriptions will enhance the competitiveness of your design. *Verbose* descriptions will degrade the competitiveness of your design.

Deliverables:

You must prepare a concise, well-written technical report detailing your team's design. The report should be in html-format with all files submitted in-class on a CD or through e-mail (e-mail submissions are strongly preferred; they must be ZIPped and are only possible for files less than 20 MB total). Projects must be submitted by noon on Friday, 9 December 2011. Late projects will not be accepted. In addition to the final project files, each group is required to submit a research poster for presentation at the "Georgia Tech 6390 Microwave Power Symposium."

Grading:

Your final proposal will be graded on the technical criteria listed above with principle emphasis on *believable economy*: base scores will be assigned according to the rank of kilowatts/hr, weighted against the rigor and extent of the design. Deductions from these base scores will then be made based on the following areas: Completeness, Technical Writing, Professional Content, Research/References, and Conciseness. Each team member *may* also receive a variable downward adjustment to their individual project scores based on internal rankings of contribution and effort.

Additionally, a portion of the project grade (30%) will be based on peer evaluations. The projects will be placed online and each member of the class will submit an evaluation for each project (other than their own). These individual evaluations will be held confidential; they will also count as a homework assignment. Thus, the projects will be posted online over the weekend and evaluations will be submitted electronically during exam week. Look online for the evaluation sheet.

Distance Learning Student Grading:

Distance-Learning students will perform the same project individually (no groups) with the following changes to the grading/submission scheme: 1) expectation of a much shorter PDF or DOC write-up on your proposed design is expected (no website required), 2) no research poster requirement, and 3) no peer-review component/requirement.

A group of co-located DL students will be required to produce a website report as well as a research poster. There will be no peer-review component. Expectation of effort will be commensurate with group size.

Space Solar Power RFP

No existing U.S. company is prepared to assume the financial risk of initiating construction of a Space Solar Power System. There are too many engineering, financial, regulatory and managerial risks for any utility or aerospace company to undertake SSP today without help. After discussion with a group of large US and international electric utilities and investors, Congress has created a Congressional loan guarantee enabling the SolarMax consortium to contract with a bidder to be selected by the consortium to eventually build Sunsats which will deliver power to rectenna (rectifying antenna) sites around the world. Your company has decided to bid for this large contract to provide Space Solar Power (SSP) to SolarMax's Energy Consortium electric power grids, initiating an SSP system.

The initial group of **eight downlink sites** – half in the US and half in other host nations – has provided detailed contract proposal information to determine the winning bidder. The order of linking to these eight can be selected by the bidder, but all should be completed by Dec 2026. Competitive selection will occur in 2012 based on your group's final proposal. The company SolarMax selects will provide eight SSP downlinks to SolarMax utilities.

Fig. 1. Our standard SunSat design – the Integrated Symmetric Concentrator

Many international companies are working on SSP, dominated by a Japanese consortium with a 2 trillion yen budget. A test satellite is scheduled for 2015, beaming a microwave energy carrier through the ionosphere.

Japanese researchers are targeting a 1-gigawatt system to produce electricity at eight yen (nine cents) per kilowatt-hour, six times cheaper than its current cost in Japan. A successful test would accelerate their goal to put space solar power into practical use by 2025.[i ii iii].

Transmission Efficiency

- **How efficiently, and cost effectively, does your antenna-rectenna pair deliver power to the customer grid?**

A key aspect to a competitive proposal will be the overall efficiency of the microwave generation, collection, and conversion system. Also important: how much power can your company design send to the customer rectenna for input to the grid on earth? What periods of interruption does your company anticipate with your proposed system? In your proposed design, what are the specifications for the large diameter rectenna and transmitter antenna pair, such as beam taper, sidelobe restriction, etc.?

Describe the rationale for choosing the center frequency of operation. Global ISM bands are preferable, such as 2.4 and 5.8 GHz, and a discussion of impact on existing terrestrial wireless users in those bands should be discussed. Also, what might be the environmental effects on atmospheric heating and potential dangers to existing satellites in orbits and aircraft that might happen to pass within the RF beam of the transfer link?

Discuss how much power each rectenna collector site could provide to the grid. The rectenna design in the 1979/1980 “Reference Study”, which used 2.45 GHz, broke up the power from the rectenna into 5 blocks for ease in use by and transmission to nearby markets. Major power plants top out at approximately one Gigawatt recognizing that it may be necessary to replace a unit which trips off line or is scheduled for off line maintenance. (Most unscheduled plant outages are caused by natural phenomena such as trees falling, wind and ice storms, ants, squirrels, etc.)

Lowering Transmitter Mass

What is the total mass of your antenna and Power Management Plan (PMP) for handling the movement of power from the PV array to the transmitter elements?

The cost of SSP is strongly tied to the cost of space transportation. Putting all that hardware (mass) in GEO is the most frequently cited obstacle to SSP construction. Reducing the mass to GEO is essential to reducing SSP construction costs.

The cost of space transportation depends on the launch rate, like typical technology "learning curves", from microwave ovens to Schottky diodes. Photovoltaics (PV), for example, another key SSP technology, follows such a curve (below).

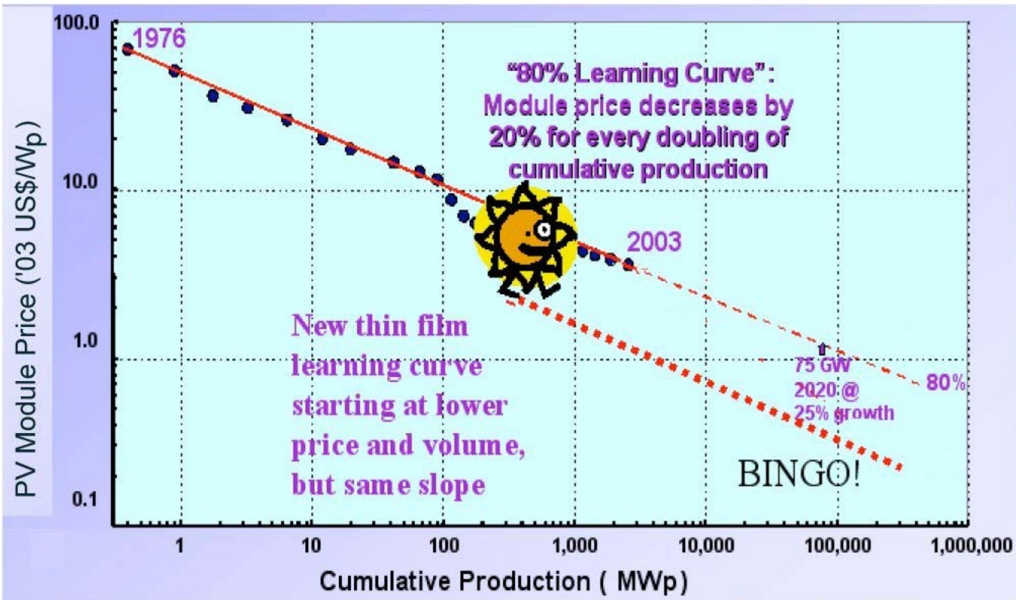

Fig. 2. Source: Ken Zweibel, NREL

Thin-film PV is one hundredth as thick as regular crystalline PV, and therefore much lighter. Space qualified thin-film cells in the lab today can provide 16.8 Kwatts/Kg - specifications more than adequate to begin SSP design and construction. The raw efficiency number is less important.

Your photovoltaics array provides 10 Gigawatts output - 5 Gigawatts each from two PV arrays each 3 km across (see Figure 3). You must distribute this power to your SSP transmitter elements to maximize the efficiency of moving that power to your customers' power grid on Earth. Your company's wiring plan is an important part of lowering transmitter mass, a critical SSP planning criterion.

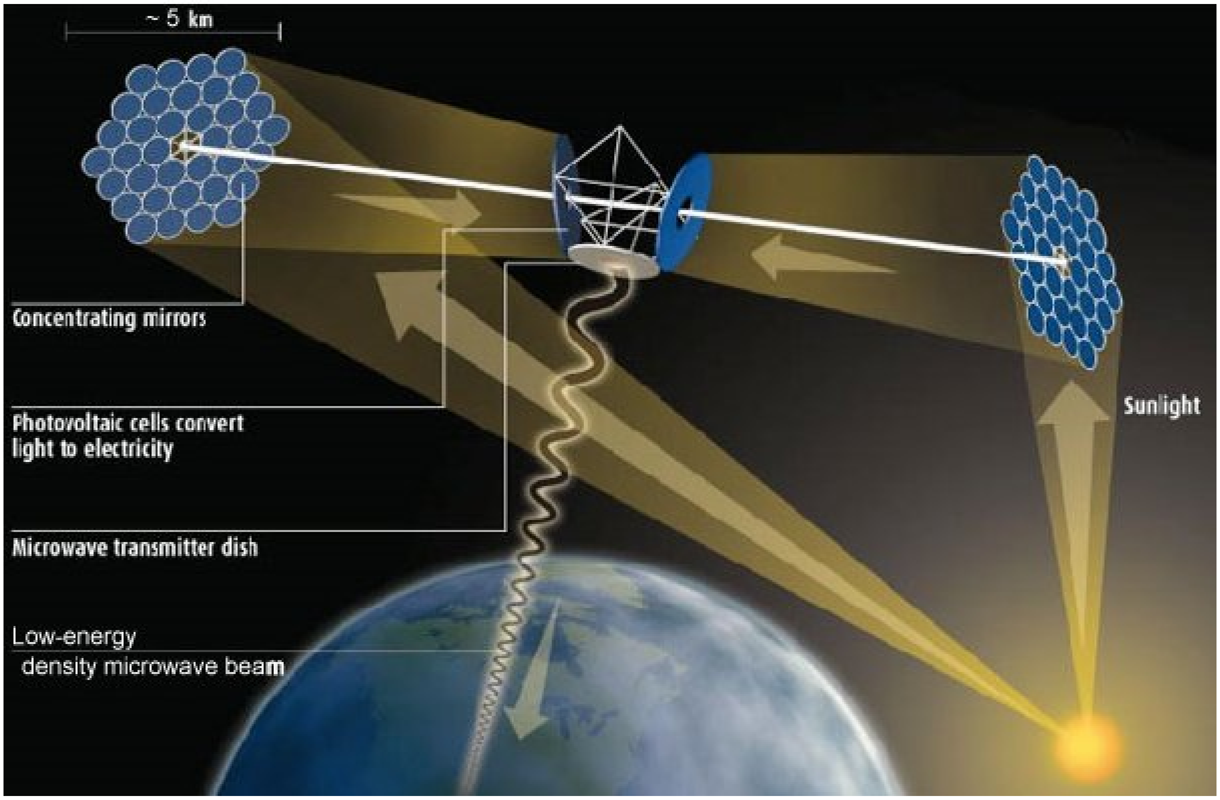

Fig. 3: Integrated Symmetrical Concentrator Concept

Some of your cabling may be SuperConducting (SC) ribbon, which may carry about 100 times as much power per kilogram of weight as the standard aluminum alloy (AL) ribbon power cabling. Superconducting applications include MRI and electric power transmission cable.

SC cabling must be kept in the suns shadow. Cable exposed to direct sunshine will rapidly exceed its normal liquid-nitrogen-temperature-limit. All cabling, including SC ribbon cabling, should be wide enough to tolerate random 2 mm micrometeorite hit during its 50 year lifetime, so it must be wider than 2 mm.

Spaceflight is not intrinsically expensive. The energy to put a pound in Low Earth orbit (LEO) is about 5.5 kWh. At U.S. residential electricity prices, the cost of enough energy to place a pound in LEO would be less than 60 cents. The reason that launch to orbit is currently so expensive is that launches are infrequent and because launch vehicles are thrown away after one use.

Speaking Aug. 2, 2011 at the AIAA/AMSE/SAE/ASEE Joint Propulsion Conference in San Diego, Elon Musk, CEO of SpaceX, talked about his plan to get launch costs to $50 to $100 per pound by making the Falcon 9 Heavy fully reusable. Elon has previously indicated that Spacex will make the Falcon 9 first stage reusable on flight five, in late 2012 or 2013.

The launch vehicles available now, Fall 2011, we will call Generation 1. Generation 2 vehicles will be available five years after they are contracted for by your company. Generation 2 vehicles can deliver freight to a GEO-transfer orbit at $100/lb at flight rates above 3162 flights per year. Ion drive tugs have been suggested for final delivery to GSO. As higher launch rates demand them, generation 3 will follow a curve like the one shown on the graph. Generation 3 system vehicles can be contracted for delivery five years after Generation 2 vehicles exceed above 3162 flights per year. The family of generation curves follows a straight line, as other learning curves do on log-log graphs.

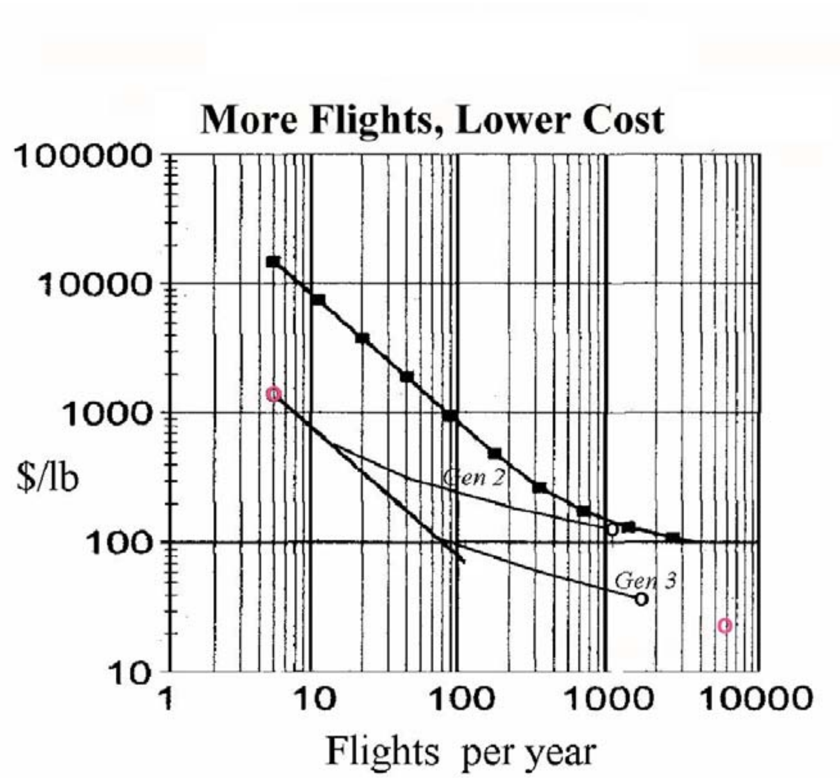

Fig. 4. Learning curve for lowering flight costs, showing RLV Generation families

Delivery to Customer Earth Station

Your bid must provide a downlink to all eight of the SMEC members by July 2025 and an additional eight sites by July 2028 following the same price curve you establish with the first eight. The long term plan is to have half the world's electric power come from SSP by an early date. Use Nov 2011 IEA forecasts for global electric power generation. At a microwave frequencies, arid regions are preferred rectenna sites. The list (in random order) of required connections, with corresponding target wholesale prices delivered to the rectenna downlink sites, are:

1. West Virginia Mountaintop site for PJM Interconnection - 19¢ per kWh. 39 degrees North Latitude.
2. South Texas site for ERCOT Interconnect - 11¢ per kWh. 27 degrees North Latitude.
3. SouthEastern Power Administration(SEPA) Interconnect in South Georgia - 12¢ per kWh. 31 degrees North Latitude.
4. Northern Mexico (Baja California Norte) site for CAISO Interconnect - - 20¢ per kWh. 31 degrees North Latitude.
5. Colombia, Ecuador, Peru Interconnect - 11¢ per kWh. 2 degrees South Latitude.
6. Japan - 22¢ per kWh. 31 degrees North Latitude.
7. Central European feed. - 26¢ per kWh. 40 degrees North Latitude.
8. Myanmar(Burma) site for China (Southern Power Grid) and India - 11¢ per kWh. 25 degrees North Latitude.

For the purposes of this study, these eight listed wholesale base prices will determine the contracted delivery price per kWh during the first six years. If the initial price is 20¢/kWh, then during the next six years the delivery price will be reduced by 10%, then 9%, 8%, 7%, 6% and 5% lower than the initial wholesale base price. E.g.:

1st year after (7th year) = 18¢/kWh

2nd year after (8th year) = 16.38¢/kWh

3rd year after (9th year) = 15.07¢/kWh

4th year after (10th year) = 14.01¢/kWh

5th year after (11th year) = 13.17¢/kWh

6th year after (12th year & thereafter) = 12.52¢/kWh [iv]

A sample draft budget will be provided which should be updated by your company. Rectenna final costs are assumed to be 10% higher than the antenna electronics alone, due to grounding, Aeolian damping, supports, and other site prep costs, which need not be considered in this project.

Note: The size of the rectenna is determined primarily by how efficient you want (and can afford) the power transfer to be. Once built, a rectenna of high efficiency can handle a large power range, primarily determined by applicable environmental regulations, including interference with cell and emergency communications devices. The transfer efficiency from the transmitter to rectenna is a key to making SSP economic.

Solarmax utilities will build and own the rectenna system that converts delivered energy into usable power on their grid, which is also physically part of *their* transmission system hardware. Rectenna design consultation is provided by your company. Local ownership ensures a major financial commitment from the end users, a commitment that would be about $1 Billion for a typical 5 GW rectenna installation, actually producing five outputs of about 1 GW each. The precise output would depend on the lead utility (customer) operational transmission needs, since more than one utility may contract for rectenna output.

Endnotes

[i] S. Sato and Y. Okada. (2009, Nov. 9). Mitsubishi, IHI to Join $21 Bln Space Solar Project (Update1). http://www.bloomberg.com/apps/news?pid=20601101&sid=aJ529lsdk9HI

[ii] K. Poupee. (2009 Nov. 8). Japan eyes solar station in space as new energy source(AFP). PHYSORG.com. http://www.physorg.com/news176879161.html

[iii] Space-based solar power set for first test, (2011 Jan 23) The Yomiuri Shimbun http://www.yomiuri.co.jp/dy/business/T110122002679.htm

[iv] Global electricity price comparisons - various sources and estimates of initial SSP premium.