Experimental Aerodynamics and Concepts Group
Daniel Guggenheim School of Aerospace Engineering
Georgia Institute of Technology
Atlanta GA 30332-0150

Project Document

SPACE POWER GRID

Spring 2011

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Dr. Narayanan Komerath
Brendan Dessanti, Nicholas Picon, Shaan Shah, Carlos Rios

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SPG Project Schedule

SPG Schedule		
Week	Date	Item
1	1/10/11	Start of Spring Semester
2	1/17/11	Enter SunSat Design Competition
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5	2/7/11	
6	2/14/11	
7	2/21/11	
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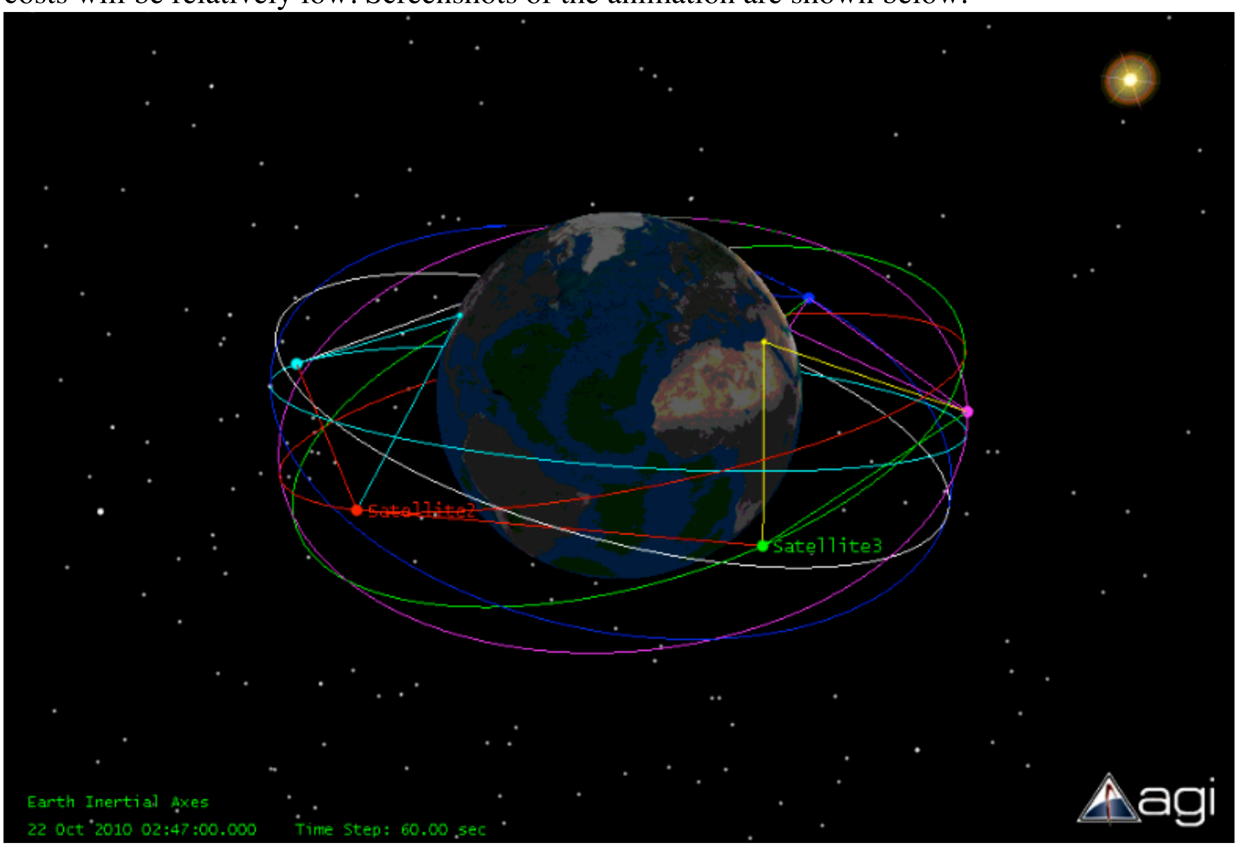
16	4/25/11	
17	5/2/11	End of Spring Semester
18	5/9/11	
19	5/16/11	ISDC Conference May 18-22
20	5/23/11	
21	5/30/11	
22	6/6/11	
23	6/13/11	

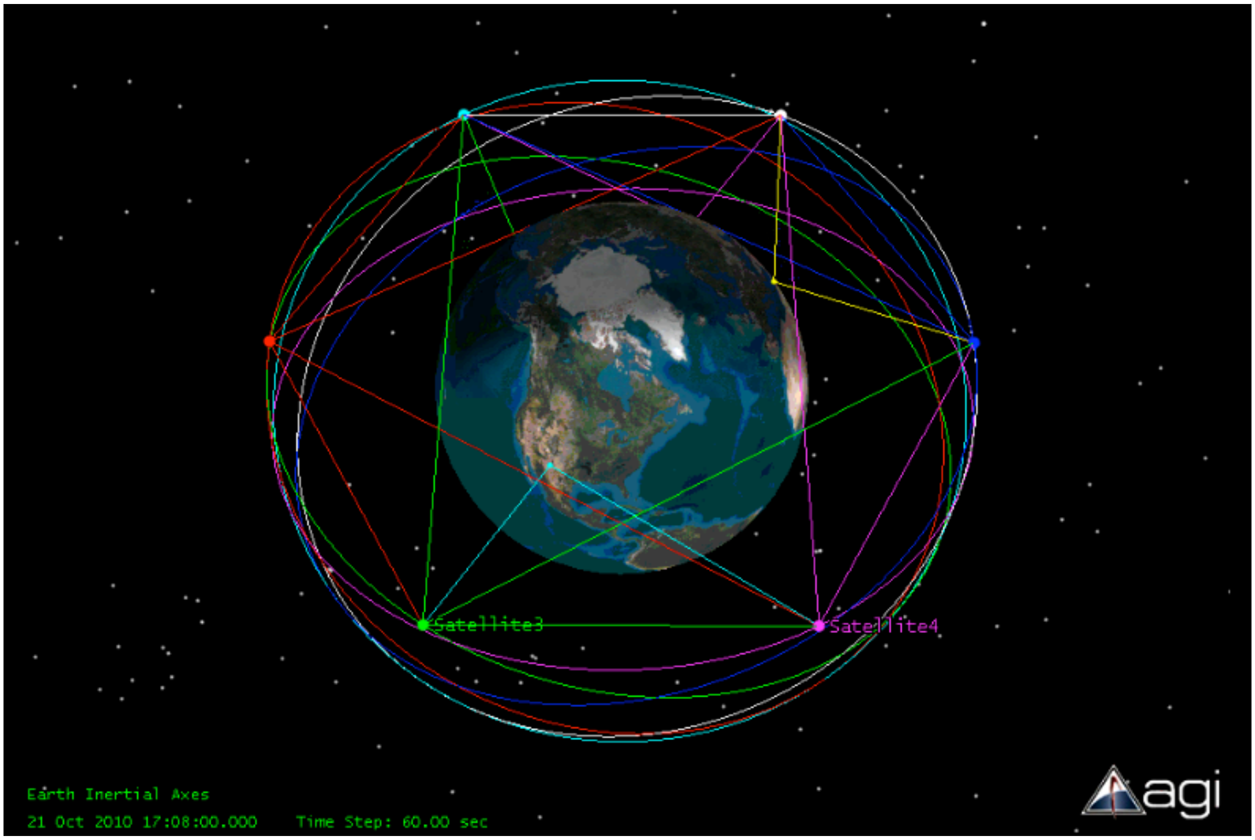
STK Demonstration Models

4 Facility Model

A demonstration model has been created in STK using six satellites and four facilities. The satellites have a near equatorial orbit with an inclination of 15 degrees. The six satellites are at an altitude of 5500 km above Earth and have evenly spaced right ascension of the ascending nodes. Using the four facilities in our demonstration, United States (New Mexico, near Las Cruces), India (near Mumbai), Egypt (near Cairo), Australia (Western Australia) this model provides 24 hour continuous beaming to all plants. This orbit was chosen because the satellites never drop "too low" on ground path to be seen by our chosen demonstration model facilities. The satellites are connected to each other continuously and at the same angle, meaning no pointing is necessary for continuous space to space beaming. The low inclination angle that is relatively close to the latitude at the launch site (Cape Canaveral, FL) means that delta-v launch costs will be relatively low. Screenshots of the animation are shown below:

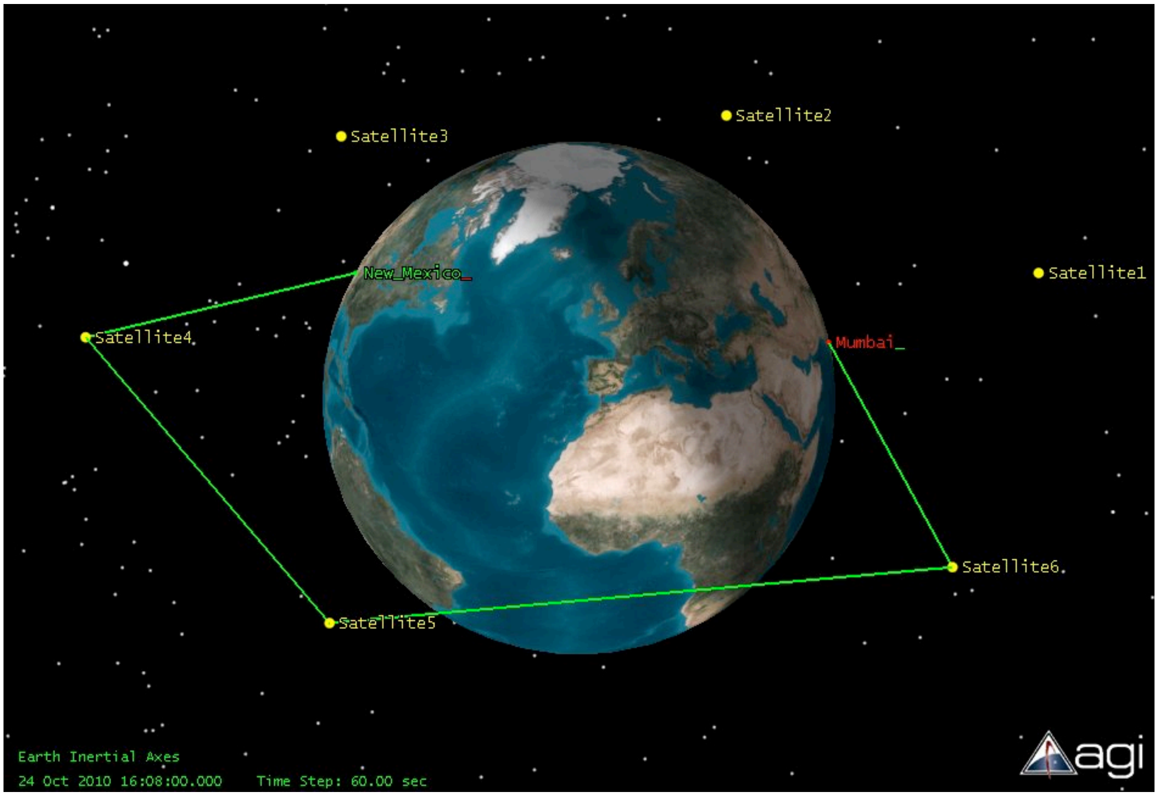


And an overhead view is shown below:



US-India Model

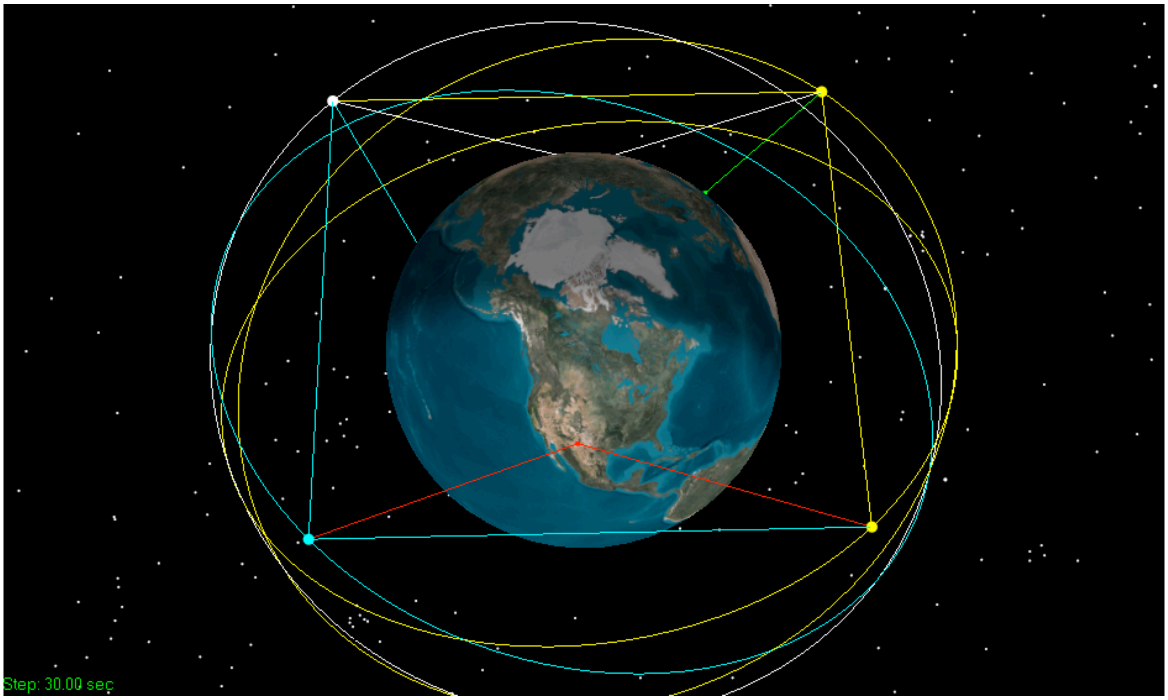
The demonstration model has been reduced to a two facility US-India model. Our model has essentially 24 hour continuous beaming, with a very small period of downtime that results because the two plants are not on exactly opposite sides of the Earth. Beaming in green represents New Mexico beaming to Mumbai; beaming in red represents Mumbai beaming to New Mexico. The model also has short periods of downtime that exist when the system is transferring from one 3 satellite chain to another.



Snapshot of Space to Space Beaming in US-India Demonstration Model

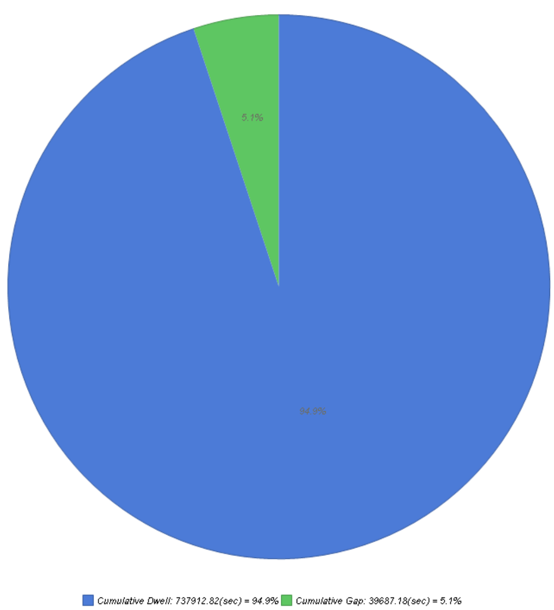
Other variations of the US-India Model have been looked at. Using a 3 satellite configuration at the current altitude (5500 km), there was very little time for beaming. Even extending the 3 satellites to 10000 km didn't give us very much time where it was just one satellite to another satellite and back to Earth beaming. I also looked at a 6-satellite configuration at 10000 km and as can be seen in the animation included, it doesn't have the gaps that the 5500 km version has when switching between satellites, in fact there is some overlap where you only need to do one satellite to another satellite and back to Earth. Therefore, the ideal altitude is somewhere between 5500 and 10000 km.

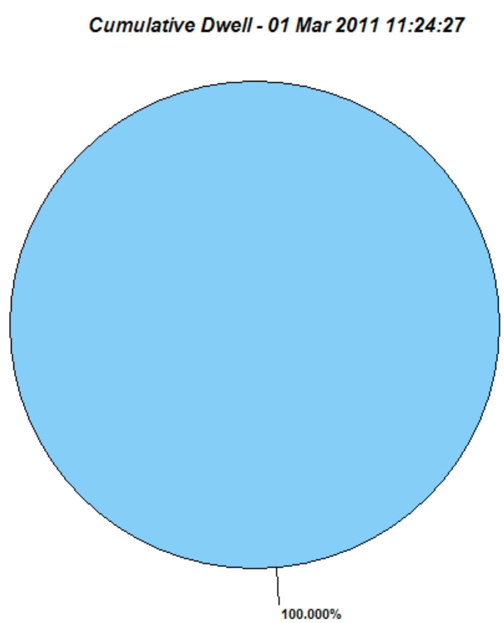
We have reduced our model to a 4 satellite model shown below. We can maintain almost complete 24 hour coverage with the 4 satellite model. A snapshot of the 4 satellite model is included below:



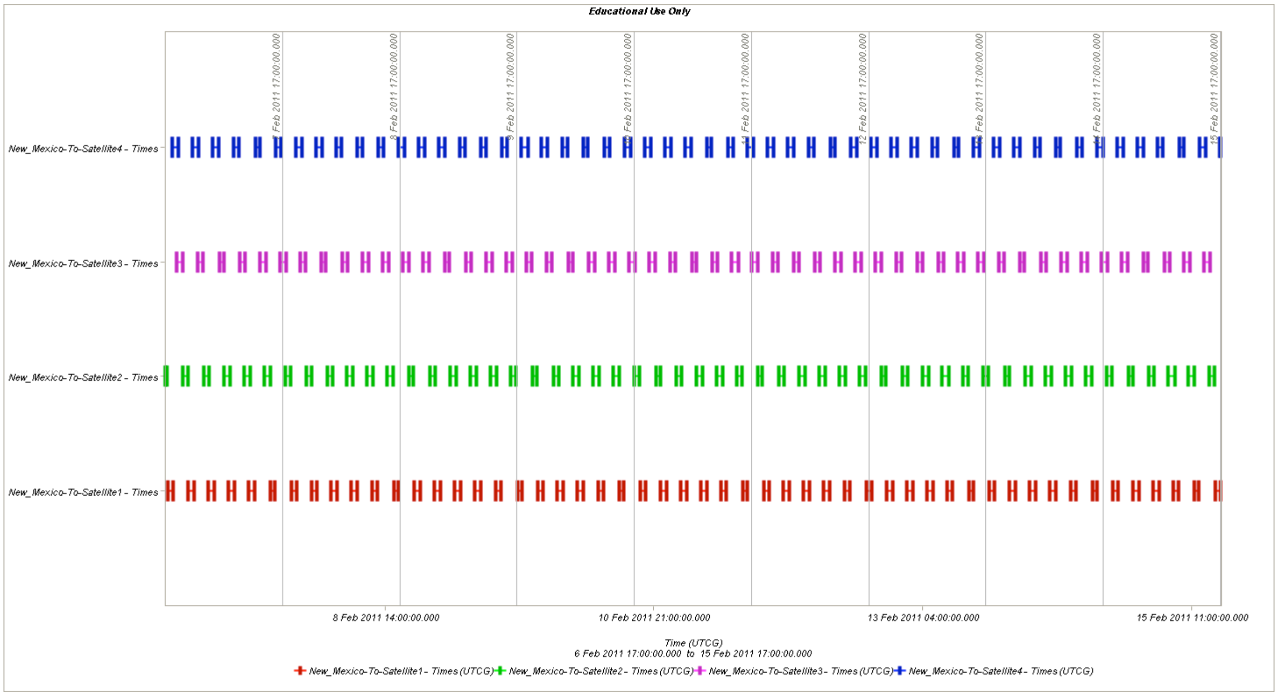
Demonstration Model Updates (3/7/11):

Charts have been created to show the amount of time each facility is capable of receiving beamed energy. The 6 satellite, 2 facility model has continuous 100% beaming. The 4 satellite, 4 facility model has continuous 100% beaming for inclinations between 0-6 degree inclination. As a result, the inclination of our orbits in our model has been changed to equatorial. At 15 degree inclination, the New Mexico plant could receive beamed energy about 95% of the time. The pie charts below show the improvement in coverage time that comes with a smaller inclination. The graph on the left is for the New Mexico Facility at 15 degree inclination, and the one on the right is also for the New Mexico Facility but at 6 degree inclination.





The graph below is another representation of the satellite coverage times for New Mexico at 15 degrees. Each line represents one satellite's communication with the facility in intervals.



Summary of what we are trying to do in this area

(Taken from an email sent to the organizers of one of several Space Solar Power Workshops)

Our contribution has been to see how to synergize the many competing interests related to SSP. I will list our findings (most of them obvious to who have been thinking of SSP for much longer than I have).

1. The $300B "Cost to First Power" cited for the GEO-based SSP architecture, is based on NASA's $100/lb-to-LEO promise claimed to get Congressional funding for the Space Shuttle back in the 1960s. An optimistic estimate today would be 10 to 30 times that, depending on one's view of the present US space program cost estimation assumptions. This is not a realistic request to pose as a good use of tax dollars.

2. The primary logical obstacle in the above is the choice of GEO, which in turn drives choice of tropical receiver locations, frequent rain and clouds, choice of frequencies below 10GHz (Note: water molecules are excited in vibration by ~10GHz waves, which is what makes microwave ovens work for cooking), the attendant massive receivers and transmitters, highly concentrated receiver locations (again driving the <10GHz choice), massive terrestrial grid architecture needed for distribution, and finally, the reality that not a single dollar of power revenue will come out of it until most of the infrastructure is working. For instance I learned that nuclear plant/reactor sizes (400MW vs. 1GW) are not driven by reactor technology in much of the world - they are driven by grid capacity.

3. The second logical obstacle is that SSP focuses on the "Space" part (yes, that's what interests me too) and immediately gets attacked by all the proponents of terrestrial solar, and Fusion power as alternative candidates for such massive public largesse. SSP is actually free fusion power and radioactive waste disposal courtesy of the Sun, with only the converter/receiver and distribution network needed - but I have heard the "fusion is so better than SSP" argument fiercely articulated by distinguished peer reviewers.

4. The third obstacle is that SSP as articulated by national space agencies again argues for their part of the funding and forgets the other stakeholders. The result is that only government (national tax) funding is seen as a practical source worth fighting for. This is not viable, for the above reasons. It is not that there is no government interest, but until there is massive commercial pull and international enthusiasm, SSP is not viable as a large-scale production source of power.

5. The fourth obstacle is that the Space-based market, which should be lucrative, has been very slow to take off. Recent DARPA initiatives and other things might induce a second look at this.

6. So our solution is to propose a 3-step architecture called Space Power Grid:

6A. **Step 1**: A constellation of Step 1 satellites (starting with 20) in 2000km-high sun-synchronous and a few near-equatorial orbits, will serve as a Space-based relay for power between large renewable power plants on earth. They will generate no power! But they will help solar and wind plants aspire for Baseload Plant status, by removing the need for creating up to

100% (usually fossil-burning) Auxiliary Power generators at each plant. Simply put, when the sun shines in New Mexico we sell power to Siberia or the Sahara - or to South Dakota wind farms, and at night they sell us power through Space.

Ideal locations for large renewable power plants are often high deserts with very rare rainfall. We avoid bad weather transmissions by using the terrestrial grid to set up transmitters at alternative sites, say 100 or 500 miles away if necessary.

We go to 200GHz instead of 5GHz, so that receivers and transmitters are small and do not drive satellite costs. Transmission is less efficient, of course, but the numbers show that we can get to breakeven NPV in 17 years at reasonable internal ROI, selling power to places where there is no 94% efficient power grid and to customers in space. The competing power costs at these locations are far above the $0.10 that US urban residential customers pay at off-peak times. We see breakeven at roughly $0.30 per KWH, with some hope of going down to $0.20. These are in Step 1, with all the power being generated on Earth. With space-based power generation in Step 3, costs should come down dramatically, but then that is what the proponents of fission power argued in the 1950s, so I don’t want to base the whole architecture on that claim.

6B. **Step 2:** As the first constellation (total of about 96 satellites with some 200 power plants participating), nears the end of its useful life, we replace those with larger Step 2 satellites carrying high-intensity converters and large collectors. This is a gradual process, and it gives us 17+x years of technology development to put on these replacement satellites, with a market and infrastructure already in place. X can be very long, essentially until we think of better ways.

6C. **Step 3:** Along with the collector/converter satellites, we launch some very large, ultralight, pointable solar collectors/mirrors, to MEO or higher. These would collect and focus full-spectrum sunlight on to the collectors with high-intensity converters in LEO. For instance, the collectors in MEO/GEO would collect 1 sun intensity, and turn that to say 10suns on the collectors in LEO, which in turn focus 300 suns or more on the high-intensity converters.

This process keeps expanding.

Even with this, to double current terrestrial primary energy supply would take a very large area of MEO collectors and many LEO satellites (saturating public acceptance and driving concerns about LEO traffic clutter), and cost (much) upwards of $150B by today's NASA/Air Force cost estimation. But this is an incremental, distributed investment into a viable market, as opposed to tax dollars put in by Congressional mandate. The expansion would proceed per market demand.

It is not feasible in an email to list all the arguments for and against various aspects, so for those I would have to suggest reading our papers, as my thinking (and bruises from presenting these at conferences to SSP experts) evolved. We have considered optimal power level per satellite, thermal management, annual rain/cloud data at viable plant locations, choice of frequency, conversion technologies, phase array transmitters, etc. etc. along with financial issues such as the UNFCCC, Carbon Market, consortium funding ROI expectations, and the effect and timing of public funds on the overall results. It turns out that there is little need or benefit from taxpayer funding beyond the initial development period - unless power costs worldwide somehow collapse in the next 10 years. The drive from military applications can of course help solve several of the development issues.

Our approach is to put all these into a single calculation stream going from frequency choice to an NPV vs. year chart, and we continue to refine and expand the capabilities of this calculation as we learn more.

There are of course many alternative paths to development, but these (so far) generally fit well with one or other aspect of the 2-step SPG architecture. This is not surprising because the architecture aims to include all developments as positive supporting advances, not as competitors. There are also several research areas opened up by this application, most going far beyond what my team can or should attempt by ourselves.

Last but not least, I am aware of the projection developed at your Workshop some years ago that massive demand for repetitive launch to GEO would bring the launch cost down by an order of magnitude. My take is that this can happen, given the other infrastructure developments and market guarantees that result from the SPG architecture. For starters, there has to be a more specific cost estimation database for repetitive, identical launches with a large production run, unlike today's databases of small-lot , large-interval satellite launches. We have not included such breakthroughs in our cost estimates so far.

Our papers include:

[1] Boechler, N., Hameer, S., Wanis, S., Komerath, N., “Evolutionary Path towards Space Solar Power”. Proc. STAIF 2006, February 2006.

[2] Komerath, N., Boechler, N., “The Space Power Grid”. IAC06-C3.4.6, International Astronautical Congress, Valencia, Spain Sep.’06

[3] Komerath, N., Venkat, V., Butchibabu, A., “Parameter Selection for a Space Power Grid”. AIAA Paper 2008-7711, September 2008.

[4] Komerath, N., Venkat, V., Fernandez,J., “Near Millimeter Wave Issues for a Space Power Grid” Proc. IASSPES, Huntsville, AL, March ’09.

[5] Komerath, N., “The Space Power Grid: Synergy Between Space, Energy and Security Policies”, Proc. Atlanta Conference on Science and Technology Innovation Policy, Atlanta, GA, October 2009

[6] Chowdhary, G., Gadre, R., Komerath, N., “Policy Issues for Retail Beamed Power Transmission”. Proc. Atlanta Conference on Science and Technology Innovation Policy, Atlanta, GA, October 2009.

[7] Chowdhary, G., Komerath, N., “Innovations Required for Beamed Retail Power Transmission Systems”. Proceedings of the International Multiconference on Engineering and Technological Innovation, June-July 2010.

Our recent focus has been to lay out the retail market issues for beamed power, so that the terrestrial "pull" can be properly figured out. This forces a hard look at the prospects for 200-220GHz technology, especially with DSP-based techniques, and some ideas for burning through clouds and rain.

(This is a paper due to be revised and uploaded in the next month for a December 2010 IEEE conference in Bhubhaneshwar, India. It's already "accepted" but with a few insults on its quality)

The next issue is to look at the space-based market, and how it will both pull and push SSP development.

(This is an abstract submitted to an AIAA/IEEE conference in Big Sky Montana in March 2011. Hope to hear about it soon, and if they say yes, we have to submit a paper for review by October or so).

Overall, my take is that this is a time to think through what can be done, since the prospects for immediate, large-scale SSP deployment do not seem particularly bright in today's environment - and anyway I believe that the current GEO-based strategies are very hard to build out to the necessary level to impact the global energy market.

Spacecraft Design:

Krypton Thrusters Information:

Summary: Krypton about 10 times cheaper cost per mass than Xenon. Can achieve almost as high specific impulse. Isp=5300s seems reasonable, perhaps we could do even better.

The typical propellant utilized in electrostatic thrusters is xenon. In terms of thruster performance, xenon is often considered to be the ideal propellant option due to its high mass and low ionization potential. However, xenon is the rarest of the stable elements on Earth, and exists in the atmosphere at only 0.087 ppm. This scarcity, combined with increasing demand for xenon in applications ranging from plasma televisions to high intensity automobile headlights, results in a very high retail cost in the thousands of dollars per kilogram, and represents a major cost hurdle for an EP mission requiring significant amounts of propellant.

The simplest option is to substitute another noble gas for xenon, allowing an almost direct replacement without having to consider propellant reactivity or phase changes. Behind xenon, krypton is the next-heaviest noble gas and has a similar ionization potential; the performance penalty of krypton relative to xenon propellant should be much less significant than that incurred by utilizing helium, neon, or argon propellants. Additionally, krypton has an atmospheric abundance of 1.14 ppm, and is 13 times more prevalent than xenon; it is typically available for less than 10% the cost of xenon by volume (15% by mass), and the cost benefit is likely to be even greater during spikes in the demand (and price) of xenon.

Metal-vapor propellants are more complicated to work with, requiring complex feed systems on a spacecraft, and posing unique experimental challenges during ground testing due, in part, to their condensability. The ideal metal propellant is bismuth, as it is easily vaporized, has the highest mass of all stable isotopes, and has a low ionization energy. Bismuth is readily available as a byproduct of various metal-refining processes and has a cost per mass approximately one thousandth that of xenon.

Properties of Krypton, Xenon & Bismuth

	Kr	Xe	Bi
Atomic Mass [amu]	83.8	131.29	208.98
Ionization Energy [eV]	14.0	12.12	7.29
First Excitation [eV]	9.92	8.32	4.04
Abundance	1.14 ppm in air	0.087 ppm in air	Abundant mineral
Element Type	noble gas	noble gas	metal
State at STP	gas	gas	solid
Rel. Cost, Order of Mag.	0.1x	x	0.001x
Toxic in Typ. Handling	No	No	No

Krypton propellant has potential performance benefits for deep-space missions because the theoretical specific impulse for a given voltage is 20 percent higher than for xenon because of krypton's lower molecular weight. During project year 2003, the performance of the high-power NASA- 457M Hall thruster was measured using krypton as the propellant at power levels ranging from 6.4 to 72.5 kW. **The thrust produced ranged from 0.3 to 2.5 N at a discharge specific impulse up to 4500 sec.**

(The following tables are from wikipedia. The values of the specific impulses were not cited on wikipedia. These values should only be used to get an approximate idea)
The Specific Impulse values for Xenon and Krypton propellant are almost the same.

The following table compares actual test data of some ion thrusters:

Engine	Propellant	Required Power (kW)	Specific Impulse (s)	Thrust (mN)
NSTAR	Xenon	2.3	3,300	92
NEXT[15]	Xenon	7.7	4,300	327
NEXIS[16]	Xenon	20.5	6,000-7,500	400
HiPEP	Xenon	25-50	6,000-9,000	460-670
RIT 22[17]	Xenon	5	3,000-6,000	50 - 200
Hall effect	Bismuth	25	3,000	1,130
Hall effect	Bismuth	140	8,000	2,500
Hall effect	Xenon	25	3,250	950
Hall effect	Xenon	75	2,900	2,900
FEEP	Liquid Caesium	$6x10^{-5}$-0.06	6,000-10,000	0.001-1
VASIMR	Argon	200	3,000-30,000	~5000[18]

The following thrusters are highly experimental and have been tested only in pulse mode.

Engine	Propellant	Required Power (kW)	Specific Impulse (s)	Thrust (mN)
MPDT	Hydrogen	1,500	4,900	26,300
MPDT	Hydrogen	3,750	3,500	88,500
MPDT	Hydrogen	7,500	6,000	60,000
LiLFA	Lithium Vapor	500	4,077	12,000

Waveguide Information

A waveguide is a structure that guides waves, such as electromagnetic waves or sound waves. There are different types of waveguide for each type of wave. The original and most common meaning is a hollow conductive metal pipe used to carry high frequency radio waves, particularly microwaves.

Some companies offer out of the box solutions for this sort of thing:
http://www.space-machine.com/index2.php?option=com_docman&task=doc_view&gid=1544&Itemid=37

A MATLAB Script is being created to study waveguide geometry.
Reference: http://www.ece.rutgers.edu/~orfanidi/ewa/ch09.pdf
Waveguide geometry is determined by:

1. Desired frequency band=220 GHz in our case
2. Amount of Power = 60MW for Phase I SPG satellite
3. Transmission losses that can be tolerated=TBD

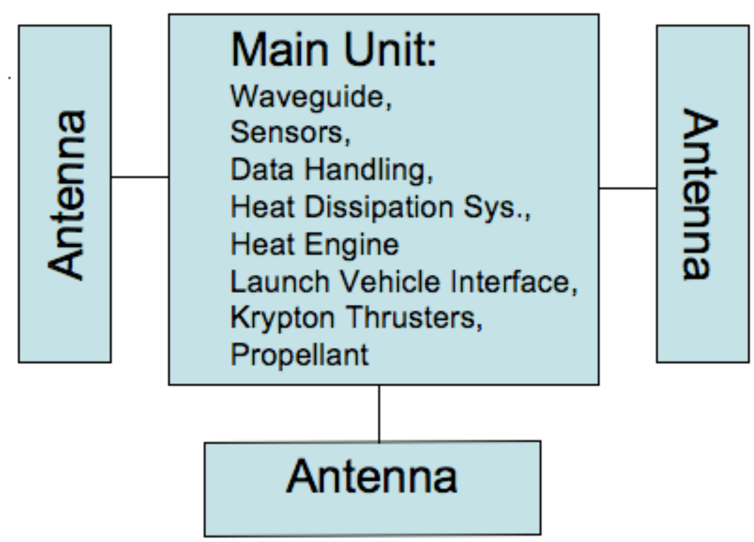
Method:
Calculate electromagnetic field: Using Maxwell's Equations to perform a Longitudinal-Transverse Decomposition
Calculate losses due to dielectric losses and conductor losses

Spacecraft Preliminary Configuration

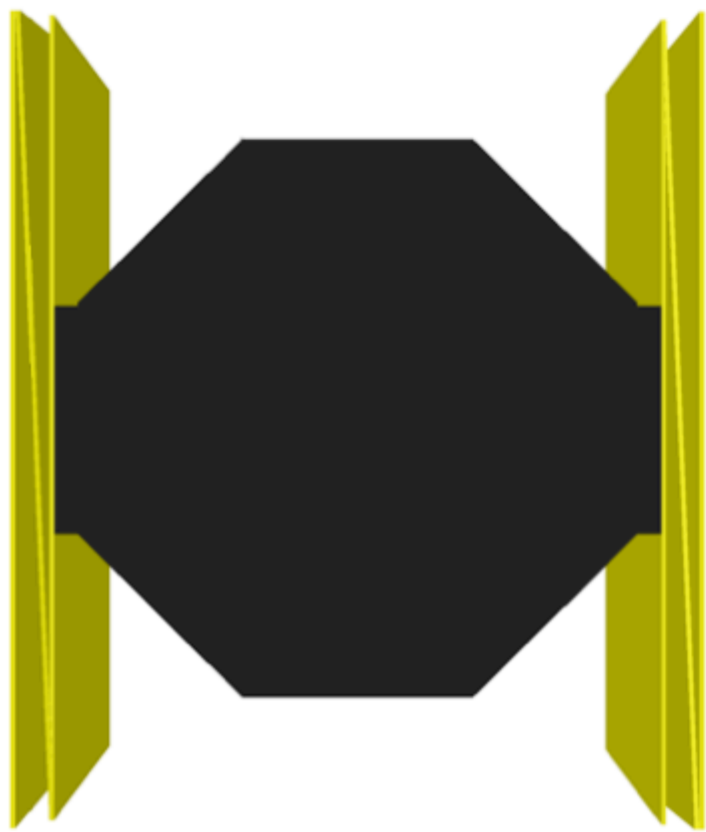
Space Power Grid Phase I Satellite Components:
Payload- Includes waveguide
Attitude Control- Actuators and sensors
Propulsion- Krypton Thrusters
Communications- Three Antennas, 2 for space-space, 1 for space-ground
Data Handling- Data recorders
Electrical Power- Heat engine connected to thermal control system
Thermal Control System- For heat dissipation
Launch Vehicle Interface

Guidelines for Integrating Components (reference- AE4356 Space System Design Course Notes, Dr. Carlee Bishop and Dr. Dave Spencer):
-Make design and mass distribution as symmetrical as possible
-Shade heat-generating components from solar radiation
-Put massive components close to launch vehicle interface
-Use modular designs
-Put electrically linked components together (reduce cabling)
-Place propellant tanks near center of mass
-Keep sensors away from thrusters
-Consider deployed fields of view
-Reduce length of appendages

Basic block diagram of SPG Phase I Satellite follows. Note that some things must be next to each other (i.e. Thrusters and propellant, heat dissipation system and heat engine). Need to work on configuration layout of main unit. Also, need to look at deployment of antennas.

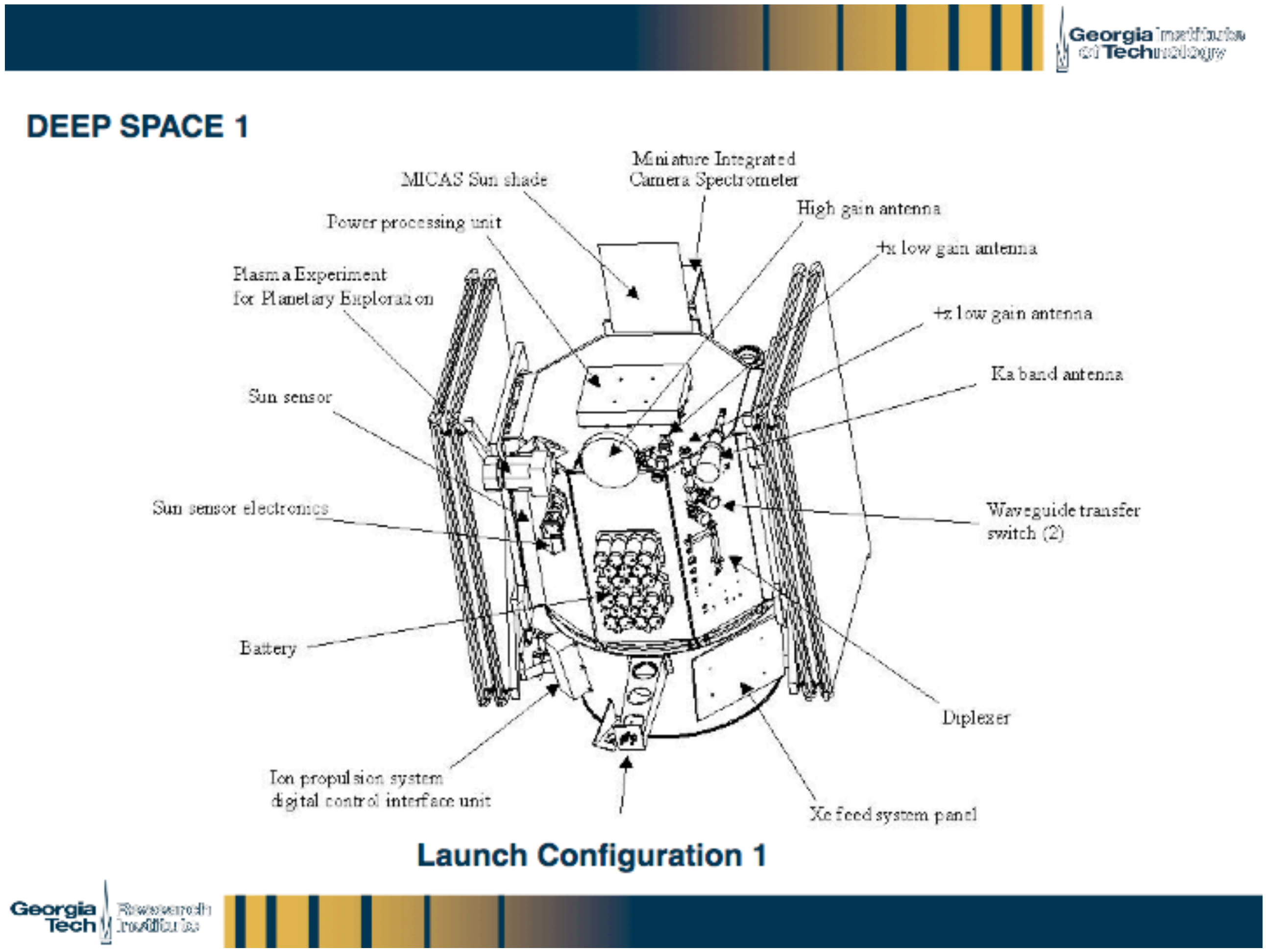


An autocad drawing of a space power grid satellite is being created. A snapshot of the drawing is included below:



Top View of Space Power Grid Satellite

Below is an example satellite configuration, pre-deployment (in configuration suitable for launch vehicle).



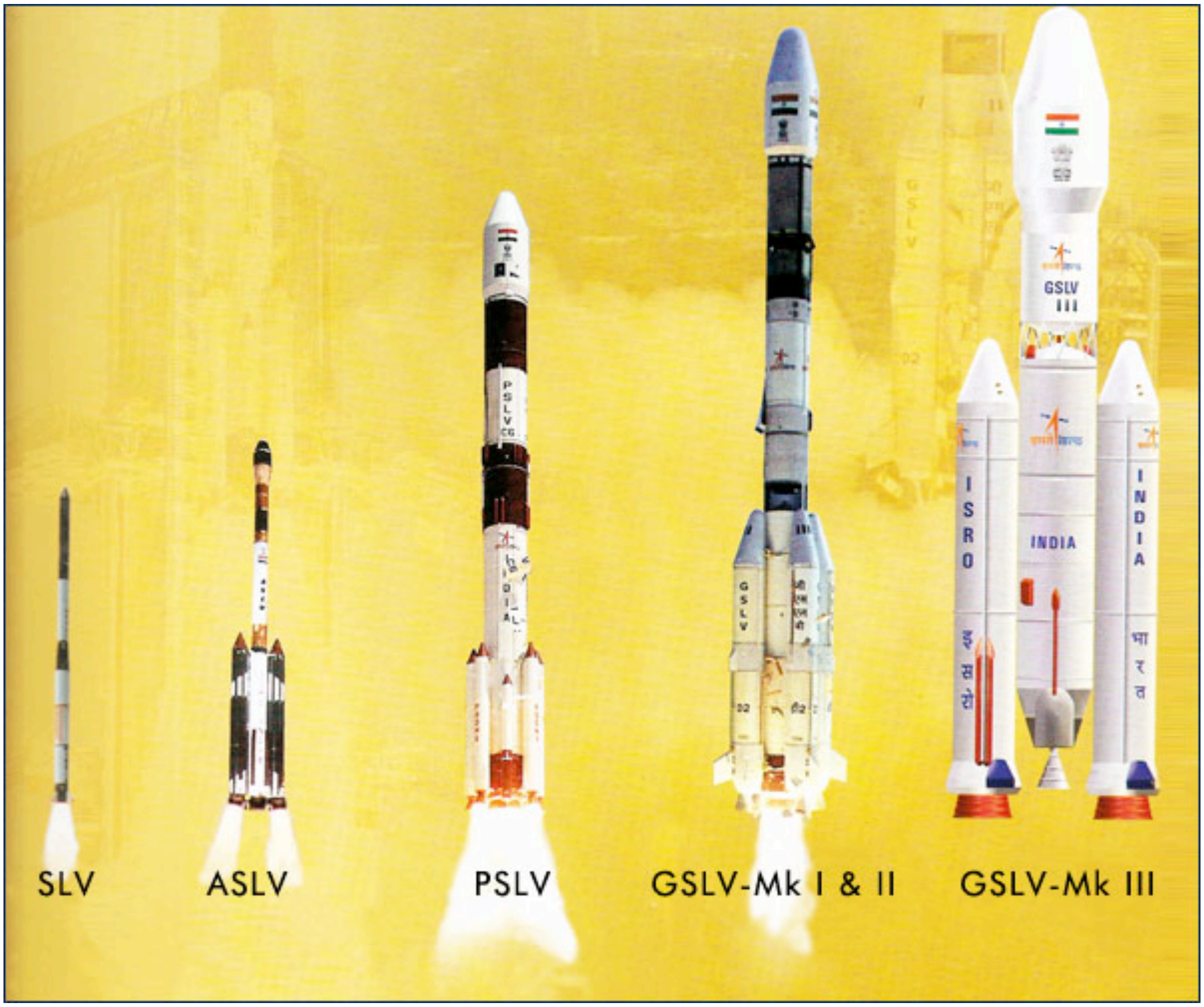
*From AE4356 Space System Design Course Notes, Dr. Carlee Bishop and Dr. Dave Spencer

Launch Vehicle Information

American Launch Vehicles:

	Cost per Launch	Payload Dimensions (meters)		Payload Mass (kgs)	
		Diameter	Length	LEO	GTO
Atlas V	187 million	3.3-4.2	7.8-9.7	9,750-29,420	4,750-13,000
Falcon 9	53 million	4.6	6.6	10,450	4,540
Falcon 9 (Heavy)	95 million	4.6	6.6	32,000	19,500
Minotaur IV	50 million			1,735	
Space shuttle	450 million	4.6	18.3	24,400	3,810
Delta II	36.7 million	2.8	4.7	2,700-6,100	900-2,170
Delta IV	155 million			8,600-22,560	3,900-12,980
Ares I (under development)	140 million			25,400	

Indian Launch Vehicle Fleet:



GSLV-Mk III is under development. Maiden flight projected at the end of 2011.

	PSLV	GSLV I & II	GSLV MARK III
LEO	3250 kg		10000 kg
HCO	1600 kg		
GTO	1060 kg	2000-2500 kg	4500 kg

	PSLV	GSLV I & II
Launch Price (1985 USD)	~30 million	~45 million
Flyaway Unit Cost (1999 USD)	~17 million	~5 million

	Height	Diameter	Gross Mass	Stages
PSLV	44 m	2.8 m	294 tons	4-5
GSLV	49 m	2.8 m	402 tons	3-4

GSLV MARK III	42.4 m	4 m	630 tons	2

Preliminary Mass and Sizing

An initial mass and size estimation of the Phase I SPG Satellite has been calculated. Total Loaded Mass estimate is currently 3526 kg. Total dry mass is estimated at 2680 kg. The current spacecraft has a volume of 17.63 m^3. The general size estimate is a length of 4.6m, with a diameter of 2.2m. A spacecraft of this size and weight could be launched to LEO using a Delta II rocket, with an estimated launch cost of $36.7 million.

Solar-Sail reciever

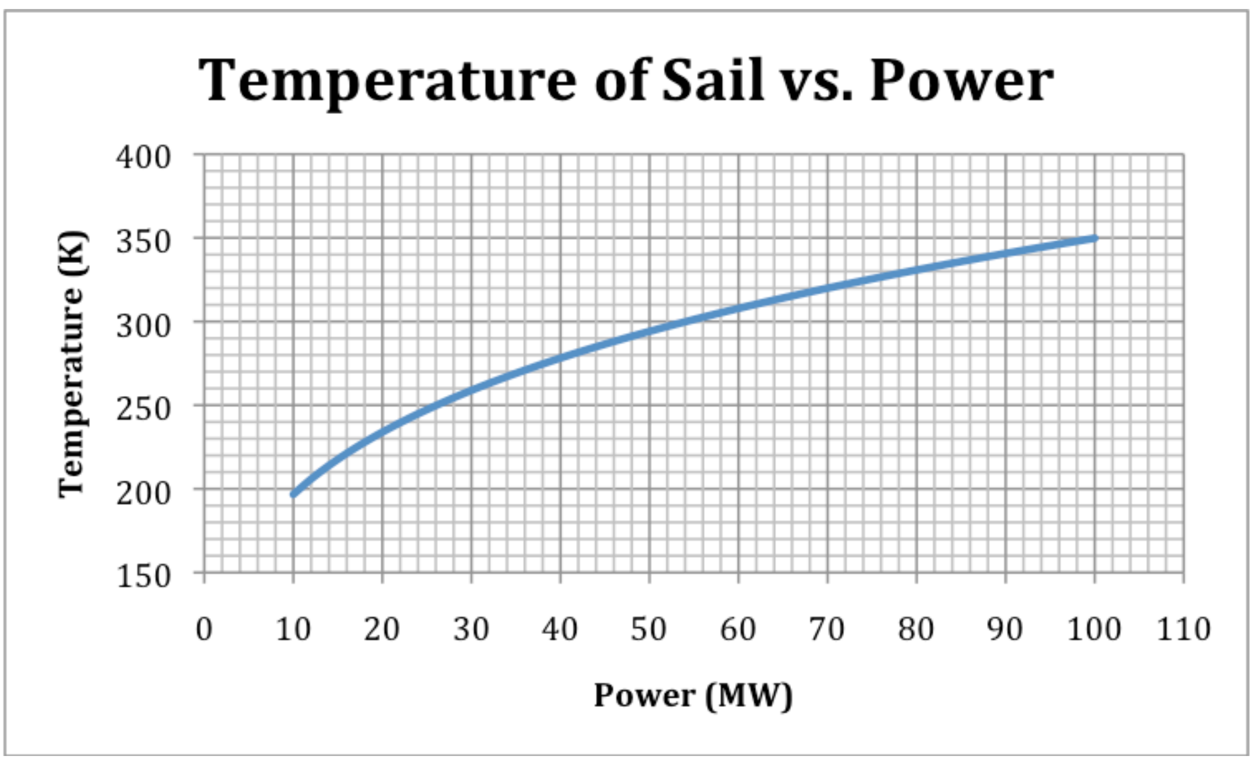
Assuming the emissivity ε of the solar sail of 50m diameter to be 0.03 and the reflectivity (η) to be 0.999, by using the Stefan-Boltzmann law, we get

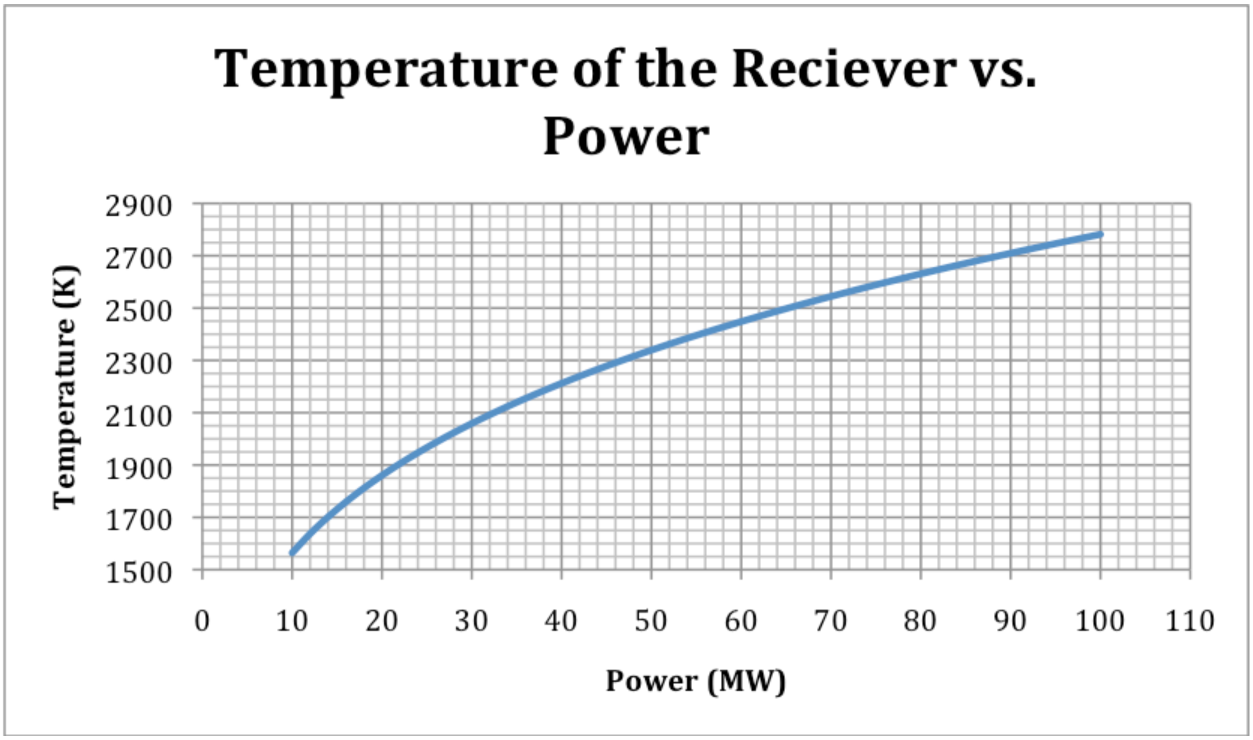
$$I = \frac{P}{m} = 2\sigma\varepsilon T^4$$

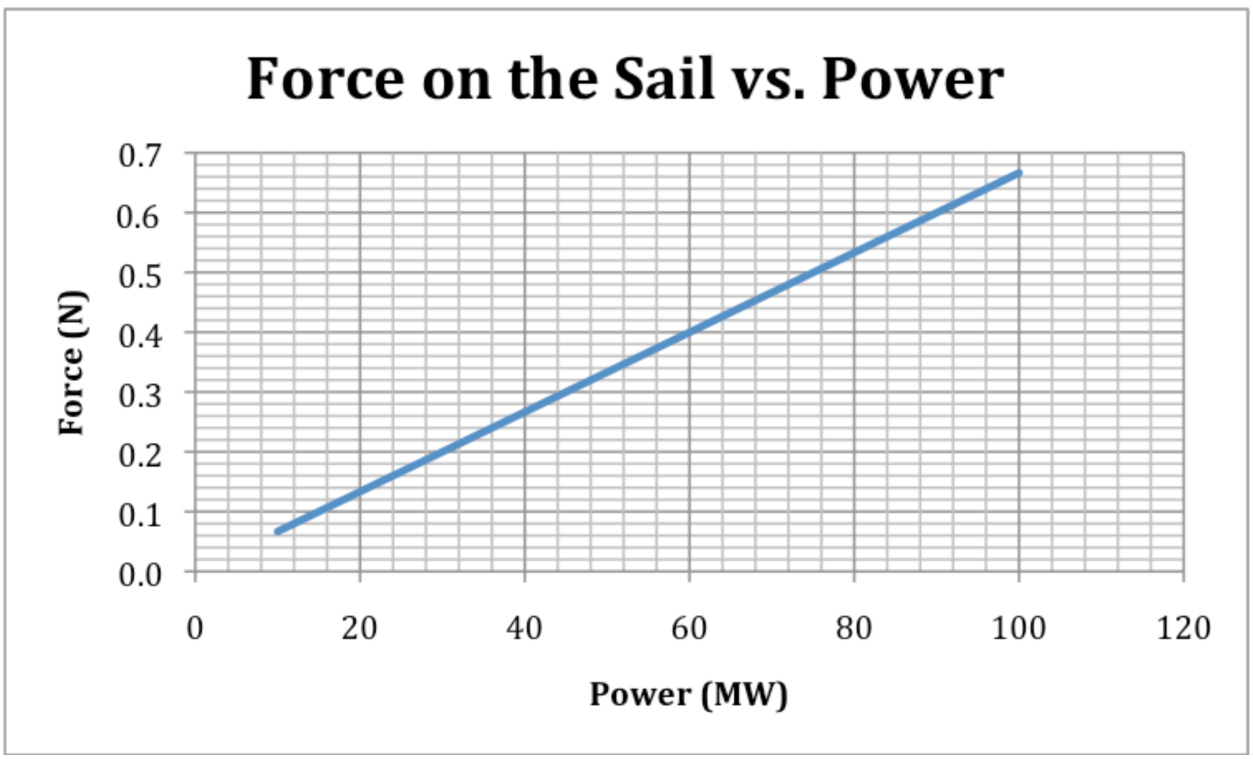
$$T = \sqrt[4]{\frac{I}{2\sigma\varepsilon}}$$

$$F = \frac{[\eta + 1]P}{c}$$

Where σ is Stefan Boltzmann constant (5.6696E-08) and Intensity 'I' is power (P) per unit area and 'c' is the speed of sound. We also assume that the diameter of the receiver is 25 m.

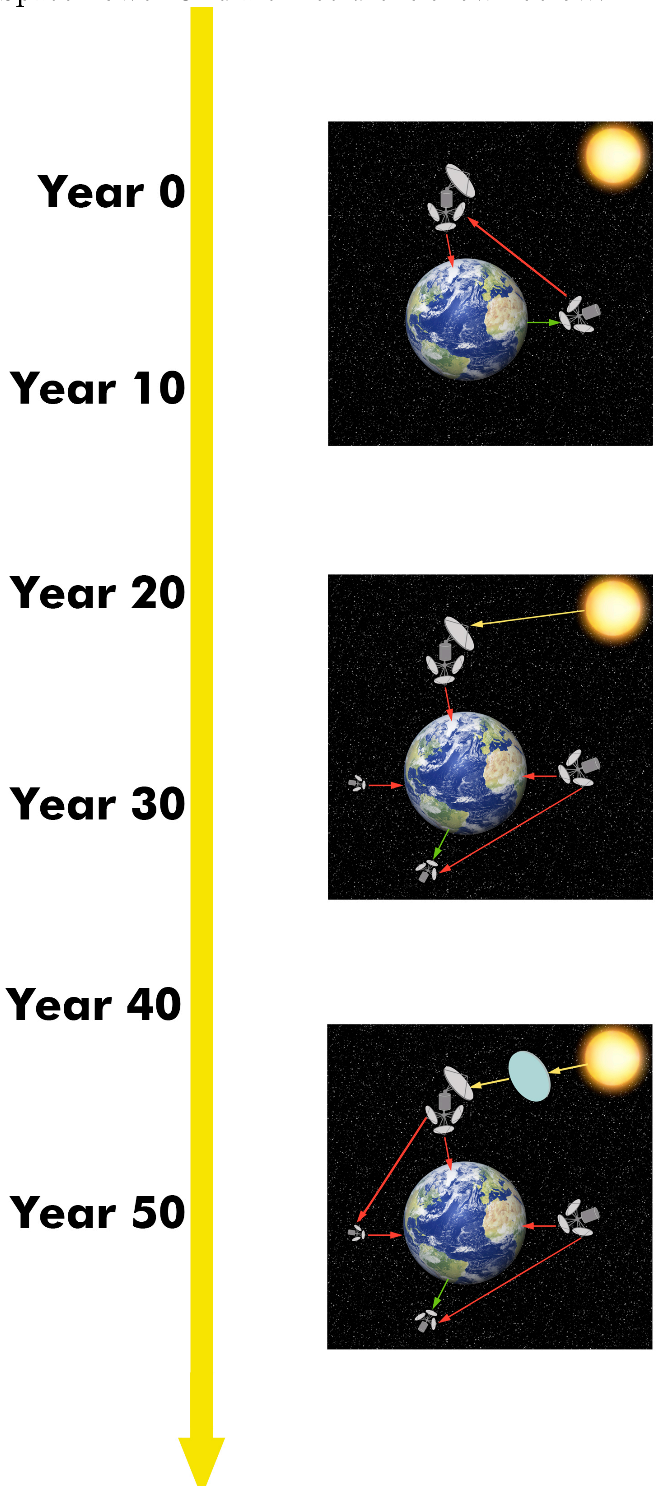



Temperature of the Reciever vs. Power
Temperature (K)
2900
2700
2500
2300
2100
1900
1700
1500
0
10
20
30
40
50
60
70
80
90
100
110
Power (MW)


Force on the Sail vs. Power
Force (N)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
20
40
60
80
100
120
Power (MW)

Power (MW)	Intensity ($W*m^{-2}$)	Force (N)	Temperature (K) of sail	Temperature (K) of receiver
10	5092.96	0.0666	196.70	1564.29
12	6111.55	0.0800	205.87	1637.24
14	7130.14	0.0933	213.96	1701.56
16	8148.73	0.1066	221.22	1759.33
18	9167.32	0.1199	227.83	1811.90
20	10185.92	0.1333	233.92	1860.26
22	11204.51	0.1466	239.56	1905.12
24	12223.10	0.1599	244.82	1947.01
26	13241.69	0.1732	249.77	1986.37
28	14260.28	0.1866	254.44	2023.51
30	15278.87	0.1999	258.87	2058.72
32	16297.47	0.2132	263.08	2092.20
34	17316.06	0.2266	267.10	2124.15
36	18334.65	0.2399	270.94	2154.73
38	19353.24	0.2532	274.63	2184.05
40	20371.83	0.2665	278.17	2212.24
42	21390.42	0.2799	281.59	2239.38
44	22409.02	0.2932	284.88	2265.58
46	23427.61	0.3065	288.07	2290.90
48	24446.20	0.3198	291.15	2315.40
50	25464.79	0.3332	294.13	2339.15
52	26483.38	0.3465	297.03	2362.20
54	27501.97	0.3598	299.85	2384.60
56	28520.57	0.3731	302.59	2406.37
58	29539.16	0.3865	305.25	2427.58
60	30557.75	0.3998	307.85	2448.24
62	31576.34	0.4131	310.38	2468.39
64	32594.93	0.4265	312.86	2488.06
66	33613.52	0.4398	315.27	2507.28
68	34632.12	0.4531	317.64	2526.06
70	35650.71	0.4664	319.95	2544.43
72	36669.30	0.4798	322.21	2562.41
74	37687.89	0.4931	324.42	2580.03
76	38706.48	0.5064	326.59	2597.29
78	39725.07	0.5197	328.72	2614.21
80	40743.67	0.5331	330.81	2630.81
82	41762.26	0.5464	332.85	2647.10
84	42780.85	0.5597	334.87	2663.09
86	43799.44	0.5730	336.84	2678.80
88	44818.03	0.5864	338.78	2694.24
90	45836.62	0.5997	340.69	2709.42
92	46855.22	0.6130	342.57	2724.35
94	47873.81	0.6264	344.42	2739.04
96	48892.40	0.6397	346.23	2753.49
98	49910.99	0.6530	348.02	2767.72
100	50929.58	0.6663	349.79	2781.74

A timeline illustration of the Space Power Grid architecture is shown below.



5 minute animation video:

Spacecraft main characteristics to show for video:
main body: 2.5m wide, 3.6m long

antennas: 90 meter diameter, similar configuration as shown in picture of satellite below. Main body similar shape as deep space I image shown above.

Video outline:

(Five Minutes)

Intro

- Opening shot of the Sun
  - Voiceover about solar energy, its unlimited resource, usefulness, etc.
  - During voiceover, zoom out
- Earth appears in foreground
  - Voiceover about how solar energy is currently being used, as well as how we can tap into using solar energy's full potential
- SPG satellite swoops in foreground in front of Earth
  - Voiceover introduces SPG Project, along with title

Presentation of Points

- Allows for a more efficient distribution of energy on a global level
- Green energy: Synergy with terrestrial plants
- Evolutionary Approach: Grow SSP as market allows
- Large scale international cooperation in space reminiscent of ISS efforts

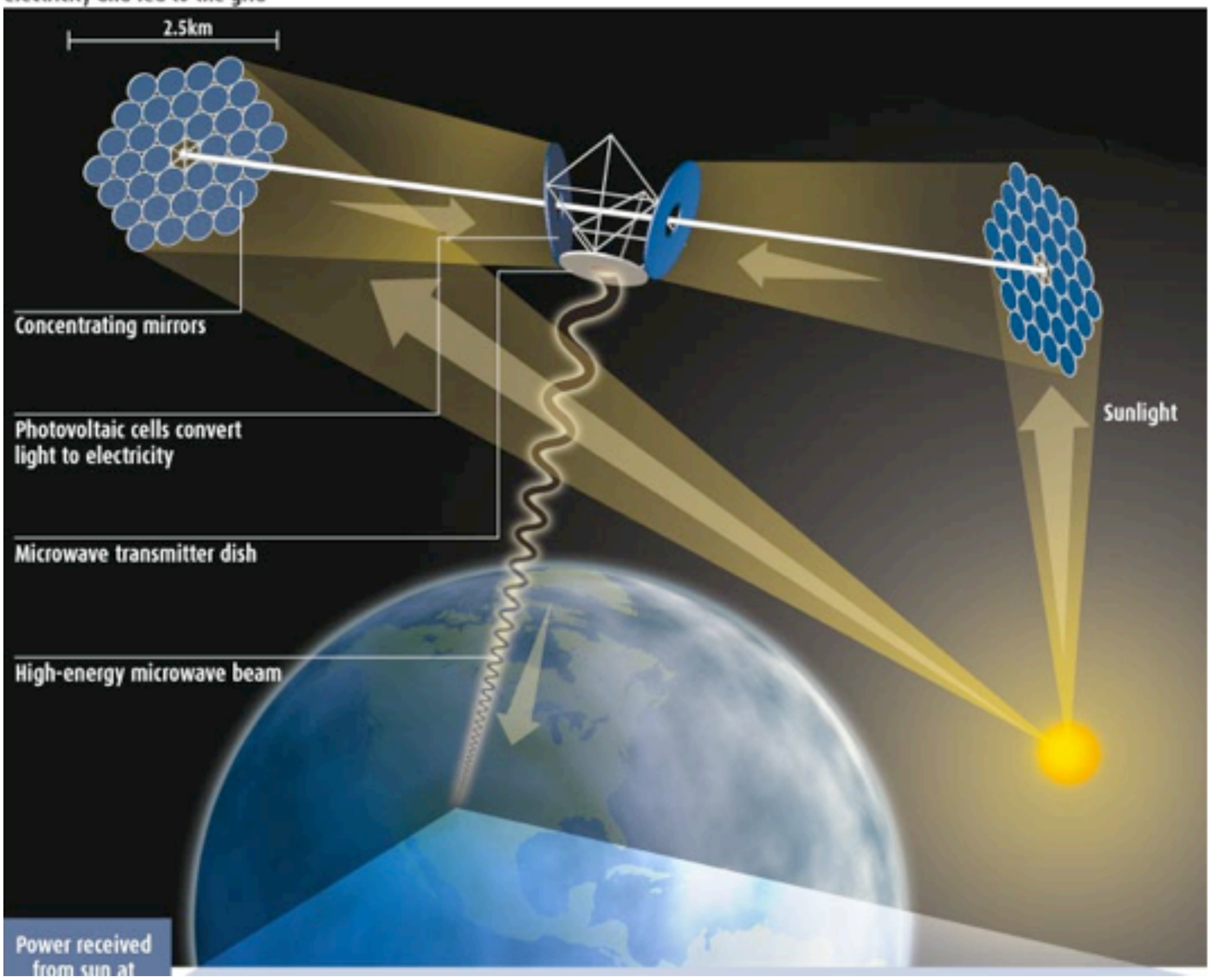
Conclusion

- Wrap up points presented earlier
- List other applications of SPG (don't go into detail, but show images, quick animations, to get audience excited and interested in learning more)
- Leave on a good note
- Credits?

Image of general idea of phase III architecture of video from:
http://martianchronicles.wordpress.com/2010/03/18/book-review-the-next-100-years/
Which also includes a 1 minute animation video on SSP.

BEAMING DOWN

A space-based solar power station will use an array of mirrors to concentrate the sun's rays on photovoltaic cells. The electricity produced is converted into a powerful microwave beam directed at an antenna on Earth, where it is converted back into electricity and fed to the grid



http://martianchronicles.files.wordpress.com/2010/03/26311601.jpg

Thermodynamic Calculations and Cycles

Ideal Brayton Cycle Heat Engine

$$\eta = 1 - \frac{T_1}{T_2} = 1 - \left(\frac{P_1}{P_2}\right)^{\frac{\gamma - 1}{\gamma}}$$

$$\gamma_{He} = 1.66$$

$$P_r = \frac{P_2}{P_1} = 300$$

$$\eta = 0.90$$

With a compressor pressure ratio of 300 for Helium, and specific heat capacity of 1.66, can theoretically achieve 90% cycle efficiency for the ideal brayton cycle case.

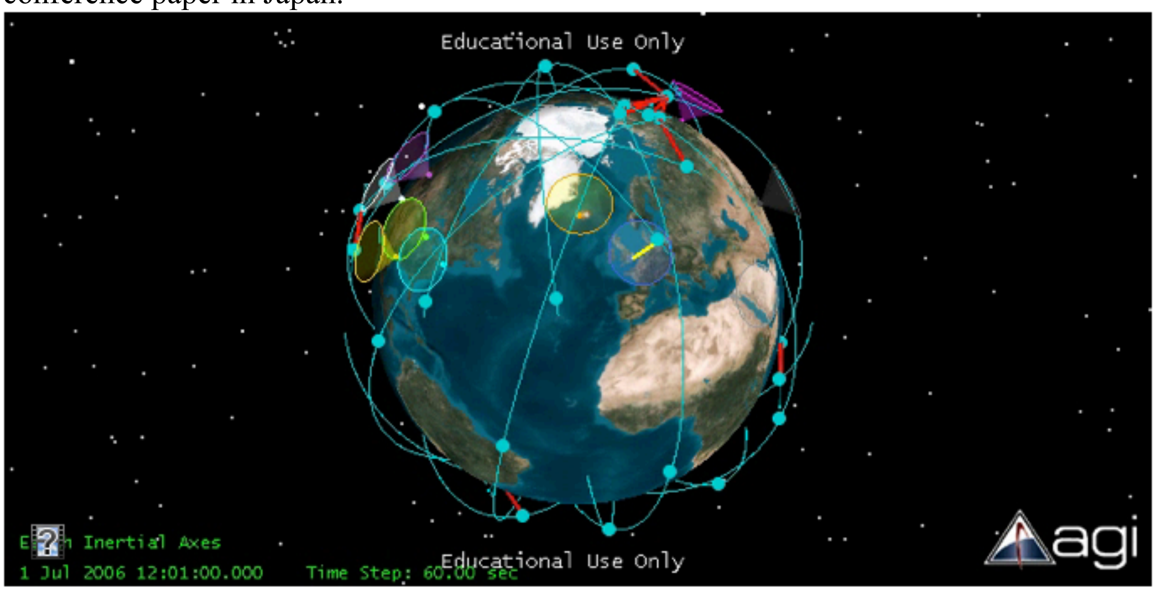
A pressure ratio of 300 requires T_1 be 200 kelvin, for a compressor exit temperature of 2000K. In order for the helium to have a temperature of -73 degrees celsisus entering the compressor, some form of cryogenic cooling I think would need to be used.

Cryogenic cooling:

In order to eliminate the remaining excess heat and liquefy/cryocool the gas, cryogenic cooling could be used. The Joule-Thompson (also known as Hampson-Linde) cycle is suggested in the NASA Draft paper on thermal management as one option for thermal management. At higher temperatures, as in our case, a Siemens cycle is more efficient. There are also saw some other ideas for efficient liquefaction/cryocooling some have suggested (like the Combined Reverse-Brayton Joule-Thompson cycle.

Previous Work

Here is an image from an animation developed by Nicholas Boechler for our 2006 IAF conference paper in Japan.



For a complete look at previous work view the Fall 2010 Final project document: SPG Report Final – Comp.doc.

Fall 2010

The team was successful in creating space to space beaming demonstration models in STK for a United States and India system, as well as a 4 facility system. Our demonstration model has illustrated that continuous space to space beaming is possible even with a limited number of satellite investment and plant participation. In addition, we have demonstrated that space to space beaming using the constellation chosen can be done without pointing between satellites, as the angles between each satellite are fixed. The team created a near-equatorial orbit constellation that we feel is best for achieving continuous beaming with as few satellites as possible. Calculations were performed for the near-equatorial orbit constellation chosen for the demonstration models.

The team performed orbit calculations to aid us in creating our demonstration models. Orbit calculations were performed that looked at estimating delta-v launch costs given a final desired orbit altitude and inclination. The results of these calculations showed that increasing altitude does not have a very significant penalty on delta-v costs, as the majority of delta-v cost occurs in getting to an Earth parking orbit. These calculations also showed that having very high inclinations such as the retrograde orbits required for a sun-synchronous orbit may mean that a sun synchronous orbit constellation may not be our most cost effective option. Calculations were also performed to analyze orbit maintenance. These calculations showed that orbit maintenance would be relatively close regardless of the altitude or type of orbit, because the perturbation in orbit due to solar radiation pressure was the largest order of magnitude. Other calculations were performed for analyzing sun synchronous orbits, for studying coverage times.

Research was also performed to gain a better understanding of the issues associated with the Space Power Grid project. Research was performed to study the possibilities of Forward Base Beaming. This research included figuring out the power capabilities of a naval destroyer and studying how UAV's can be used to receive and transmit energy. Other research was performed to look at how waveguide can be used for transferring energy through our spacecraft in the form of millimeter waves. Another area of study included looking at how orbit constellations work.

The team put together presentations and posters to increase awareness about the Space Power Grid Project. A poster was created and presented at the Georgia Tech Undergraduate Research Fair to interest students in our project. Work was done on presentations sent to the Air Force and the National Space Society. Animation files of our demonstration models were created to show a visual of how space to space beaming could work.

Spring 2011 Summary

The team refined the US-India Demonstration model to have continuous beaming to all four facilities using just four satellites. Preliminary mass and sizing calculations were performed for a Phase I Space Power Grid satellite. Satellite calculations were performed and an initial satellite configuration was developed. The team is currently working on an animation video of the Space Power Grid Concept.

The team has presented and documented work to spread awareness of the Space Power Grid concept. Nick Picon presented a poster on "Wireless Power Beaming" at the AAAS Conference in Washington DC, winning 2nd place in the AAAS poster competition. Brendan Dessanti presented an oral presentation entitled "Space Power Grid" at the Georgia Tech Undergraduate Research Spring Symposium. The team submitted a paper entitled "Millimeter Waveguide Spacecraft Architecture to the NASA ESMD Paper Competition (document available on Space Power Grid T-Square website). The team will be attending the National Space Society

International Space Development Conference in May to present an animation video of the Space Power Grid Concept and to present a paper on the US-India Demonstration.

Future Work

Future work will focus on the spacecraft design and on millimeter wave beaming issues. The conceptual spacecraft design will be refined. Analysis of the atmospheric absorption spectrum around 220 GHz will be performed to determine if narrow lines exist in the spectrum where improved beam efficiency can be obtained. Research also will be conducted to study the problem of transmitting through rain and fog. Methods for “burn through” will need to be developed, whereby a path would be burned through rain/fog by heating a path from the ground through the atmosphere through which energy can be transmitted efficiently. Some of the research topics to expand upon are listed below:

DSP for conversion to 220GHz

Why is 220 GHz absorbed?

Strategies for burning a conductive path for 220GHz

Burn-through frequency

Burn-through effects

Antenna geometry

Waveguide geometry

Phase array antenna basics

PLL basics

Appendix 1: Abstract submitted to the Big Sky Montana AIAA/IEEE Conference

Implications of Inter-Satellite Power Beaming Using a Space Power Grid

Narayanan Komerath

Daniel Guggenheim School of Aerospace Engineering

Georgia Institute of Technology

Atlanta, GA 30332-0150

Abstract

The Space Power Grid concept uses terrestrial power exchange in an evolutionary path towards Space-based solar power generation. Prior work established the frequency range, power level, orbit height range and constellation size of the satellite system, required for a system that could break even though power transaction economics. In this paper we consider the implications of such a system for space-to-space power beaming, both for the space component of the terrestrial power exchange, and for the development of space-based markets for power generation and delivery. The global positioning system constellation and the Iridium constellation are used as generic examples for possible future markets in mid-earth and low-earth orbits respectively. Results are derived for the cost of space access, given the availability of in-space, on-demand power delivery, for specified constellation sizes and different customer applications. The cascading nonlinear effects include a major drop in cost per unit functionality, and hence a lowering of the threshold for viability of space-based businesses.

Synopsis of Results

GEO-based concepts for Space Solar Power concepts based in GEO or the Moon [1-9] are driven to use microwave transmission below 10GHz by weather concerns, in turn resulting in very large receivers. The cost to first power is beyond contemplation. The Space Power Grid (SPG) architecture seeks to overcome the hurdle of cost to first power by establishing an evolutionary path, promoting the establishment of renewable power plants in remote areas. Past work [10-15] has shown that with a starting constellation of no more than 20 satellites in 2000km-high near-equatorial and sun-synchronous orbits, and about 100 participating power plants, an economically viable power exchange system can be set up, able to reach customers in most parts of the world with power from distant generating stations at reasonable cost of power.

Transmission frequencies below 100GHz are not viable because of the antenna size and the attendant weight penalty on the satellites. There are acceptable transmission windows near 140 and 220 GHz. In rain, neither window offers acceptable transmission; however, alternative reception and transmission paths can usually be found given the sun-synchronous orbits. Several areas favorable for locating solar and wind plants are located in high deserts where humidity is low and rain is rare. Once such a system is established, it can generate enough revenue to be able to break even in 17 years at a power cost of between \$0.3 and \$0.4 per KWh. A second generation of spacecraft built with revenue from these operations would then incorporate high-intensity solar collector-converters. A constellation of ultra-light reflectors in high (GEO or beyond) orbits would beam visible sunlight down to these collectors, with conversion being done using the best technologies available at launch time. The converted power would be fed into the space power grid. The system would eventually grow in a self-financing mode to the desired system size.

In this paper, we extend the system model to consider the space-based market for terrestrial power, delivered though the SPG. The issues are to model the receiver sizes, reception intervals and required power levels for customers located in three different sample orbits: LEO orbits typical of the Iridium constellation, MEO orbits typical of the GPS system, and GEO locations of communication satellites. There is a tradeoff between carrying solar panels for independent power generation, or millimeter wave receivers to buy power from the SPG, and thus a maximum cost of power where the tradeoff favors the SPG. Results to-date indicate that the breakeven power cost for the SPG-based system is substantially below the maximum viable cost for the customer satellites for the LEO and MEO constellations, but the tradeoff is more complicated in the case of GEO satellites because of the immense beaming distance to GEO and the resulting receiver size.

The second aspect in the paper is to extend the implications of such on-demand power supply, on the space economy. Where there is a substantial weight and complexity saving from not having to deploy large solar panels or other power generators, a large gain in payload can be achieved. This aspect actually has even greater impact on the GEO satellites, where the cost per unit functionality (e.g., cost per transponder) comes far down when beamed power supply replaces on-board power systems. The lowering of access cost thresholds enables consideration of other essential steps to expand space-based economic activity with such businesses as refueling and on-orbit maintenance and resupply.

The Georgia Tech Integrated SPG model, relates choices of beaming frequency and orbits to a breakeven analysis and thus obtains the power cost for a given return on investment. Orbits are calculated using the STK software package, and costs are based on standard Air Force / NASA cost models for consistency.

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