Proceedings of the

2011 Microwave Power Transfer Symposium

Georgia Tech Campus
15 December 2011

General Chair: Darel Preble, Space Solar Power Institute
Executive Chair: Gregory D. Durgin, Georgia Tech
Keynote Speaker: Dr. Frank Little, Texas A&M
Competition Co-chairs: Blake Marshall and Marcin Morys, Georgia Tech

Special Thanks:
Chris Valenta, ECE 6390 class, ECE 4370 class, Prof. Narayanan Komerath

Event Patrons: Space Solar Power Institute, The Propagation Group, Georgia Institute of Technology
Message from the “Organizing Committee”

The idea for the Microwave Power Transfer Symposium came this past summer when Darel Preble and I were brainstorming on ways to generate some interest in space solar power. Actually, I was initially interested in learning more about this topic, since most of my activity in microwave power transfer has come from the very low-powered field of sensors and RFID. After inheriting the senior-level Antenna Engineering in Fall 2011, which was coincident with the graduate Fall Satellite Communication & Navigation Systems class, the stars seemed aligned to try an ambitious mini-symposium on the topic of microwave power transfer. The seniors in Antenna Engineering would work on 5.8 GHz energy-harvesting antennas and charge pumps that would be used in a fun competition for the longest distance for lighting a diode. The graduate students in Satcom would design Space Solar Power systems that used microwave power to beam MegaWatts back to earth stations. Everyone would have a good time over a pizza reviewing and admiring one another’s work.

Darel Preble upped the ante by inviting Dr. Frank Little to give a truly excellent keynote on the topic of space solar power. With a standing-room audience of over 60 very attentive attendees, Dr. Little delivered an excellent culminating talk on the subject of microwave power transfer for space and various other applications. His slides as well as the design project posters from both classes are included in these proceedings. Special thanks to Darel Preble for his determination and willingness to promote the symposium, to Blake Marshall and Marcin Morys for running the rectenna competition, and to all the participants. Well done, everyone.

Keep Shooting for those Stars!

Sincerely,

Prof. Gregory D. Durgin
Georgia Tech School of Electrical and Computer Engineering
Come to the inaugural 2011 Microwave Power Transfer Symposium! See cutting edge work on topics in Microwave Power Transfer and Space Solar Power. Admission is free.

Event Schedule

<table>
<thead>
<tr>
<th>Time</th>
<th>Event Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>3:00 – 3:15</td>
<td>Introductory Remarks: Prof. Gregory D. Durgin, Room 102A.</td>
</tr>
<tr>
<td>3:15 – 4:00</td>
<td>Keynote Talk, Room 102A: “Opportunities and Challenges in Wireless Power Transmission” by Frank Little, Associate Director of the Center for Space Power, Texas A&amp;M.</td>
</tr>
<tr>
<td>4:00 – 4:15</td>
<td>Rectenna Device Presentation, Room102A</td>
</tr>
<tr>
<td>4:15 – 6:00</td>
<td>Poster Session: Microwave Power Transfer Projects&lt;br&gt;&lt;br&gt;<strong>Track A, Room 102B:</strong> Design of a Space Solar Power Network. Results from the Georgia Tech ECE 6390 Satellite Communications’ Space Solar Power Project. Roving judges will evaluate posters and designs of the various student projects. <a href="http://www.propagation.gatech.edu/ECE6390/project/Fall2011/Project11.htm">http://www.propagation.gatech.edu/ECE6390/project/Fall2011/Project11.htm</a>&lt;br&gt;&lt;br&gt;<strong>Track B, MiRC Hallway:</strong> 5.8 GHz Rectenna Design and Implementation. Results from the Georgia Tech ECE 4370 Antenna Engineering Rectenna Design Competition. Posters on display for devices in the rectenna shoot-out. <a href="http://www.propagation.gatech.edu/ECE4370/projects/projects.html">http://www.propagation.gatech.edu/ECE4370/projects/projects.html</a></td>
</tr>
<tr>
<td>4:15 – 4:45</td>
<td>Microwave Rectenna Shoot-off: MiRC hallway or courtyard (weather permitting). 5.8 GHz Rectennas will be used to energize an LED in a competition for the longest range.</td>
</tr>
<tr>
<td>4:15 – 6:00</td>
<td>Pizza Party, Room 102A: Pizza and light refreshments served.</td>
</tr>
</tbody>
</table>

General Chair<br>Darel Preble<br><br>Executive Chair<br>Greg Durgin<br><br>Competition Co-chairs<br>Blake Marshall, Marcin Morys<br><br>Confirmed SSP Judges: Frank Little, Darel Preble, Greg Durgin
Posters for ECE 6390 Project Teams

http://www.propagation.gatech.edu/ECE6390/project/Fall2011/Project11.htm

**Fall 2011 Space Solar Power**

<table>
<thead>
<tr>
<th>Project Statement</th>
<th>Resource Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>HELIOS</td>
<td>Star Tek Enterprises</td>
</tr>
<tr>
<td>Sunwire</td>
<td>L.E.E.CO.</td>
</tr>
<tr>
<td>Sting-Ray Solar</td>
<td>IRIS</td>
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<tr>
<td>Death Raytheorp</td>
<td>The Van Allen Co.</td>
</tr>
</tbody>
</table>
The HELIOS project team has proposed the development and implementation of a revolutionary new Space Solar Power system that will deliver clean energy to the Earth’s electrical grid.

The initial project goal is a group of 8 downlink sites completed and ready for use by December 2026, with an additional 8 downlink sites ready by July 2028. The long term goal is to have half the world’s electrical power provided by SSP.

Orbital Parameters
- GEO orbit is used.
- 16 satellites installed by 2028, with a total of 230 satellites by 2050.
- G1, then G2, then G3 rockets will be used sequentiaely as costs come down to launch equipment for SSP satellites
- Slingshot and conventional launches used to achieve 1500+ launches per year.
- ISS and planned LEO assembly sites will provide locations for staging and construction.

Timeline
2012 to 2016:
1. Build SSP module on ISS
2. Begin launching satellite equipment
3. Start exploring new launching strategies
4. Use G1 rockets for trips to LEO (more economical)
5. SSP module on ISS
2017 to 2021:
1. Use G2 rockets to put first SSP into GEO
2. Build rectenna sites
3. Use G2 rockets to put second SSP by 2021
2022 to 2028:
1. Use G3 rockets with higher payloads
2. Start putting in 3 SSP sats/4 years and install more LEO assembly stations
3. Employ new strategies to make 1000+ launches per year
4. Eight downlinks to earth by 2026
5. Sixteen downlinks to earth established by 2028
2028 +:
1. Aim to meet 50% of world needs
2. More number of launches make trips more economical
3. Reusable rockets will reduce costs

DC to Microwave Conversion
- Output: ~1kW to 10MW
- Frequencies: ~10 MHz to 100 GHz
- Efficiencies: ~70% to 90%
- Poor phase and frequency control
- Costs only ~$13 per kW

Space Hardening
- Solar flare particles have energies of 10 MeV to 1 GeV, and typical flux densities of ~3×10^10 p/cm²
- Galactic cosmic rays typically have energies of about 10 GeV, although some particles can have energies of over 10^16 eV, and energy density is approximately ~1 eV/cm² in GEO.
- The thin-film solar panels are the limiting factor for the lifespan of each satellite, and can be expected to provide nearly full power for 30 years.

Thin-Film Solar Cells
- ~20% cell efficiency
- 0.05 mm thick, about 100x thinner than crystalline materials
- Made of amorphous-Si or CuInGaSe₂
- Specific power of 16.8 kW/kg
- Can be folded or rolled for stowing during launch, greatly reducing costs

Satellite Array
- Configured in 5GW arrays
- Each 5GW array requires 9km² for deployment in space
- Will be independently pivoted such that the incident sunlight is always normal to the surface of the cells

Communications Link
- Operating frequency: 418MHz
- Modulation scheme: GFSK
- Coding scheme: CDMA
- Power consumption: 10 MW Magnetrons
- Overall efficiency: 50%-55%
- Cost per satellite: $10 billion

For references, see HELIOS on the GATECH Propagation website at http://www.propagation.gatech.edu/ECE6390/project/Fall2011/group1/heliosweb/index.html
Space-Based Solar Power Solution
Microwave Energy Transfer from GEO

**Concept**
- One Satellite per Earth Station
- GEO Orbit
- Multiple low cost shuttles to LEO
- Ion drive transfer to GEO
- Sun light reflected off mirrors
- Solar Cells convert to electricity
- Gyrotron converts DC to RF
- Waveguides send power to 100m dish antenna
- Dish transmits at 24 GHz
- 5 km diameter array of 100m dishes collect
- Rectenna converts to DC power
- Energy then sent to the grid

**Orbit**
- Assembled in LEO
- Hohmann Transfer from LEO to GEO
- Final position: One satellite in GEO above each Earth Station

**Earth Stations**
- Year 2025 Locations (Green)
- Year 2028 Locations (Yellow)

**Reliability**
- RADHARD space-certified components
- NASA-certified materials to mitigate outgassing
- Mechanical shielding against space debris and meteorites (< 2mm)
- Use leaded solder to avoid tin whiskers
- Extensive pre-flight/in-orbit testing
- Target lifespan: 50 years

**Power**

**Harvest**
- 5 km x 5 km / 2500 100 m x 100 m
- 94% Reflective
- Polyimide flexible film on metal mesh

**Mirrors**
- 8 Suns concentrations
- 60 % Efficiency in the future
- Capable of 2000 W/kg and 120 kW/m²
- Size: 1.5 km²

**PV Array**
- Gyrotron: 50% Efficiency
- 500 kW each
- 6000 converters
- Network of waveguides to transmitter
- Commission PV manufacturer to output at 24GHz

**Transfer**
- 100 m dish antenna
- 24 GHz
- 5 km array of 2150 antennas
- 100 m diameter dish
- Surface Roughness: 0.5 mm

**Communication**
- Sat-Sat Link provides control of satellites from any Earth Station
- DSSS + AES Encryption

**Efficiency Calculation**
- DC-RF 0.5
- Free Space / Collection 0.24
- Atmospheric Losses 0.89
- RF-DC 0.98
- Overall Efficiency 0.103

Visit our website for more information
https://sites.google.com/site/6390sunwire

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- Assembled in LEO
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Visit our website for more information
https://sites.google.com/site/6390sunwire
**Spacecraft Propulsion**
- VASIMR Ion Engines (42 per sat.)
  - $I_{sp} = 5000$ s
  - Thrust = 5N
  - 200kW pwr. consumption

**Communication System**
- 8GHz (uplink), 7.5GHz (downlink)
- 3.37MHz Bandwidth
- 9/10, 16APSK dvbs2 modulation and coding
- SHA-256 encryption

**RF Link**
- 94 GHz transmit frequency
- 300 m sat antenna
- 1 km rectenna
- Gyroklystron amplifier DC-to-RF

**Ground Stations**
- Rectenna Array: PCB slot antennas plus diode

**Star Tek Enterprises:**
Space Solar Power Symposium

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**Revenue ($B)**

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<th>Year</th>
<th>FY12</th>
<th>FY13</th>
<th>FY14</th>
<th>FY15</th>
<th>FY16</th>
<th>FY17</th>
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<th>FY25</th>
<th>FY26</th>
<th>FY27</th>
<th>FY28</th>
<th>FY29</th>
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<tr>
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<td>15.0</td>
<td>16.0</td>
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<td>13.5</td>
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<td>12.2</td>
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<td>15.6</td>
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<td>28.3</td>
<td>32.9</td>
<td>33.9</td>
<td>30.5</td>
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</table>

**Budget ($B)**

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<tr>
<th>Year</th>
<th>FY12</th>
<th>FY13</th>
<th>FY14</th>
<th>FY15</th>
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<th>FY27</th>
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<td>19.3</td>
<td>9.0</td>
<td>9.0</td>
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</table>
Scalable LEO Space Power Grid Concept

**ORBITS**

**SATELLITE DESIGN**

- 2.4 GHz communication link
- 40 GHz collector to relay link

**ANTENNAS**

- 40 GHz input from collector
- 40 GHz relay transceivers
- 14.88 GHz link to each receiver

**POWER AND REVENUE**

- 5GW TO ALL SITES BY 2025

- Break-even by 2029

**Investment:** $476.7B

**Profits:** $36B/yr

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Antenna Design
Primary Considerations
1. Gain Pattern
2. Center frequency (24.125GHz)
3. Bandwidth
4. Polarization – Circular
5. Beam taper
6. Radiation pattern
(Must also describe Beamwidth, HPBW, Reflection Losses, Radiation Resistance, Max Rated Power, VSWR)

Antenna Features
- Omnidirectional Architecture
- 0.24mm (12u)
- Cosically Polored

Dish Antenna Trade-off
- 1. Assembling D (in the sky) = 100m, C = 3e8, D = 20.2e6, so D1 = (20.2e6/100) = 2.0236m (worst case for MEO)

Array of Antenna Circuits
- Each beam consists of 2 arrays of the same designs
- We need to put multiple rectenna circuits together to create an array of antenna elements
- 10,000+ # of square power level rectenna arrays would be needed to produce at least the 1GW of electric power that is desired
- The peak power of each individual DC output unit is 10Kw per square meter DC power using monolithic rectennas as our approach in rectifying the microwave power through the collector dish. The microwave power can be realized
- Each Rectenna circuit can produce an output between 3 and 10Kw per square meter DC power using monolithic rectennas as our approach in rectifying the microwave power through the collector dish. The microwave power can be realized
- A better approach to increase the effective radiation resistance of the array elements is to design the array elements to be radiating at a constant phase angle and at a frequency above 200GHz.

Array shape: Circular
Element spacing, d = (1900/20.2) = 94.3m
Element separation angle = 7.95° ± 3.75°
Element separation distance = 1.2° ± 0.7°
Element separation phase = -5° ± 3.5°
Array element pattern
- Array Element
  - Element diameter, D = 1000m
  - dish depth, d = 7m
  - (Geometric length = (746/146) = 326m, D = 20.2m, so d = 10°
    - array in d = 10°

- Other Parameters
  - Beam pattern to accommodation
  - Array pattern = Array element pattern x Array factor (AF)
  - Beamwidth (FWHM): Beamwidth (Angular Beamwidth Error)
- Bandwidth
- Angular size enlarges when the geometric size is increased.
- Array elements are radiating at a constant phase angle and at a frequency above 200GHz.

Array diameter = 2,512 km
Element spacing, d = (1900/20.2) = 94.3m
Element separation angle = 7.95° ± 3.75°
Element separation distance = 1.2° ± 0.7°
Element separation phase = -5° ± 3.5°

Matrix Antenna Arrays
- The microwave power through the collector dish. The microwave power can be realized

Array Elements
- Primary Considerations
- Gain Pattern
- Bandwidth
- Sidelobe restriction
- Beam taper

Array Features
- Max Rated Power, VSWR

Communications
- Designed with security in mind – protection from interception, jamming, spoofing
- Can function at 24.125GHz with security in mind – protection from interception, jamming, spoofing
- Can function at 24.125GHz with security in mind – protection from interception, jamming, spoofing
- Can function at 24.125GHz with security in mind – protection from interception, jamming, spoofing

Satellites
- Orbit Design
- The orbit elements for this mission are two Borealis orbits and a high altitude circular orbit. The inclination and angle of these three orbits are tuned such that the orbit do not see any syzygy. A syzygy explains the phenomena when the Sun, Earth, and Moon line up to cause eclipses of the Sun and Moon. Therefore, the solar panels will always point towards the Sun with a need for active control (interfering polarization)
- The Borealis orbit was chosen because of the large area that it covers. The Borealis orbit has an altitude between 600km to 1000km above the Earth. The circular orbit was chosen to cover the ground stations located in the Southern Hemisphere. Each orbit month has four cycles, for a total of twelve rectenna cycles. Below is a table of the orbit parameters.

Subsystems
- Power
- The power transmitted to ground stations is gathered using thin-film solar panels with an efficiency of at least 18.9% (3%). If this efficiency, 995,000 kg of solar panels must be used to generate the desired 1GW. Assuming a 1% degradation in efficiency every 5 years, a total of 700,000 kg of solar panels must be launched initially and approximately 150,000 kg of solar panels must be replaced every 5 years.

Antenna Features
- The thermal conditioning system will consist of passive convection placed on the roof of the solar panels. The main body of the satellite will perform thermal conditioning through the use of active heat pipe pumping.

ADAS
- Could be an issue with a laser communication threat as it is easier to jam laser communication than to jam RF communication
- The Space Environment
  - Micro-meteorite Environment
  - Micrometeorites are in space and can trap charges shown in figure below
  - The Space Environment
  - Solar Flares
  - 3rd year
  - 5th year
  - 7th year

Additional Data
- 32 Satellites
- 16 Satellites
- 3200 Flights per year
- 32 Satellites
- 16 Satellites

Communications
- Designed with security in mind – protection from interception, jamming, spoofing

Table C.1. Communications Sub-System Overview
<table>
<thead>
<tr>
<th>Modulation Scheme</th>
<th>Data Rate</th>
<th>Center Frequency</th>
<th>Upstream Bit Error Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical Fiber</td>
<td>10Gbps</td>
<td>1310nm</td>
<td>10^-9</td>
</tr>
<tr>
<td>Satellite</td>
<td>15GHz</td>
<td>1400nm</td>
<td>10^-9</td>
</tr>
</tbody>
</table>

Microwave Power Hardware
- Magneto-Dynanmic Amplifier (MDA)
- A microwave device is needed to convert the collected DC power from the photovoltaic cells to RF microwave power. The process is done through a Magneto-Dynanmic Amplifier (MDA)
- The MDA is composed of two perpendicular magnetic fields in a single space
- The output power is proportional to the input power
- The power module is composed of 40 units of units in two, each output unit is composed of a magnetic device
- The MDA can generate megawatt microwave power output in the order of GW of power.

Budget And Logistics
- Estimated Budget for 16 SSPS and Earth Stations
  - Total $1,200,000,000,000
  - Of this, $6,389,279,124,554 is allocated to SSPS

Launch Costing and Scheduling
- Launch Costing and Scheduling
  - Cost for 16 Satellites
  - Total Cost for 16 Satellites
  - Total Cost for 32 Satellites

Added Cost and Weight From Space Hardening
- Added Cost and Weight From Space Hardening
  - Extra Maintenance Cost Per Year
  - Extra Maintenance Cost Per Year
  - Total Mass (Kg)
  - Total Mass (Kg)
Low Earth Electric Co.

Brendan Dessanti, Mitchell Powner, Ryan Redmond, Christian Vorndran

**Orbital Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Orbit Type</td>
<td>MEO</td>
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<tr>
<td>Inclination</td>
<td>51.6°</td>
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<tr>
<td>Argument of Perigee</td>
<td>248.5°</td>
</tr>
<tr>
<td>Right Ascension of Ascending Node</td>
<td>150.4°</td>
</tr>
<tr>
<td>Mean Anomaly</td>
<td>10°</td>
</tr>
</tbody>
</table>

**Power Transmitter**

- **DC – RF Conversion**
  - Class F GaN converters
  - > 70% conversion efficiency
  - ~ 20 W maximum output
  - Low phase noise
  - Output harmonic filters

**Power Beam**

- 600 m diameter phased array
- \( \lambda/2 \) element spacing
- Gaussian power tapering:
  - Retrospective pointing (left)

**Rectenna**

- 1.982 km diameter circularly concentric array
- \( \lambda/2 \) element and ring spacing
- 38,318 concentric circles

**Elements**

- Printed dipole, CPS line
- Si Schottky diode rectification
- 82.7% overall efficiency

**Budget and Timeline**

- Proposal Timeline
- Revenue, Costs, and Cash Flow Analysis

**ECE 6390**
Space Solar Power: The Sun, Electricity, Death Rays, and You

Malik Kadish,1 Thomas Pappas,2 Gregory Watkins,3 Breneman Whitfield1

1. School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332; 2. The Daniel Guggenheim School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA 30332

Our Plan
We will have 90 satellites directly between the sun and the earth with over 20 square miles of thin-film photovoltaics converting sunlight into electricity. This electricity will be converted into a laser beam using photodiodes and transmitted to our satellite in geosynchronous orbit. From there, the power will be converted to a 30 GHz microwave beam, amplified through a parabolic dish antenna, transmitted to our Earth station, and then straight to you.

Orbits
Earth-Sun L1 Point
Our harvester satellites will be in Halo orbit around L1 and remain between the Earth and Sun. The Earth-Sun L1 point is about 1.5 million km from Earth. Weekly station-keeping must be performed.

L1 Satellite
Each satellite will feature a 160x4500m solar array. The satellite bus will be dominated by the laser array and cryogenics. The laser must be able to track the GEO satellite though a range of about ±1°. The satellite bus also contains a small communications antenna, as well as the ion thrusters and propellant.

GEO Satellite
The satellite array will be harvested using a monochromatic PV array. The dominant feature of the GEO satellite is a 150m diameter inflatable transmit antenna.

Power Link
The satellite will transmit using a parabolic dish 150m in diameter, giving it a gain of 93.5dB. The power will transmit with a beamwidth of 0.0036° which will cause the received beam to be approximately 2.33km in diameter. For our given frequency and transmitted power, atmospheric absorption was calculated to be 0.2dB and therefore negligible. Estimating a 3% power loss in moving the collected power to the grid, 58.05MW of power will be added to the grid per collection satellite. The combined link operates at 86% efficiency.

Communications Link
During the nighttime, when the L1 satellite is not visible, any necessary communications will be relayed through the GEO satellite. A CDMA coded QPSK system using a half-rate turbo code will be used. A 128-bit AES end-to-end encryption with the capability to over the air relay will be added for further security. X-band will be used. A 70m ES dish will be used and the dishes on the satellites will be 10m.

Earth Stations
We will have one earth station located in the Nevada desert. This station will house the rectenna for receiving and converting RF energy to electricity as well as the necessary communications equipment for the management of the satellite systems. The 9km² rectenna will consist of an array of 227 billion half-wave dipoles arranged in an equilateral triangle orientation (see Figure 3). Each side of these triangles is 64mm (0.64m) in length.

References
2. solarnow.nasa.marin.edu/pics/images/kepler_orbit.gif
Project Goal

The objective of this project is to deliver safe, clean, and reliable power to 8 locations throughout the world by 2025. An additional 8 sites will be ready for use in 2028. All told, we intend to deliver 80GW of power to support a sustainable energy economy.

Orbital Parameters

Each SSP constellation consists of 10 satellites in a circle 1km in diameter. The constellation circles the Earth in a LEO orbit 1500km above sea level with 0 degrees inclination [1]. There will be one constellation launched per rectenna site.

Microwave Power Link

The satellite power delivery system is designed around creating a 1km dish of satellites in space. There are 100 satellites per constellation and the satellites are phase locked with each other through the use of a ground based beacon. GPS satellites could also be used as a phase reference source. The link budget below describes the output power required from each satellite.

Earth Station Design

The rectenna is a grid array of patch antennas, which collect the RF energy, rectify it, and transfer it to a central collection station. Rectenna efficiencies are reaching 85% in the lab, and we expect that this will be commercially viable by the time the rectennas are constructed.

Cost & Schedule

The budget and schedule for this space solar power grid is centered around meeting the target power costs ($/KWh) at the first 8 target locations by the target of 2025 and the next 8 locations by 2028. The program is broken into five phases: planning and development phase, prototype phase, grid installation phase, grid expansion phase, and the maintenance phase.

Acknowledgments

Thanks to Professor Durgin for organizing the SSP Project.

References


Gammenthaler, S. "Basic Antenna Relationships and Design Considerations for Rectennas". Moon Society, Inc. 2007.


Posters for ECE 4370 Project Teams

http://www.propagation.gatech.edu/ECE4370/projects/projects.html

5.8 GHz Energy-Harvesting LED

Project Statement

Group 1  Group 2

Group 3  Group 4

5.8 GHz Directional PCB Antenna

Project Statement

Group 1  Group 2

Group 3  Group 4
ECE 4370 Design Project

Design of 5.8 GHz Antenna and Charge Pump

Ali Bibonge
Anh Le
Curtis Evans
Jeff Dube

Antenna Design
- The antenna must match to a 50 ohm SMA connector
- Must operate in the 5.725 – 5.850 GHz ISM band
- Receive a 10 dBm signal at 5.8 GHz with optimal gain and minimum loss
- Must fit within a 10cm x 10cm x 1cm box

Antenna Design Process
- A rectangular patch antenna was chosen for the design
- Patch antennas provide efficiency and simplicity to the overall design
- These formulas were used to determine the optimum dimensions of the patch antenna

\[ Z_0 = \frac{120\pi\h}{W\sqrt{\varepsilon_{\text{eff}}}} \]
\[ r_{\text{eff}} = \frac{1}{2} + \frac{1}{2} \left( 1 + \frac{15\varepsilon - 1}{W} \right) \]
\[ \Delta f = 0.4123 \left( \frac{\varepsilon_{\text{eff}} + 0.3}{\varepsilon_{\text{eff}} - 0.256} \right) \left( \frac{W}{W_{\text{eff}}} + 0.264 \right) \left( \frac{W_{\text{eff}}}{W} \right) + 0.8 \]

\[ f_c = \frac{c}{2\sqrt{\varepsilon_{\text{eff}}(l + 2\Delta f)}} \]

Final Antenna Design

Charge Pump Design
- The charge pump must take a 5.8 GHz signal from the antenna as input
- The signal must be converted to a DC signal of necessary power to light an LED
- The charge pump must be matched to 50 ohms
- Consists of SOT-323 package RF Schottky Diodes, an L62705CT-ND LED, and 820 pF capacitors
Charge Pump Design Process
- A Dickson charge pump design was chosen for the device
- Dickson charge pumps are optimal for low-voltage designs
- Schottky diodes provide low forward voltage drop, so the charge pump is more efficient

Two-stage and three-stage charge pumps were built and tested in the design process.
- The three-stage charge pumps were found to perform consistently and provide more power to the LED.
- The figure shows the three-stage design built in Multisim.

Final Charge Pump Design
- The three-stage charge pump was fabricated on a standard FR-4 board

Results
- The charge pump yielded a return loss of -11.54 dB
- Using a horn antenna as the transmit source, the charge pump was able to light the LED consistently when the patch antenna was at least 6 inches away from the source.
DOUBLE BI-QUAD ANTENNA

Stephane Charles, Chunhee Cho, Allen C Finkenaur, Yujing Pan, Daniel Smith

Introduction

Antenna
-- vertically polarized 5.8 GHz
-- double bi-quad directional
-- 50 ohm SMA connector
-- four equally sized squares radiating element and one reflector
-- peak gain(14 dBi)

Design and simulation

The double bi-quad antenna was first created and simulated in NEC software before fabricating the antenna.

Figure 1. Double bi-quad antenna constructed in NEC.

Elements:
● Wavelength: 5.8 GHz, or 13 mm
● The ground plane: 3.4 mm

Simulation:
● 5.8GHz
● 14 dBi peak gain
● 4.6 + j8.6 ohms impedance

Fabrication

The double b-quad antenna was milled on to a printed circuit board which is composed of a substrate layer of FR4 and a 1.4 mil layer of copper on one side of the FR4.

Figure 3. 3D model of double bi-quad antenna with overlayed 3D radiation pattern in NEC.

Figure 6. Dimensions of the fabricated double bi-quad antenna.

Experiment & Result

Once the antenna was printed on to a circuit board, it was tested using a network analyzer.

Figure 7. Final double bi-quad antenna produced with milling machine.

Figure 8. Return loss (S11 parameter) of the antenna measured with network analyzer.
Return loss (S11 parameter) ---- 6.30GHz and 7.82GHz

Conclusion

The produced antenna would indeed work at the desired 5.8 GHz, but turned out to be a far more effective antenna at 7.82 GHz.
RF energy is constantly being transmitted in modern environments. This energy typically goes to waste when no receivers are present to pick up the signal. A microwave charge pump can be used to gather this energy and convert it into a low-leveled power supply. An array of antennas provides a continuous 5.8 GHz signal to the energy harvesting circuit. The circuit will convert this signal into a DC power source to light a low power LED.

The antennas to be used in this design are patch antennas. Patch antennas have advantages as they are not only cheap and easy to fabricate but also versatile in terms of resonant frequency, polarization, pattern, impedance, and conformability to planar and non-planar surfaces. They can also easily be placed in an array as long as their feeds are matched and phased correctly. In this design, four identical patch antennas have dimensions of: 460 mils in length and 630 mils wide. A 50 Ω SMA connection was soldered at the halfway point along the central microstrip line. The components used in the charge pump include: RF Schottky Diodes, 850 pF capacitors, and a low power LED - modeled here as an 85 Ω resistor. This energy harvester consists of 4 stages. Each stage provides more energy to the load and is made of 2 capacitors and diodes. The long stub

The optimization performed was mostly comprised of the microstrip matching network used to feed the multiple patch antennas. Both the antenna and the microstrip are printed using copper. When placing the antennas in an array, the matching network is incredibly important in keeping the impedances matched and also make sure the antennas are in phase.

A simulation was performed on a single patch antenna in HFSS and its directivity is plotted in dB. An infinite ground plane was placed 1.5 mm underneath the antenna in order to increase our peak gains. There are nulls at the origin because of this ground plane and a maximum peak of 8.777 dB in the +z direction.

The antenna design was simulated in ADS which graphically displays the S11 in dB. At the resonant frequency of 5.8 GHz, the maximum power is being received. The simulation in the figure above shows a minimum of -20.7 dB at the operating frequency. A network analyzer was used to measure the same parameter after the antenna was milled. The results show a minimum of -31 dB.
Abstract
By implementing a patch antenna array on a printed circuit board with a charge pump, we were able to light a small LED.

Introduction
With wireless systems becoming an ever more important part of our daily lives, the ability to wireless harvest energy is becoming a necessity not only for smaller RFID systems that must power up an onboard microchip, but also a possibility for mobile device charging. By using an array of patch antennas (Figure 1) tuned to the desired frequency of 5.8GHz coupled with a charge pump of either 3 or 4 stages (Figure 3), we can realize a large gain in a specific direction and harvest enough energy to light a low power LED. Simulating our antenna design in CST Microwave studio (Figure 5), we were able to roughly predict the performance of our antenna and charge pump design before fabrication (Figure 7). After construction, the S Parameters were measured and we can see a large return loss at our desired frequency.

Materials and Methods
Construction of the charge pump and antenna was done using EAGLE CAD. Both the designs were fabricated on FR4.

Results
The antenna (figure 2), with the dimensions

\[
\text{width} = \frac{2}{\varepsilon_r + 1} \cdot \frac{c}{2 \cdot \lambda}
\]

was then entered into CST Microwave studio and optimized there. All of the patches are square, and the reflector and director patches were scaled to be consistent with traditional Yagi-Uda Antenna design. The geometric parameters of the antenna were then optimized using CST to attempt to both improve the bandwidth and improve the strength of the null in the S11 parameter. We measured a –7.42 dB return loss (Figure 6) in the S11 parameter at 5.8GHz and noted a shift upwards in frequency due to the fabrication process. The charge pump (Figure 4) was unsuccessful in our trials, however, the method used in the lab may not have been comprehensive. Further testing may vindicate our design.

Acknowledgements
James Steinberg for his assistance in helping us mill the printed circuit boards.
Opportunities and Challenges in Wireless Power Transmission

by Dr. Frank Little
Associate Director of the Center for Space Power
Texas A&M University
OPPORTUNITIES AND CHALLENGES IN WIRELESS POWER TRANSMISSION

Frank Little
Space Engineering Research Center
Texas A&M University

Wireless Power Transmission Background

• Tesla Experiments with standing wave
• Magnetron tube development
• Rectenna development
  – William Brown at Raytheon
• Laser
Background continued

Lastly, there is a third and most attractive method of acquiring velocity. This consists in the transmission of energy from the outside, from Earth.

The projectile itself need not carry “material” energy, i.e., extra weight, in the form of explosives or fuel. This energy could be transmitted to it from the planet in the form of a parallel beam of shortwave electromagnetic rays.

...This method of imparting velocity raises quite a few difficult problems, the solution of which I shall leave to the future.

K.E. Tsiolkovsky, *The Spaceship* (1924)

WPT Demonstrations

- 1964 – Raytheon tethered helicopter
- Beam riding helicopter
- Raytheon 54% end-to-end test
- Raytheon/JPL Goldstone demonstration – 30 kW received over 1 mile
- Beam powered rover
- Canadian SHARP scale airplane flight
- Japanese MILAX scale airplane flight
- Japanese ETHER
- Kansai Power point-to-point
- MINIX sounding rocket
- ISY-METS sounding rocket
- Discovery Channel Maui to Hawai‘i Demonstration
- “Furoshiki” sounding rocket
- Microwave plasma thruster
- Laser rover and flight demonstrations
- Centennial Challenge — laser powered climber
- Airborne Laser
The First Opportunity

- William Brown Raytheon Helicopter
- Peter Glaser Solar Power Satellite patent
- 1970s energy crisis leads to NASA/DoE study

Night-time Earth
World-wide Energy Need

• Increase in global power demand
  – 1990 use—12.2 TW: 2025 need—20-25 TW
  – Greatest need in developing countries
• Desire to maintain CO₂ neutral energy source
• Sustainable energy requires non-conventional sources
• Solar power from space is one option

World-wide rate of energy use increasing-renewables and nuclear flat*

* From US Department of Energy Energy Information Agency
**International Energy Outlook 2006**
Economic development linked to energy — slight improvement in efficiency

* From US Department of Energy Energy Information Agency
  “International Energy Outlook 2002”
Electric Power

International Energy Agency "Renewables in Global Energy Supply", an IEA fact sheet
Alternative Carbon Neutral Strategies

Terrestrial Solar

**CO₂ Sequestration**

**Nuclear Fission/Fusion**

Solar Power Satellite

- Imports energy from space
  - Convert solar energy to electricity in space
  - Transform to radio frequency or laser energy and transmit to earth
  - Receive radio frequency or laser energy and convert to electricity via rectenna or photovoltaic array
- Solar Power Satellite provides almost continuous power
SPS Foundations

- Wireless Power Transmission
  - Raytheon experiments
  - NASA/Raytheon experiments
- DOE/NASA definition study, 1977-1980

Microwave atmospheric absorption

Reference System Design

• 300 GW system of 60 satellites in GEO orbit
• 5 GW Solar Power Satellite
  – Photovoltaic primary energy conversion
  – Wireless energy transmission at 2450 MHz
  – Low microwave power beam density (23 mWcm⁻²)
  – Assembly on orbit by human assisted machinery
  – Retrodirective beam control
  – Proposed 30 year operational life

Reference System Design Limitations

• Technical obstacles
  – Low efficiency photovoltaics
  – Large structure — space and ground
  – Human assembly on orbit
  – Single point failure
• Economic obstacle
  – $100,000 Million to first satellite
Other Past Wireless Power Transmission Opportunities

- Study of terrestrial wireless power transmission for remote village in Alaska
- 1995 NASA Fresh Look study evaluated progress on space based solar power
  - Emphasis on economic evaluation
  - Featured 5.8 GHz wireless power transmission
- SPS 2000
  - 10 MW transmitted
  - 1100 km circular equatorial low earth orbit

“Fresh Look” Study

- Based on technical advances since reference System design
  - Photovoltaic cell efficiency increase
  - Robotics and autonomous assembly
  - Higher frequency microwave transmission
  - Wireless Power Transmission experiments
- Considered many new design concepts
  - Selected a MEO and a GEO design for study
  - Used economic analysis as discriminator
Integrated Symmetric Concentrator Concept

- Multi-faceted thin-film primary concentrator mirror
- High efficiency photovoltaic arrays
- Transmission at 5.8 GHz
- Transmitter can be cooled by radiation

Sandwich concept

- Concentrator mirror
- Photovoltaic array coupled directly to transmitter
- Eliminates high voltage PMAD
- Thermal management problem
**SPRITZ Sandwich Concept**

- Solar simulator
- Photovoltaic array
- and rf transmitter

---

**5.8 GHz GEO transmission efficiency**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Scan Angle (deg.)</td>
<td>0</td>
</tr>
<tr>
<td>Antenna Efficiency</td>
<td>0.950</td>
</tr>
<tr>
<td>Rectenna Edge Power Density (mW/cm²)</td>
<td>0.69</td>
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<tr>
<td>Rectenna Efficiency</td>
<td>0.820</td>
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**Transmitter Efficiency**

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>Value</th>
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<tbody>
<tr>
<td>Subarray Random Electronic Failures</td>
<td>0.960</td>
</tr>
<tr>
<td>Antenna Efficiency</td>
<td>0.900</td>
</tr>
<tr>
<td>Beam Coupling Efficiency</td>
<td>0.921</td>
</tr>
<tr>
<td>Antenna Scan Loss</td>
<td>1.000</td>
</tr>
<tr>
<td>Rectenna Scan Loss</td>
<td>1.000</td>
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</table>

**RF Circuit Efficiency**

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain RF Power Amp. PAE</td>
<td>0.993</td>
</tr>
<tr>
<td>RF Filter Insertion Loss</td>
<td>0.891</td>
</tr>
<tr>
<td>RF Circuit Efficiency</td>
<td>96.37%</td>
</tr>
</tbody>
</table>

**RF Power Into Antenna (MW)** | 2283.65 | 2283.65 |

---

**Other Calculations**

- Nadir Beaming Distance (km) = 35,786
- Transmitted Diameter (m) = 500
- dc Power into transmitter (MW) = 2847
- Gain Link Margin (%) = 3.8
- Element Spacing (λ) = 0.971
- Element Area (cm²) = 23,462
- # Elements = 401
- Mass Density (kg/m³) = 12.7
- Element Mass (g) = 22.66
- Total # Elements = 83,841,253
- Total Transmitter Mass (kg) = 2,689,989
- Total Transmitter Mass (lbs) = 5,930,410
- Total Transmitter Mass (metric ton) = 2,690
- Scan Angle (deg.) = 0.6
- Phased Array VSWR = 1.1
- Rectenna @ Scan from Broadside (deg.) = 0.003
- Scan slant range (km) = 30,796
- Rectenna Array VSWR = 1.1
- Rectenna Random Failures = 0.990
- Rectenna Scan Loss = 1.000
- Rectenna Efficiency = 72.35%
## Recent Space Based Opportunities

- **JAXA roadmap for space based solar power**
  - Operating geostationary pilot plant in 2030s

- **Solaren purchase agreement with Pacific Gas and Electric in California**

- **ISU study of mm wave frequency SBSP**

- **Portable power from space**

- **Electric propulsion**
  - Earth-to-orbit
  - Orbit raising
  - Deep space

## Solaren

- Signed 15 year contract with Pacific Gas and Electric to deliver 200 MW of electric power from space beginning 2016
  - Renewable energy rate premium

- **System characteristics**
  - Free-flying satellite system
  - Microwave wireless power transmission
  - Requires only 4-5 existing heavy lift launches
Solaren Patent figures for reflected transmission (left) and phased array (right) showing formation flying solar power satellite elements
Wireless Power Transmission for SBSP

- **Microwave**
  - Wavelength <10GHz
    - Continuous power
    - Large aperture
    - Tapered beam
  - Single satellite system
    - High initial cost
  - System efficiency high
  - RF interference
  - RF safety issues

- **Laser**
  - Visible or near IR
    - Weather dependant
    - Smaller aperture
    - Uniform beam
  - Multiple satellites
    - Lower cost to “first beam”
  - System efficiency improving
  - No RF interference
  - Laser safety issues

---

Microwave atmospheric absorption

Laser atmospheric absorption

\[ \eta_b \sim 1 - \exp(-\tau^2) \]

\[ \tau = \pi D_t D_r/(4\lambda R) \]

Beam Coupling Efficiency

Microwave Aperture Coupling

Laser Diffraction Limit

\[ r(\text{receiver}) = 0.61 \, d \, \lambda/r(\text{transmitter}) \]
Portable Space-Based Solar Power Electric Energy Supply

Laser-Microwave Hybrid System Concept

- Geostationary Satellite
  - Collects and converts sunlight to electricity
  - Direct sunlight to laser possible
- Laser transmission
  - Small beam size
  - Can use frequencies absorbed by atmosphere
- High altitude air ship
  - Stationed at 20 km altitude
  - Convert laser to electricity with PV cells
  - Uses some power for station keeping
- Microwave transmission
  - Transparent to atmosphere (10 GHz)
  - 30 m diameter transmitter
- Rectenna
  - 40 m diameter receiver
  - Uniform beam maximum intensity – 1 sun/MW

Terrestrial Opportunities

- Point-to-point to remote sites
  - Strait of Belle Isle in Newfoundland, Canada
  - Grand-Bassin on La Réunion
- Long duration aircraft
- Earth-to-orbit small satellite launch
- Remote charging of electric vehicles
Microwave Thermal Propulsion*

Beam heats ceramic heat exchanger

H$_2$ in chamber heated to $>2300$ K and $>160$ atm

Beam tracks rocket through ascent

* Kevin Parkin Thesis 2006

In-Space Opportunities

- Surface power from orbit
- Point-to-point surface from a central station
  - Satellite facilities and habitats
  - Rovers
- Earth orbit raising
  - Direct thermal
  - Electric propulsion
Challenges

- Political
  - Spectrum Allocation
  - Perception
    - Militarization of space
    - “Fear of frying”
- Technology
  - Efficiency
  - Frequency
  - Control
  - Materials
- Beam safety
  - Energy density
  - Ionosphere interaction
- Demonstration
  - Space
  - Terrestrial

Current Component Efficiencies

- Electric transmission
  - Microwave
    - Transmitter
      - Magnetrons at 2.45 GHz reported at 83%
    - Rectenna
      - 2.45 GHz linear dipole element at 91% (Brown)
      - 5.8 GHz at 82% (TAMU)
      - 35 GHz at 70% (ARCO)
  - Laser
    - Electric to laser about 40%
    - 25% direct solar to laser conversion
    - Laser PV conversion about 50%
- Beam propulsion
  - High power tubes
    - 140 GHz Gyrotron at 1 MW CW at 50%
    - 170 GHz Gyrotron at 1 MW at 50%
  - Laser
    - MW class demonstrated
Electronic Component Improvement

- Solid state power amplifiers
  - Literature report 80% efficient F-class GaN HEMT at 2GHz
  - 45 W GaN HEMT up to 6GHz at 60%
- Phase Shifters
  - BST thin film – low voltage S-band shifter
- Solid state and fiber optic laser

![Graph](image1.png)

Microwave atmospheric absorption

![Graph](image2.png)

Laser atmospheric absorption

High Frequency Electric Transmission

- Millimeter wave
  - US Navy WARLOC 94 GHZ radar
    - 10 kW continuous wave
  - Raytheon active denial system
  - JPL 94 GHz rectenna design
- Laser
Beam Control and Steering

2nd Harmonic Retrodirective Array

- Pilot beam from receiving antenna
  - Phase detected across antenna face
  - Phase information used to create conjugate phase information for power beam steering
- Transmitting antenna
  - Modular phase shifted transmitting elements
- Rectenna
  - Efficient low power density conversion
Retrodirective Guidance

• How does it work?
  ⇒ The pilot signal is received at each subarray.
  ⇒ The received phase is used to generate the proper transmit phase.

• What are the advantages?
  ⇒ instantaneous
  ⇒ independent control at each subarray
Classic RF retrodirective array

2\textsuperscript{nd} Harmonic Retrodirective Array
Software Retrodirective System

Optical Retro-Directive Beam Control Architecture
Faster Electronics

• Software controlled retrodirective beam
  – Improved digital signal processor to enable high frequency conjugate phase angle calculation
  – High speed broad bandwidth ADC-DAC (12.5 GS/sec)

Materials

• Influences nearly all aspects of WPT
• Enables technology
2nd Harmonic Retrodirective System

Hardware Retrodirective Control
5.8 GHz Hardware

Solid state transmitter panel

Circular polarized rectenna

Hardware at World Space Congress
Measurement

broadside pattern

Measurement

pattern steered to 2°
Objective: Design and optimize transmitter taper for efficiency while reducing thermal constraints at center of antenna.

System Specifications
- Frequency: 5.8 GHz
- Geosynchronous orbit
- Earth based rectenna
- DC output power: 1.2 GW
- Rt: 250 and 375 m
Antenna thermal management

Proposed Solution

• Study of various tapers
  • Split tapers
  • Energy distributed tapers

Space and Terrestrial Experiments

• Risk reduction
  • New technology – proof of concept
  • Technology improvement
  • Space experiment (if necessary)
  • ISS nadir pointing transmitter
• Technology demonstration
  • Necessary for acceptance
• System scale-up demonstration
  • Japanese plan vs Solaren
Hybrid Technology Demonstration

- Objectives
  - Demonstrate space to earth microwave WPT
    - Measure beam shape and density
    - Demonstrate beam control (retrodirective control)
    - Receive a measurable amount of power (light a diode)
  - Demonstrate laser WPT pointing and control
    - Space to earth
    - Space to space (satellite)

- Use International Space Station
  - Experiment transported to ISS on ATV or HTV
  - Docked on ISS at JEM-EF (Kibo)
  - Placed on ISS robotic arm for experiment

Constraints

- Mass — compatible with requirements for JEM-EF <550 kg
- Size — fit into ATV or HTV carrier and occupy 1.5 docking locations at JEM-EF
- Power and thermal — only available when docked at the JEM-EF
- Electronic — no interference with ISS communications
Hardware Design Goals

- Provide a greater microwave transmitter aperture than the surface of the experiment package
- Use space qualified components
- Provide autonomous power and thermal systems
- Develop retrodirective control system for microwave and laser

Conceptual Design

- Microwave — 35 GHz, TWT tubes
- Laser — CW fiber optic
- Electrical system — dual (120/28) voltage system with Li-ion battery energy storage
- Thermal — ISS fluid loop when docked at JEM-EF, otherwise loop heat pipe with radiators on back of transmitter panels
- Target tracking — gimbal on end of robotic arm for coarse tracking, retrodirective systems for microwave and laser fine tracking
Experimental Package

Experiment

• Package transferred from JEM-EF to robotic arm
• Microwave transmitter panels deployed
• Mechanical coarse tracking of target
  – GPS information and inertial sensor
  – Three-axis gimbal
• Retrodirective system fine tracking control
  – Pilot beam for phased array microwave
  – Retroreflector system for laser gimbal
Portable Space-Based Solar Power Demonstration

Microwave Beaming Demonstration

End-to-end retrodirective microwave beaming system demonstration

Collaborative project with Managed Energy Technologies and Kobe University
Mid-range Test — Transmitter Array

Mid-range Test — Rectenna Array
Long-range Test — Transmitter Array and PV

Long-range Test — Transmitter Array
More Power to Us

How the world works

• Science tells us what we can do
• Economics tells us what we should do
• Politics tells us what we will do
Conclusions

• “It was the best of times, it was the worst of times, it was the age of wisdom, it was the age of foolishness, it was the epoch of belief, it was the epoch of incredulity, it was the season of Light, it was the season of Darkness, it was the spring of hope, it was the winter of despair, we had everything before us, we had nothing before us, we were all going direct to heaven, we were all going direct the other way - ...”

Charles Dickens “A Tale of Two Cities”
ECE 6390 Survey Results

16 Respondents

<table>
<thead>
<tr>
<th>Statement</th>
<th>strongly agree</th>
<th>Partly agree</th>
<th>either way</th>
<th>partly disagree</th>
<th>strongly disagree</th>
</tr>
</thead>
<tbody>
<tr>
<td>This class was the first time that I had ever heard of the concept of space solar power.</td>
<td>9</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>As a student, the end-of-term Microwave Power Transfer Symposium is a valuable experience and worth the time to attend.</td>
<td>7</td>
<td>7</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>The website format of the final report is preferable to a conventional final written report.</td>
<td>7</td>
<td>6</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>I would have preferred an individual project to the group project.</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>I do not like the competitive aspect of the group project.</td>
<td>0</td>
<td>3</td>
<td>6</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>The Space Solar Power group project made this class more work than the average graduate engineering course.</td>
<td>1</td>
<td>8</td>
<td>4</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>As a result of the Space Solar Power project, I have more interest and appreciation of RF engineering.</td>
<td>4</td>
<td>9</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>As a result of the Space Solar Power project, I have more interest and appreciation of solar cells and/or microelectronics.</td>
<td>1</td>
<td>8</td>
<td>5</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>As a result of the Space Solar Power project, I have more interest and appreciation of antennas and/or electromagnetic waves.</td>
<td>5</td>
<td>6</td>
<td>5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>As a result of the Space Solar Power project, I have more interest and appreciation of system engineering concepts.</td>
<td>5</td>
<td>7</td>
<td>3</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>By the end of this project, I have come to the conclusion that Space Solar Power is an impossible undertaking that will never result in an economical energy source for mankind.</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>As a result of this class and project, I plan to study space solar power more in the future.</td>
<td>0</td>
<td>6</td>
<td>5</td>
<td>3</td>
<td>2</td>
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